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The relevance of Magnetized Target Fusion (MTF) to practical energy production

A white paper for consideration by the fusion community and the Fusion Energy Sciences Advisory Committee
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Executive Summary.

The MTF approach is intermediate in fuel density between conventional MFE and IFE. Therein lies an intrinsic advantage in cost because the fusion volume is much smaller than with MFE, and the power requirements are much reduced compared with IFE. The relevance of MTF to practical energy production is not immediately appreciated in many parts of the fusion community, so this white paper is offered as a working document that will be used at Snowmass, and updated and maintained as the issues are studied during the proposed proof-of-principal program [fusionenergy.lanl.gov]. Recent workshops at Los Alamos and Sandia addressed the energy issues of MTF, and this document reflects the results of those workshops. Two possible design approaches were identified, which can be categorized by fast or slow liner speed. In the fast-liner approach, first subjected to engineering analysis in the 1970s [Moses 79], the target chamber and general power plant features have considerable similarity to Inertial Fusion Energy. Thus the fast-liner MTF approach can be viewed as an IFE look alike, and much of the research on IFE power plant systems can be applied to MTF as well. The major difference concerns driver stand off and protection of the driver from the explosive release of energy. A number of feasible solutions were discussed at the workshops and are summarized in this document. One approach is to choose materials for electrical conductors that are compatible with the coolant, and to remanufacture the portion destroyed on each pulse. The alternative slow-liner approach avoids remanufacturing by using liquid metal (Pb-Li) to serve as liner, neutron shield, coolant, and tritium-breeding blanket [Turchi 84]. The advantages and issues associated with these approaches are presented below. Finally, preliminary estimates are made of development cost with the MTF approach to fusion. It appears that MTF would allow fusion to be developed for 1/5 the cost and in half the time compared with conventional approaches. Given the scientific richness of MTF, given that several feasible paths to an MTF power plant have been identified, and given that MTF is *intrinsically* a low-cost approach to fusion, the case for proceeding with the MTF proof-or-principle program seems compelling.

I. Background

With regard to energy application, the 1996 FESAC report on alternate concepts established reasonably low requirements to qualify as proof-of-principle. It assumed that exploratory work established the basic equilibrium, stability, and potential for energy gain. Then it called for physics and engineering analysis to be done during the proof-of-principle program that would identify key issues and further define the research program. As discussed in the April 1998 community-based R&D roadmap [see fusionenergy.lanl.gov], and the proof-of-principle proposal reviewed in July 1998 [Schoenberg 98], the MTF team believed that MTF easily met the requirements for PoP. The proposed budgets for a PoP program included $500K per year for energy system analysis (this was recently increased to $900K), and relatively little effort was directed towards the question of energy relevance for the purpose of proposing MTF for PoP funding.

At issue now is whether MTF merely qualifies for Proof-of-Principle status, or whether it should be considered a serious alternative to other fusion concepts in the long-term quest for practical fusion. If MTF is not relevant to energy, it should not be done, because funding MTF might displace valuable activity that has been judged relevant to fusion energy.

It seems that many fusion researchers view MTF with skepticism in an energy context. The PoP peer review committee served as an accurate and helpful barometer of community opinion when they stated that MTF is "…an innovative proposal that represents a true alternative to existing magnetic and inertial fusion concepts," but the majority of the panel felt "…it is unlikely that this concept will ultimately result in commercial fusion energy production." We disagree with the second part of this assessment, but in fact, the proposal included relatively little information on prospects for energy, and clearly more attention is needed on this aspect of MTF.

Pulsed systems in general, including both MTF and IFE, must struggle with what Jim Tuck called the kopeck problem: the revenue generated by a single pulse of energy is rather small, and any hardware consumed must be replaced for a small fraction of that revenue. (The kopeck also has small monetary value.) Specifically, at 5 cents per kilowatt hour, one gigajoule of electricity is worth $14. Also, the repetition rate of pulses must be large enough that the total power generated provides enough revenue per unit of time to pay for the plant investment. Typically MTF assumes a few GJ per pulse and a rep rate of a pulse every few seconds, a factor of 3-10 larger pulses than IFE, at a correspondingly slower rep rate for power in the range of GW. The allowed cost to prepare hardware for each pulse is therefore a few dollars.

For all these reasons the MTF community has begun to direct more attention to the issue of energy relevance. A workshop on the applications of MTF was held at Los Alamos in February 1999. A second workshop addressing both MTF and Sandia's fast Z pinches for xrays was held at Sandia National Laboratory in April 1999. This white paper grows out of those discussions. It is a working document like the community R&D Roadmap, which we intend to make available and update on the web as work progresses.

I. Los Alamos MTF Applications Workshop

On February 18-19, 1999, thirty four scientists met at Los Alamos, New Mexico, to discuss potential applications of magnetized target fusion (MTF). In an informal poll, about half the attendees began the workshop with the opinion that MTF was highly unlikely or doubtful to result in a practical source of fusion energy. At the end of the workshop a majority stated MTF was possible or highly likely to result in practical energy, and everyone reported a more positive view than they had at the outset.

Scientists attended from 13 institutions: G. Hutch Neilson PPPL, Dick Siemon LANL, Irv Lindemuth LANL, Ron Moses LANL, Kurt Schoenberg LANL, Glen Wurden LANL, Tom Intrator LANL, Ron Kirkpatrick LANL, Fred Wysocki LANL, Martin Taccetti LANL, Richard Gerwin LANL retired, Rod Thurston LANL retired, John Scott LANL, Ricky Faehl LANL, Jim Degnan AFRL, Peter Turchi Ohio State University, Keith Thomassen LLNL, Grant Logan LLNL, Dmitri Ryutov LLNL, Rick Spielman SNL, Per Peterson UC-Berkeley, Steve Dean Fusion Power Associates, Francis Thio NASA MSFC / Massey University, John Santarius Univ. of Wisconsin, Ron Miller UC-San Diego, Anatoly Buyko VNIIEF, Vladimir Chernychev VNIIEF, Boris Grinevich VNIIEF, Vladislav Mokhov VNIIEF, Aleksandr Petrukin VNIIEF, Valery Yakubov VNIIEF, Art Sherwood LANL retired, Damon Giovanielli Sumner Associates, Mike Frese NumerEx

The workshop began with a series of talks that provided concept descriptions, listed the key advantages of MTF, and identified the major scientific or technical challenges in need of resolution. Working groups were formed for the purpose of a) defining critical issues, b) ranking the issues, c) identifying what present knowledge and capabilities can be applied to addressing the critical issues, and d) estimating the cost and time involved in resolution of these issues.

Workshop Agenda

8:30	Overview of MTF	R. Siemon
9:00	LINUS and lessons learned	P. Turchi
9:30	Pulsed spheromak power plant	P. Peterson
10:00	Break	
10:30	CFAR and MHD conversion	G. Logan
11:00	Fast liner power plant study	R. Miller
11:30	Electrical leads: a critical issue	R. Moses
11:45	Stand-off drivers	D. Ryutov
12:00	MTF for Heavy Ion Fusion	I. Lindemuth
12:15	MTF for space propulsion	F. Thio
12:30	Lunch Catered	
1:30-5:00	Break-out groups A&B: Identify and discuss problems, advantages and needed analysis for MTF applications.	

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8:00-9:00	Break-out groups A&B to prepare summary statements	
9:15	Group A synopsis and discussion of results	D. Giovanielli
10:00	Break	
10:15	Group B synopsis and discussion of results	K. Schoenberg
11:00	Group discussion: Assessment of MTF's potential for power or other applications.	R. Siemon

Additional issues included a) what factors determine the economics with lower cost pulsed power drivers, b) target chamber design, c) plasma issues that remain after a successful proof of principle. It was emphasized that the stand-off and plasma issues should be addressed now (up-front), especially concern over impurities. The issues for a LINUS system included a physics update, plasma considerations such as formation and stability, liner energy recovery, material properties, working fluid plumbing, and plasma configurations. Issues for a Fast Liner system included the yield/rep-rate parameter space, COE sensitivity to Q, waste disposal and recycling, energy conversion options, blankets, debris in chamber, neutron and gamma environment and their effect on any vacuum systems, current joints, and optimum plasma configuration. Many of the technology issues are similar to those encountered in other pulsed inertial fusion approaches.

The two major and inter-related concerns were cost (the “kopeck problem”) and technical solutions. The major advantages were that high density relaxes the physics constraints, and recently proposed working fluid liners for pulsed power plants. The cost per pulse and rep rate defined the kopeck problem, and electrical stand-off capability constituted the major technical hurdle. Apart from detailed power plant issues, the $50-100M cost for a break-even demo device is much lower than for either inertial or magnetic burning-plasma facilities, and cost of development was identified as a major advantage for MTF.

A historical review by Peter Turchi outlined the two complementary approaches with different technologies – slow (msec) LINUS approach and fast (μsec) Fast Liner Power plant (FLR) time scale repetitively pulsed power plant cycles. These power plant studies are 20 years old, and one conclusion of this workshop was that these could be updated to reflect modern technological advances with a minimum of cost and effort. As a result, the MTF community is proceeding in this direction.

Per Peterson (UCB) outlined issues for liquid protection (FliBe, LiPb) of pulsed MFE power plants. Pulsed systems address major problems of MFE such as first wall materials and magnet cost.

Ryutov described a Fowler design for a cyclic pulsed MTF power plant with liquid liner wall. He also outlined a scheme for converting the kinetic energy of fast projectiles into magnetic energy, by using a disposable flux compressor that would be dropped every second or so into reaction chamber together with the attached (disposable) liner assembly.

G Logan described interesting ideas for coping with large impulse fuel cycles in the Yield>Gjoule/pulse range, many of which originated with Velikhov, including direct MHD conversion, vaporizing blankets for a thermodynamic Rankine cycle. It was thought that while MHD and direct conversion are extremely interesting and potentially very important, at the present time it would be better to focus on things that rely less on new technology for energy conversion.

RL Miller of UCSD described the FLR study (Moses, Krakowski, Miller) with a rep rate of 0.1 Hz that addresses many current MTF issues and could be updated at minimum effort. Discussion of the radioactive disposal problem led to the realization that on-site remanufacturing of electrode and mechanical parts (eg FliBe) minimizes this problem. Nevertheless, it became obvious that most of the MFE community (including MTF advocates) have mostly forgotten the LINUS and FLR studies.

Lindemuth outlined the parameter regimes of ICF and MFE, and the advantages of MTF which is between these two extremes. Magnetically insulated fusion dramatically increases the confinement over ICF, at much lower cost.

Thio outlined the space propulsion needs of NASA for the next generation of fusion based rockets. NASA is showing considerable interest in MTF, and Thio has an innovative idea for stand-off delivery of power.

It is necessary to provide mitigation of the blast and radiation effects produced by the fusion target on each repetition of the system. Ron Moses presented an analysis that showed the cost of material leads could rise to a substantial fraction of the ultimate cost of electricity. It is possible that a more energy efficient design and recent advances in manufacturing of complex items could reduce the costs, but this issue was deemed one of the most critical. The space propulsion application pushes the frontier for stand-off drivers by avoiding the use of material electrical connections, and both experimental and computational work is encouraging for a demonstration of this approach.

Additional major issues included a) what factors determine the economics for low-cost repetitively pulsed power drivers, b) target chamber design for blast containment, c) plasma issues that remain after a successful proof of principle. It was emphasized that the stand-off and plasma issues should be addressed now (up-front), especially concern over impurities. The issues for a LINUS system included a physics update, plasma considerations such as formation and stability, liner energy recovery, material properties, working fluid plumbing, and plasma configurations. Issues for a Fast Liner system included the yield/rep-rate parameter space, COE sensitivity to Q, waste disposal and recycling, energy conversion options, blankets, debris in chamber, neutron and gamma environment and their effect on any vacuum systems, current joints, and optimum plasma configuration.

Assuming that an MTF program gets underway, a plan of research based on liquid walls for chamber protection was proposed to address the major issues. First, new work will be required to address the stand-off, rep-rate and connections issues: a) perform an analysis of each stand-off concept, b) derive rep-rate ranges for each, and c) define, design, and perform key experiments. Next, it is important to establish what gain is required for each approach. This is greatly facilitated by previous systems studies, including the Fast Liner Power plant study. Finally, integration of the potential system components such as chamber, driver, waste management, etc., will require a baseline power plant system study, including scoping studies and cost estimates. One estimate of the effort required to address the major issues was about 6 FTEs, which would cost roughly $900K per year.

II. Fast Liner Power plant

Two possibilities for stand-off delivery of MTF power have been discussed:

A. beam or kinetic energy transport of power through openings in the blanket structure; or
B. delivery of power with electrodes that are integrated into the blanket/coolant material and are partially destroyed on each pulse.

Here we briefly discuss case A, which is most similar to conventional IFE. Case B introduces significant new issues, and these are discussed at greater length below.

In case A, laser, electron or heavy ion beams could be used to implode the pusher of a magnetized target in a manner similar to the way in which such beams are used to implode conventional, unmagnetized inertial confinement fusion (ICF) targets. Many ideas are possible and have been examined in a preliminary way to establish their feasibility [Drake 95]. Preheating and magnetization of the target could be achieved by a number of means, including, for example, an auxiliary beam [Bangerter 78]. Power plant considerations would be similar to conventional ICF power plant systems. However, the reduced driver requirements (lower power, lower intensity, larger target diameter, reduced convergence and hence drive symmetry, reduced ρr, and no pulse shaping requirements) potentially offer advantages in cost and efficiency to such a power plant system. In fact, if the focusing required for conventional ICF targets cannot be obtained, heavy ion fusion may be feasible only with magnetized targets, and this possibility has been recently discussed by the European fusion community [Sharkov 97 and Churazov 97]. At this point in time, the feasibility of power production based upon beam driven magnetized targets simply has not been evaluated to the same degree that unmagnetized target systems have been evaluated.

A second example for delivering stand-off energy through openings in the blanket structure would be to transfer energy with a high-velocity solid projectile launched at a distance from the reaction region. Solid projectiles can be energy rich but do not have the velocity required for a conventional ICF target. However, the lower implosion velocity required by magnetized targets matches more closely the realm of performance realizable with solid projectiles [Tidman 80]. Alternatively, flux compression could be used to convert kinetic energy to electrical energy, which in turn could drive a higher-velocity liner.

In the remainder of this fast liner section we focus on case B: the specific possibility of replacing current-carrying electrodes on every pulse. The major advantage is elimination of the high-cost driver in conventional IFE by substituting a much lower-cost electrical pulse generator. Also, because electricity goes around corners, the electrodes and blanket/coolant material can be arranged to avoid any low-density escape route for the neutrons. With no need for power-delivery ports, replaceable current leads through the blanket can provide good neutron shielding to sensitive items such as the connection hardware between the pulsed power supply and the replaceable hardware. This approach is the most direct extrapolation of the proposed proof-of-principal experiment. It also seems to generate the most skepticism with researchers who are unfamiliar with the concept, so a focus on the subject is appropriate in this white paper.

A Conceptual Design of the Fast-Liner Reactor (FLR) for Fusion Power [Moses 79] provided a self-consistent analysis of all the issues important to remanufactured electrodes for power delivery. That study forms a good basis for reexamining the potential of MTF today. The strategy of fast liners is intrinsically pulsed. The idea is to work with megagauss magnetic field, megabar pressures, and therefore small plasma size and energy [Siemon 99]. By "fast" we mean 3-30 mm per microsecond, which is fast compared with LINUS (described below), but slow compared with Z pinch radiation sources studied at Sandia National Laboratory.

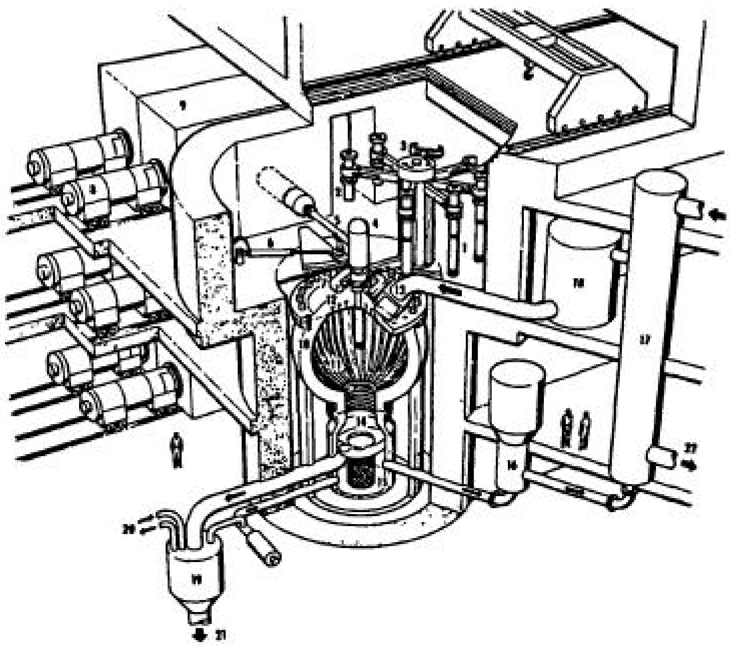


Fig. II-1. Isometric drawing of Fast-Liner Reactor nuclear island for the low-yield case given on Table II.I. Component identification: (1) liner/leads assembly ready for implosion; (2) remains of imploded-liner/leads assembly; (3) liner/leads carousel; (4) plasma preparation; (5) power leads; (6) hydraulic arm to move power connection; (7) blast vessel head and liner/leads feedthrough; (8) homopolar motor/generator; (9) inductive transfer element, transfer capacitor, and switches; (10) blast vessel (2.6-m radius, 013-m wall thickness); (11) shock extending ribs; (12) lithium-spray spargers; (13) lithium inlet and control valve; (14) solid debris skimmer; (15) lithium sump and storage; (16) lithium pump; (17) Li/Na heat exchanger; (18) lithium surge and storage tank; (19) solid debris separation; (20) lithium drag stream to tritium recovery; (21) solids debris to recovery and refabrication; (22) secondary sodium coolant.

The various issues of explosion containment, thermal-hydraulics of liquid walls, tritium processing and so forth were considered in the FLR power plant study and have been addressed since that time in greater detail in the literature on inertial fusion energy (IFE). In the FLR, Fig II-1, the blanket and blast absorbing material was liquid lithium, and the liner and electrode structure was assumed to be copper or aluminum. Recent HYLIFE studies [Moir 96] have identified FLIBE as a preferable coolant for safety and neutronics reasons. A useful assessment of safety issues can be found in a recent INEL report [Cadwallader 99]. To a large extent, MTF fast-liner energy systems can look like IFE systems, and the focus here is on what distinguishes MTF from IFE.

How disposable electrodes would work. Material selection is a major consideration. As one possibility, Per Peterson suggests that FLIBE might be used for the main insulator and blanket/coolant material, and that tin (Sn) be considered for the electrode material in what he terms a binary-coolant materials system. FLIBE melts at 459 °C, and tin melts at 232 °C. As indicated in Fig II-2, the electrode/insulator assembly would be prepared in the target factory at a temperature less than 232 °C. Each pulse of fusion power would melt most of the assembly, and the residual solid electrode material would be dropped into a molten mixture at the bottom of the target chamber. The energy for melting the residual would be 1.4 MJ/kg, or less than 100 MJ/target compared with yields of several GJ. Tin is much denser than FLIBE and readily separated because it is immiscible.

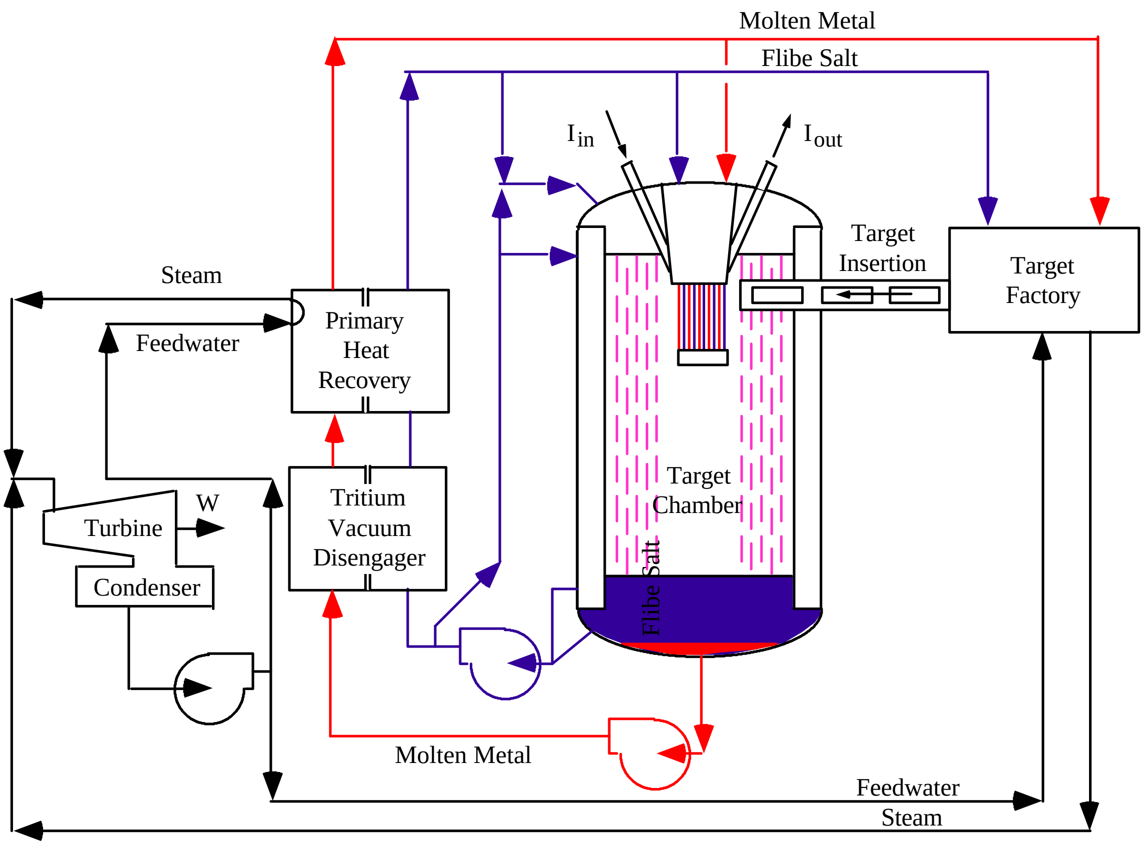


Fig. II-2. Schematic flow diagram for the binary-coolant system in a pulsed-power fusion electrical plant.

The largest and most complex structure to be replaced involves the tin electrodes used to deliver current to the imploding liner. Fortunately the electrodes do not require close tolerances in fabrication. Possibly an injection molding process for tin conductors would be used with cast insulating parts made of FLIBE. At the recent SNL workshop Jim Hammer suggested making the electrodes in the form of many wires strung by a mechanical sewing-machine-like device. The insulator would be a continuous layer of solid FLIBE between the conductors (wires or solid) as shown in Fig 2. In the power plant chamber environment, these solid materials would be like ice cubes at room temperature that have life times measured in minutes. The estimated melting rates are under 1 mm/minute, giving electrode lifetimes substantially longer than the required few seconds.

In addition to the high-current electrodes for liner drive, a low-current conical theta-pinch coil fed by relatively light-weight electrodes is required for plasma formation, and a quartz envelope to contain DT gas is needed as indicated in the sketch of Fig. 2. The one precision component is the imploded liner, which can be inexpensive because of its simple shape and relatively small mass (typically less than 1 kG).

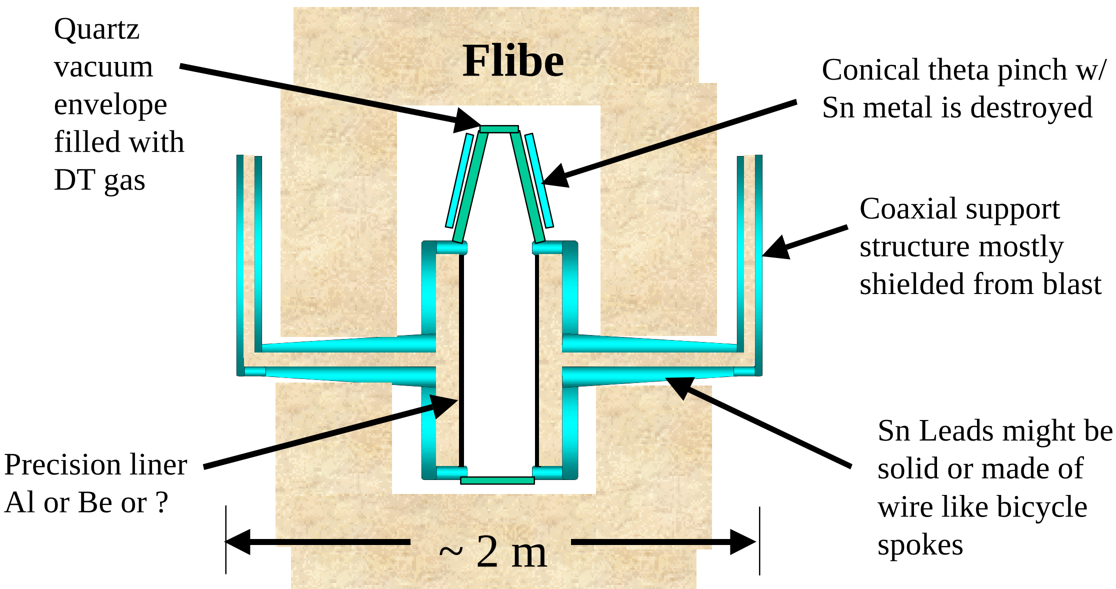


Fig 2. Components of MTF target system.

To illustrate cost feasibility, we assume that the imploded liners (targets in IFE terminology) generate 4.0 GJ of fusion energy. For a repetition rate of 0.25 Hz, 10% recirculated power and 45% cycle thermal efficiency, the net electrical power generation is 400 Mwe. With electricity revenues of $0.05/kWh, each target provides total revenue of $22. If 10% of the total electricity cost ($2.20/target) is allocated for constructing the fabrication plant for casting, machining and assembling targets, the target fabrication plant must be constructed for an overnight capital cost of $225 million (with a 7% annual interest rate). Most materials are recycled and by choice of binary coolant materials little energy is involved in the fabrication. Meeting the cost requirements may be seen as reasonable when one realizes that coke bottles, which require melting glass and equipment for injection molding to sub millimeter tolerances, are manufactured in large numbers for a few cents per bottle.

In addition to good electrical conductivity and suitable melting temperature, tin is also attractive because of its low induced radioactivity. While remote fully robotic processing is required for electrode fabrication, the decay curve shown in Fig 3 is attractive from a radiation waste perspective. Isotopic conditioning of the tin would have potential to further improve waste disposal characteristics, and these issues will be studied as part of planned MFE liquid wall investigations for lithium-tin systems.

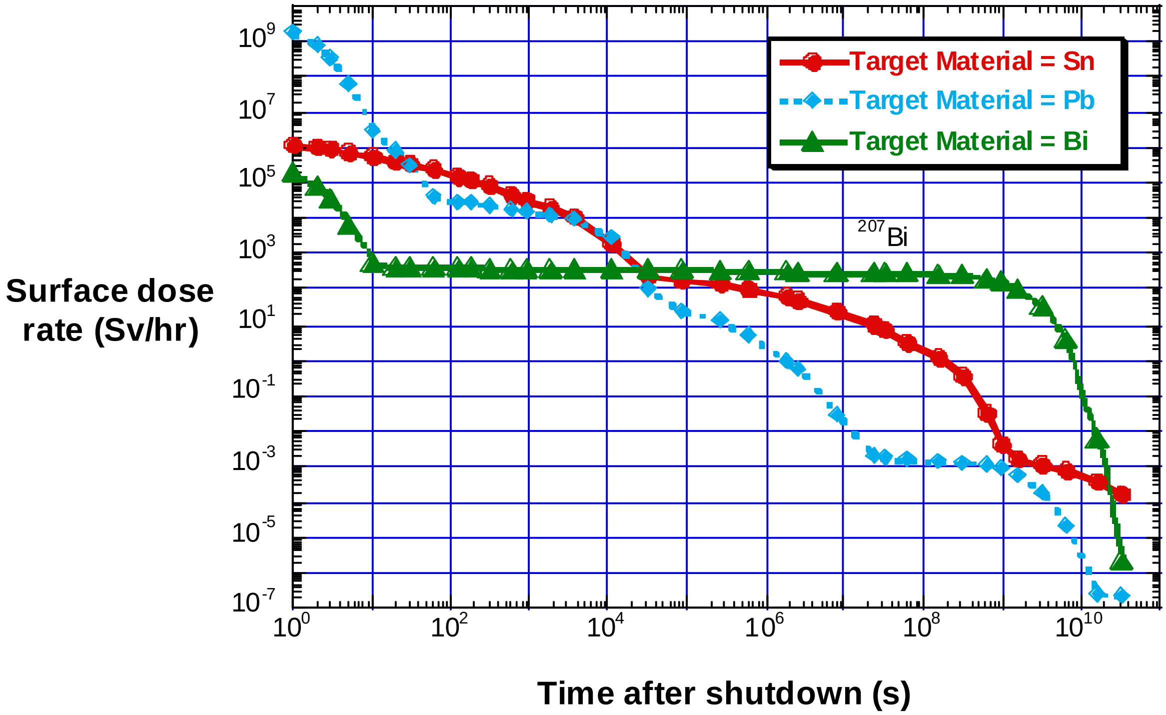


Fig 3. Surface dose rate from proposed MTF target materials following 30 years of irradiation at 2500 MW fusion power. Assumes that target materials are recycled on a weekly basis. (Credit J. Latkowski, LLNL)

Many of the generic advantages to Inertial Fusion Energy can be seen in the HYLIFE studies. Modular development is a major attraction. The necessary driver and chamber engineering can be developed mostly independent of target physics optimization. This is true for both MTF and IFE. From the chamber perspective, the attractive features to HYLIFE include:

- Structure is highly shielded from 14-MeV neutron damage by a thick liquid blanket
- Structure engineering is conventional and uses standard materials
- FLIBE greatly reduces safety hazards associated with liquid Li
- FLIBE is effective for tritium breeding and allows low tritium inventory

FAST LINER Advantages, issues and work needed.

To summarize, in addition to the HYLIFE features described above, the fast-liner approach has the following **advantages**:

- Plasma energy-confinement requirements are quite modest (microseconds in real time, and small compared to many characteristic plasma times such as impurity-penetration time scale).
- The pulsed nature of the process makes unimportant a whole class of instabilities with growth times exceeding the implosion time. In particular, instabilities developing on the resistive time-scales of a plasma and/or of a liner occur on a time scale long compared to the implosion and burn time.
- Facilities to study and develop the concept are small and inexpensive.
- Electrodes can be made of a metal such as tin compatible with FLIBE as the primary blanket/coolant material.
- Complete shielding of the surrounding blast-containment structure is consistent with feeding electrical power through the blanket/coolant (*ie.*, no ports penetrate the blanket).

Energy system **issues** that require further study include the following:

- Fabrication details, methods of making connections, and cost estimates for electrode structure
- Mechanical, electrical, and chemical (corrosion) properties of FLIBE, tin, and other needed materials
- Blast containment and thermal-hydraulics associated with GJ energy release
- Detailed estimates for cost of plasma formation hardware and implications of a quartz insulator
- Rep-rated electrical power system

III. LINUS (slow-liner) Power Plant

We argue in the fast-liner section that the MTF approach to energy application can be an IFE look alike, with some advantages and certain additional issues, such as electrode remanufacture in the case of that specific design approach. Here we consider a completely different alternative that arose in the 1970s with precisely the issues described above in mind. A. Robson, P. Turchi, and colleagues suggested an approach that retains many of the advantages of liner compression to achieve small high-energy-density fusion, while avoiding the major draw back of replacing hardware. They studied the use of a liquid metal liner.[Turchi 84] The essence of the LINUS approach is to recover a large fraction of the kinetic energy of the liner following implosion. A lead-lithium eutectic was selected as the liquid liner. The recovery of kinetic energy is made possible by rotating the liquid to avoid Rayleigh-Taylor modes at peak compression, which maintains control over fluid motion throughout the cycle. The liquid must move at a speed considerably smaller than the speed of sound (about 1600 m/s for Pb-Li). This avoids energy density that would vaporize the liner and energy losses associated with compressibility of the liquid metal.[Turchi 74] The slower liner also implies less peak pressure than with fast liners, and the maximum magnetic field is on the order of 0.5 megagauss. The plasma size must be initially on the order of 1 meter, and the dwell time is on the order of 1 millisecond. The plasma must therefore have relatively better energy confinement and requires more thermal energy content than with fast liners. Energy, on the other hand, with a liquid-metal liner can be very inexpensive, because it can be stored and delivered with compressed gas. The work done by a 3000-psi piston (200 atmospheres) moving 50 cubic meters of liquid metal is 1 GJ!

A detailed summary of the LINUS project can be found in [Turchi 84]. A thick liquid liner adiabatically compresses a pre-formed Field-Reversed Configuration (FRC), which would be translated into the liner (prior to its implosion) from a formation region. The liner was assumed to be made of LiPb (20 atomic percent of Li, 80 atomic percent of Pb), and have a thickness ~ 1 m, so that it would almost completely absorb fusion neutrons and thereby protect the outer part of the fusion power plant from the neutron damage. It would also be used to breed the tritium.

To stabilize the inner surface of the liner near the turn-around point, the use of rotating liners was suggested [Book 74, Barcilon 74, Turchi 76]. The centrifugal force is directed against the effective gravity force near the turn-around point for stabilization. Rotation can be achieved by tangential injection of the liquid metal near the outer radius. The NRL program demonstrated the feasibility of rotational stabilization in a number of experiments. Rotating liners of liquid sodium-potassium alloy were imploded electromagnetically [Turchi 76], providing the first experimental verification of rotational stabilization [Baricilon 74] of Rayleigh-Taylor modes on the inner, decelerating interface between liquid metal and vacuum magnetic field. The concept of piston-driven implosions to stabilize the outer surface of the liner implosion was also developed and demonstrated, with reversible liquid implosions of excellent quality and efficiency provided by axisymmetric piston-drive techniques [Turchi 77, Burton 77].

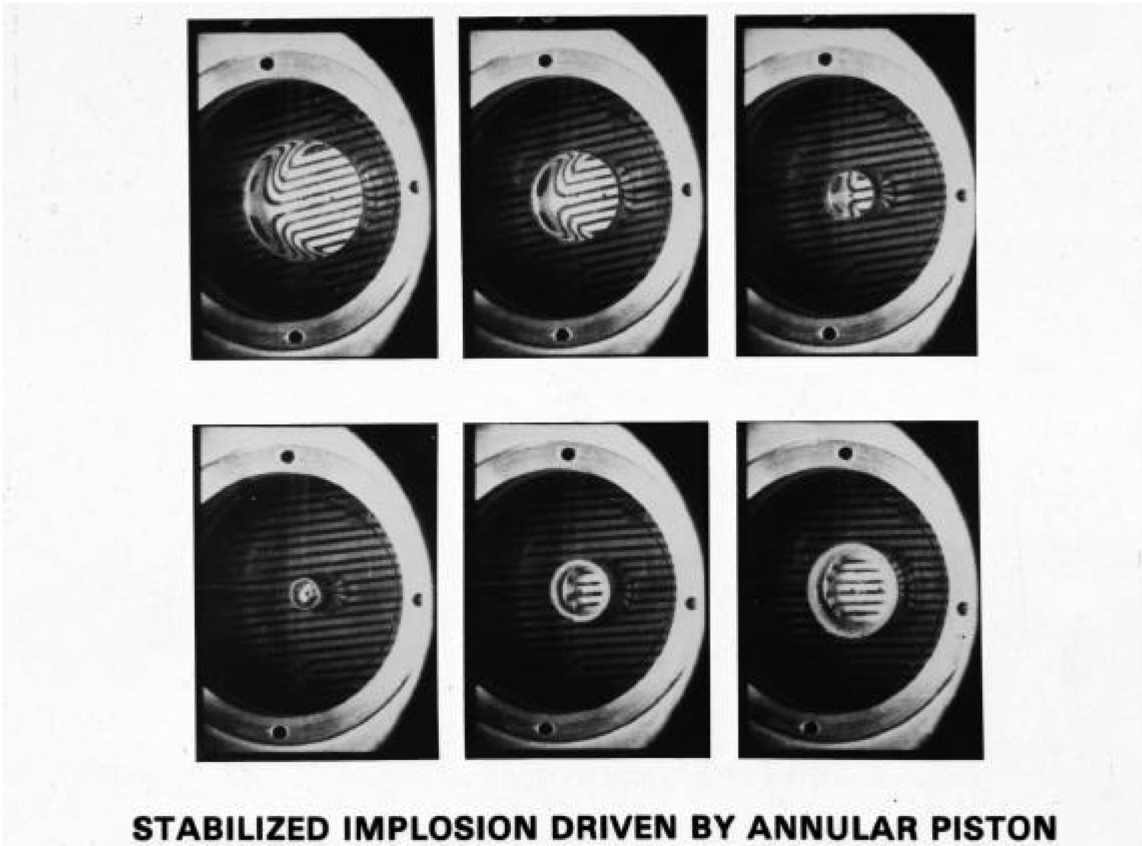


Fig IV1. Experimental data from NRL showing a stable liquid inner surface during implosion and rebound.

For liner compression in a power-plant context, the use of mechanical pistons driven from outside by a high-pressure gas was envisaged. The pistons need to be shaped in such a way as to impart not only radial but also (inward) axial momentum to the liner, so as to prevent axial ejection of the liner material.

A schematic of the power plant is shown in Fig. IV2. The FRC will be injected into the liner from the left, whereas the right end will be used for the pumping. The FRC needs to be compressed in the radial direction only. The FRC equilibria are such that, if the FRC is compressed radially, it also contracts in the axial direction. For the radial convergence a (defined as the ratio of the initial to the final radius) the axial contraction (defined as the ratio of the initial to the final length) is $a^{2/5}$ [Grossman 80]. The plasma density in the final state will be ~10^{18} cm^{-3}, the plasma temperature ~ 15 keV, and the magnetic field ~ 0.5 MG (i.e., the magnetic pressure in the final state will be 50 times higher than the drive pressure, which will be 200 atm).

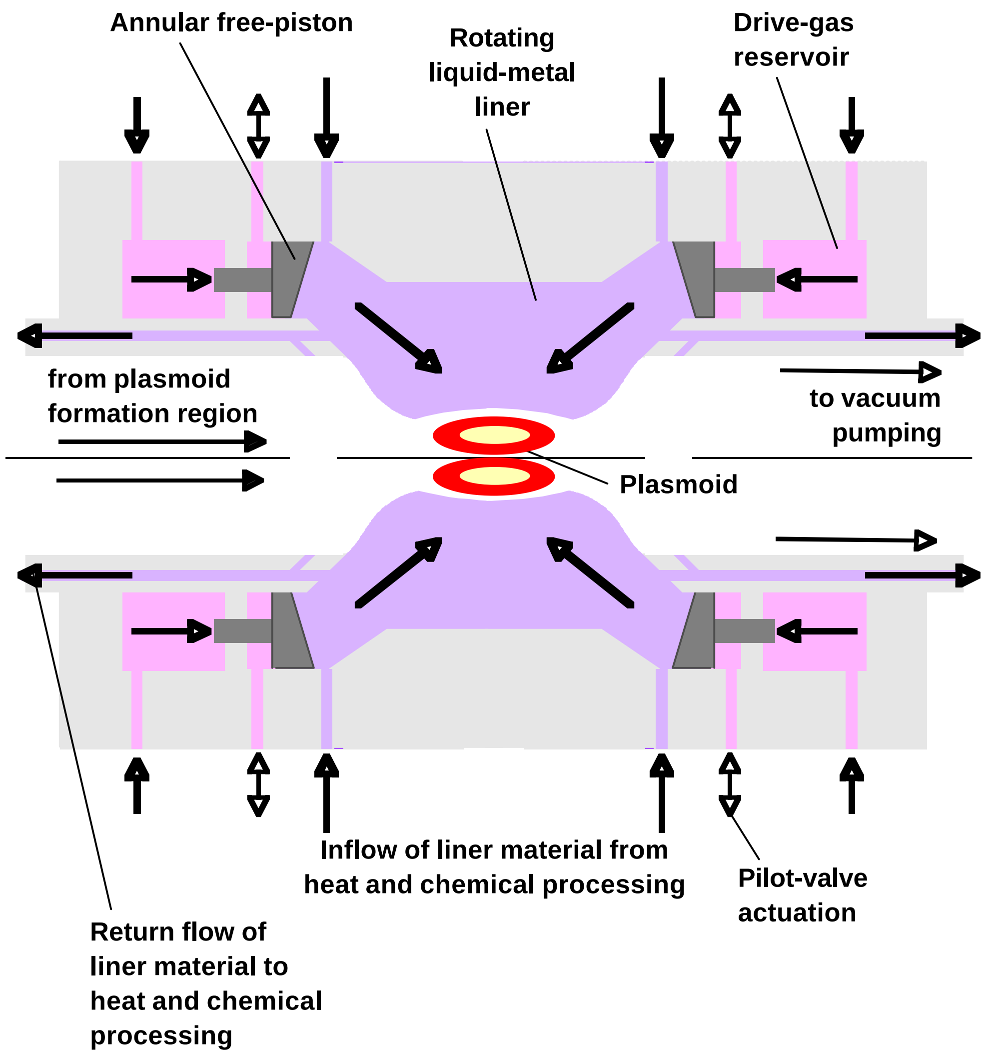


Fig IV2. Schematic arrangement of a LINUS Fusion Power plant

Some other power plant parameters are presented in Table 1 (a somewhat shortened version of the Table IV of [Turchi 84]). Note that a relatively low Q value is still compatible with good economic characteristics of the fusion power plant, because the liner energy is almost completely recovered after each shot.

TABLE 1

Sample LINUS power plant design [Turchi 84]

DESIGN CHOICES	CALCULATED PERFORMANCE
Liner Material: Pb-Li	Output Thermal Power: P_H=1790 MW(H), ν=1 Hz
Radial Convergence: α=10	Liner Rotation Power: P_R=19.1 MW(e)
Compressed Plasma Temperature: T=15 keV	Plasmoid Source Power: P_p=33 MW(e)
Drive Pressure: P_D=200 atm	Total Electric Power: P_T=597 MW(e)
	Minimum Circulation Fraction C_m=9.2%
DERIVED VALUES	Net Electric Power: P_N=507 MW(e)
Outer chamber Radius: r_T=5.1 m.	
Compressed Field: B=0.54 MG	
Operating Q-Value: Q=1.55	
Initial Plasma Temperature: T_i= 377 eV	
Initial Plasma Radius: r_0=1.9 m	
Initial Plasma Length ℓ_0 =7.8 m	
Compressed Plasma Length: ℓ=3.1 m	
Initial Plasmoid Energy: E_i=13 MJ	

Significant developments have occurred since the pioneering work of the 1970s that may significantly improve power plant potentialities of a LINUS system. These developments include:

1. Experimental demonstration of a possibility of translating the Field-Reversed Configuration (FRC) by a distance exceeding several its lengths [Rej 86, Himura 95]. The FRC was even reflected from the magnetic mirror without a significant loss of energy - a sign of the robustness of this configuration.
2. Realization of the desirability of the regimes of a so-called wall confinement. From the studies carried out during the past decade, it became clear that the confinement of plasma with beta less than 10-20 does not lead to a radiative collapse of the near-wall plasma layers [Vekshtein 90, Ryutov 98]. The wall-confined FRC is to be compressed not only radially but also axially, maintaining its initial elongation, and making implosion geometrically self-similar, with contraction equal to the convergence [Drake 95]. This, in turn, allows one to reach higher Q's with the same radial convergence, or reduce requirements on the radial convergence, or reduce requirements to the FRC formation system.
3. Realization of the existence of a number of plasma configurations suitable for the subsequent adiabatic compression by the conducting shell [Drake 95, Siemon 99]. These configurations include, in addition to the FRC, a spheromak, a diffuse Z-pinch, and a linear system with end-plugs. Basic scaling laws for all these systems in 3D geometrically self-similar implosions are essentially identical [Drake 95].
4. Identification of significant potentialities for the shear-flow stabilization of the FRC configuration [Steinhauer 98]. This mechanism may considerably

increase the parameter domain where FRCs are sufficiently stable. A region of s-parameters approaching many tens may become attainable.

5. Identification of a new non-MHD effect which may provide much better (than previously expected) stabilization of the curvature-driven modes [Ryutov 95]. This effect is related to a presence of mirror-trapped particles in the zones of a weak magnetic field near the X-point, where the curvature is large, and the drift frequency exceeds greatly the growth-rate of MHD perturbations.

There has not been a recent analysis of the LINUS concept. One can however expect an improvement in the power plant parameters by introducing a 3D compression and reaching regimes with beta~3-10.

At the Los Alamos February 1999 workshop, some new ideas closely related to LINUS were presented. They are based on the spherical adiabatic compression of a pre-formed spheromak using a LiPb working fluid. An analysis by Ken Fowler is available as a LLNL report [Fowler 99]. Main parameters of a power station based on this approach are listed in Table 2, and the schematic of the power plant is shown in Fig.IV-3.

The spherical nature of the implosion allows one to reach fusion temperatures starting from a lower initial temperature than in the LINUS case, although the radial convergence is the same. Also, it allows one to start from the initial state with a beta<<1 and still reach beta~1 in the final state. This is an important advantage in the case of a spheromak, because there exist well established experimental techniques for forming beta<1 spheromaks (whereas it has not yet been shown experimentally that beta~1 spheromaks can be formed). This design does not exploit the possibility of beta>1 in the final state; such regimes may become attainable at somewhat higher initial betas or increased convergence and may further improve power plant parameters.

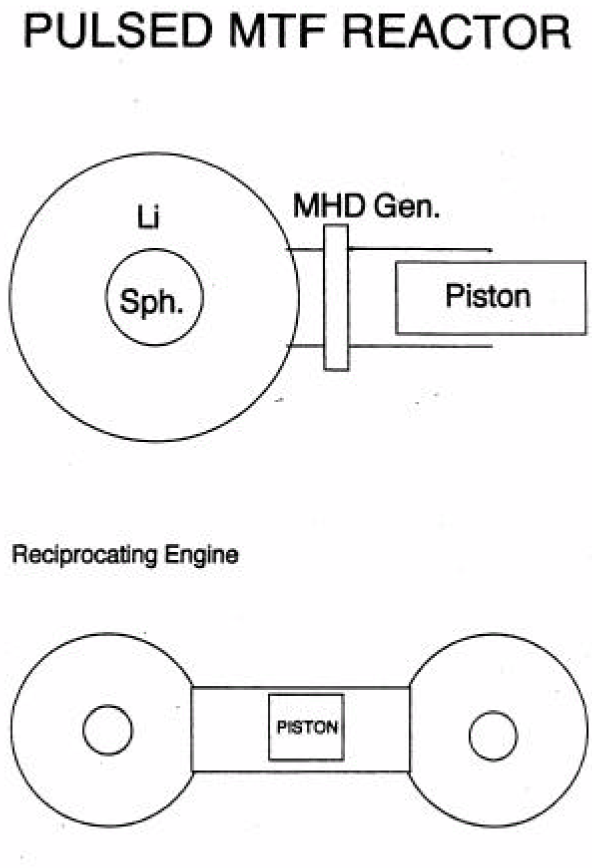


Figure 1. Pulsed Spheromak Reactor with Adiabatic Compression

The feasibility of controlling hydrodynamic evolution of the liner in the LINUS concept, or of the working fluid in the compressed spheromak concept, needs study. This part of the problem could possibly be addressed in medium-scale hydrodynamic experiments. Effects of a finite compressibility of LiPb should be studied more carefully. It would also be desirable to demonstrate the feasibility of forming initial plasma configurations with necessary parameters. Related experiments outside the MTF project are underway: the FRC experiment in the University of Washington, and the spheromak experiment at LLNL.

TABLE 2

Example parameters of a spheromak-based MTF power plant (from [Fowler99])

INITIAL PARAMETERS	COMPRESSED STATE
Initial Density 10^{15} cm^{-3}	Compression Ratio 7
Initial Temperature 0.2 keV	Compressed Field 0.65 MG
Initial Field 13 kG	Dwell Time 1.2 ms
Initial Flux Conserver Radius 180 cm	Yield 3 GJ
Initial Magnetic Energy 10 MJ	
ENGINEERING PARAMETERS	
Maximum Magnetic Pressure 17 kBar	
Rep. Rate 0.4 Hz	
Net Electric Power 250 MW	

Advantages, issues and work needed.

To summarize, the slow-liner approach has the following **advantages**:

- The kinetic energy of the liner is mostly recovered and no replaceable electrodes (or other target fabrication issues) are involved.
- The blanket and coolant material serves also as a medium for liner compression.
- The conversion of compressed gas energy to plasma energy is inexpensive.
- Plasma energy-confinement requirements, while larger than with fast liners, are still modest by the standards of fusion with conventional magnetic field strength.
- As with fast liners, the pulsed nature of the process makes unimportant a whole class of instabilities with growth times exceeding the implosion time. In particular, instabilities developing on the resistive time-scales of a plasma and/or of the liner occur on a time scale long compared to the implosion and burn time.
- Relatively modest facilities would allow significant progress on this concept.

Slow-liner **issues** that require further study include the following:

- Plasma formation and confinement properties required for the slow-liner regime
- Hydrodynamics including turbulence for rotating Pb-Li liners including three-dimensional effects in the velocity regime of interest.

- Wall-plasma interactions under the conditions of peak compression.

IV. Cost of Development for Fusion

The fusion program is faced with a dilemma. On the one hand the program is urged to focus on the scientific underpinnings of fusion, and to forget development strategies because energy is abundant and cheap. On the other hand the program, and scientists making proposals, are asked to justify directions for research in part on whether they lead to interesting energy systems and low-cost development paths. A good resolution of this dilemma is found in the recent community-based road map (http://www.fusionscience.org/roadmap.pdf), which offers an R&D process to evaluate opportunities rather than a pert-chart-like schedule for development of a specific product.

In the same spirit that the fusion program roadmap sets targets for development costs, we now discuss the targets for development that apply to MTF. The numbers are obviously less certain than for the more mature fusion concepts being studied, but the intrinsic advantage of small size and low-power drivers suggests such a large reduction of development cost that the inaccuracy of the numbers is probably not important.

For estimates we base MTF development cost on the HYLIFE studies. As already noted, MTF with fast liners looks very similar to IFE in development requirements. We have also reviewed the LINUS approach with respect to costs, and it appears to be surprisingly similar. However, for the present purpose we take the more extensive and up to date work represented by HYLIFE as the most reliable.

HYLIFE vs. MTF 1-GW
Capital Costs ($M)

Rough guesses

		HYLIFE II	MTF
	Balance of plant	637	637
Different →	Driver	909	300
Different →	Target Chamber	117	234
	Flibe coolant	35	35
	Structures	67	67
	Remote Maint.	50	50
Different →	Target Factory and tritium mgmt.	121	363
	Total	$1935	$1800

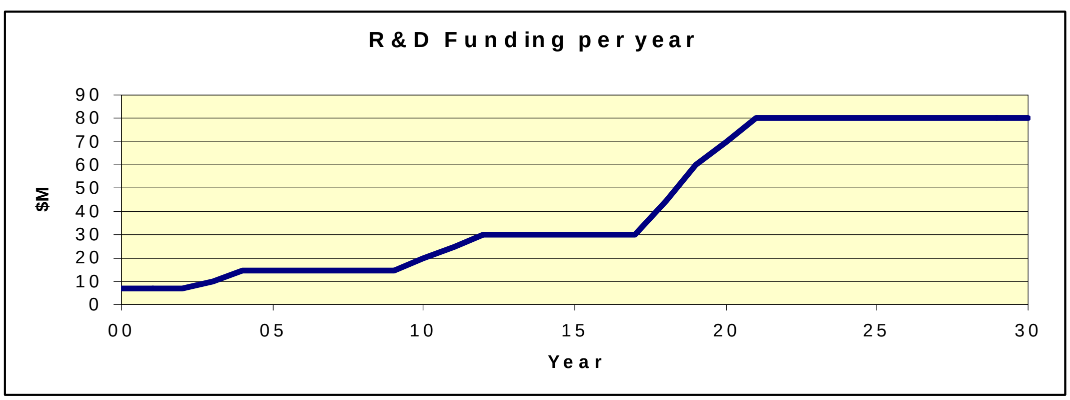
Electricity ~ 5 cents/KW-hour

As seen in the above table, the most significant cost element in a HYLIFE system is the driver cost. With the fast-liner MTF approach, this could be reduced considerably. It should be noted that much larger and more rapid electrical energy pulses are needed in an inertial system using lasers or heavy ions than in an MTF system. And electrical power is only one aspect of conventional ICF driver requirements. The number chosen here is based on the assumption that rep-rated energy would cost about $3 per joule, and about 100 MJ of energy would be required to drive the fast liner.

The cost for the target chamber must be larger to accommodate higher yield so the HLIFE estimate is doubled. The target factory is expensive, so the HYLIFE estimate is tripled, which is consistent with the earlier discussion of target fabrication. For all the remaining items there is no distinction between MTF or IFE.

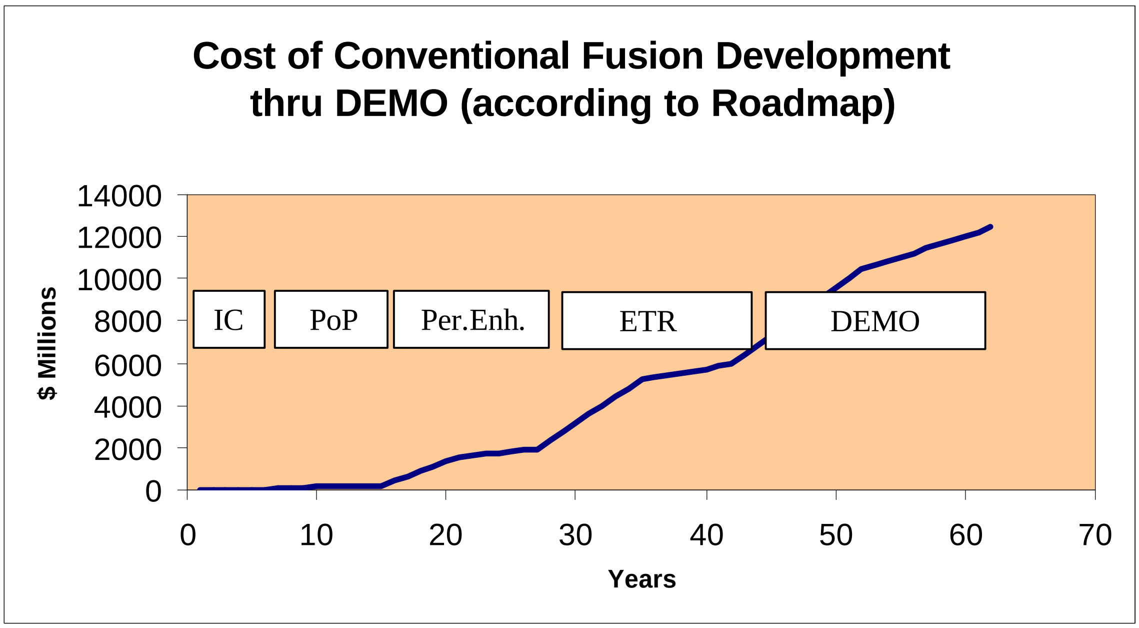
One concludes that a sensible estimate for the cost of a GW MTF power plant is $1.8 billion. Using a roll-back logic, a DEMO that addresses many critical engineering issues should be possible to construct for about half that amount, or say $800 million The anticipated steps of development can be summarized as follows.

PoP	Use Shiva Star at Phillips Laboratory to document FRC heating to keV temperatures by liner implosion, with Q_{equiv} = (DT equivalent fusion energy)/(liner KE) = 0.01-0.10 3 years at $7M/year ($10M facility already exists)
Perf.Enhanc.	Expand efforts to optimize plasma targets (spheromaks, etc…) Use ATLAS at Los Alamos to obtain Q_{equiv} = 0.1-1.0 in ~2 years Optimization and assessment requires ~ 7 years at ~ $20M/year ($50M ATLAS facility will be available)
ETR	Choose LINUS or FLR approach. Test rep-rated power supply in finite duration burst mode. 8 years at ~ $30M/year (requires $250M facility)
DEMO	250-MW unit; 1-10 GJ yield; 0.1-1 Hz; Reliable rep-rated containment. Issues of nuclear materials and tritium handling. 12 years at $80M/year (requires $800M facility)

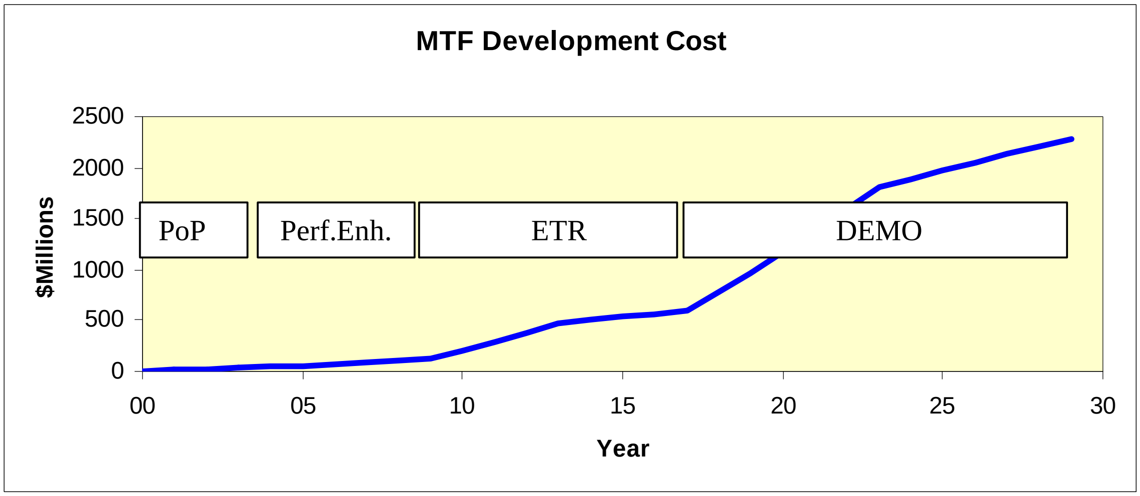


The needed operating budgets are estimated in the above figure, assuming that operating budgets should be on the order of 10% of facility cost and ramp up during construction.

It is especially important to realize that in such a development scenario, scientific optimization would continue during the ETR and DEMO stages in parallel using inexpensive single-pulse facilities. A major advantage to ICF and MTF is that burn physics can be studied without addressing chamber engineering and rep-rated power supplies. From the perspective of the scientific community, there is no reason that a small university group might not invent an improved MTF target plasma design that could be tested quickly at full performance and full energy using the single-pulse facilities. When improvements are developed, they could be retrofitted at small cost in the DEMO device, because the plasma, blanket, coolant, and so forth in the chamber are much less coupled for MTF than with conventional MFE systems that use superconducting magnets.



In the community-based roadmap strategy discussed for fusion energy, a “middle of the road” estimate for integrated total cost and total time is found as shown in the above chart.



On the other hand, if one uses the above numbers for MTF, both the total cost and the years required would be considerably reduced as shown in the second chart. The cost is about 1/5 of the expected norm for fusion, and the time scale is half!

Clearly there are many technical issues to be addressed, but this extraordinary possibility deserves to be examined. Furthermore, no investment is required for facilities to begin MTF research because excellent defense program facilities exist and new ones are under construction. These considerations altogether represent an unusually strong argument for going forward with the proposed proof-of-principle program.

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