Challenges for Achieving the Low-Cost Optimum for Fusion Power

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To confront challenges of new technology, perhaps some historical perspective is useful.

Suppose in the 19th century that the government was investing in aeronautics. *How would flight technology have developed?*

**Proven technology for sustained human flight**

--- Montgolfier brothers (c.1783)  
paper sheets, buttoned together, hot air from fire

**Government program**

--- Larger balloons, stronger paper, better buttons, lighter gases

**Success!**

--- Dirigibles bomb London (c.1915)
--- Trans-Atlantic dirigible service (c. 1930)

It would have been unlikely to down-select to heavy structures kept aloft by repeated explosions. But we know what happened due to war and market forces.
The urge to down-select has led to multi-billion dollar investments in particular technologies.

**Magnetic Confinement Fusion**  
(c. 1980-88)  
- Mirror machines  
- Theta-pinch program  
- Tokamaks

**Inertial Confinement Fusion**  
(c. 1972-85)  
- Gas lasers  
- Light- and heavy-ion beams  
- Glass lasers

As with hot-air balloons, this works if big enough.

“Conservative” decisions were based on available experience, but may have missed optimum solutions.
Energy costs $w$ decrease and power-density costs $s$ increase with higher plasma density, offering a minimum total cost between the conventional magnetic- and inertial-confinement concepts.

The equivalent pressure of a megagauss field is 40,000 atm, which is difficult to obtain by steady electromagnets in useful volumes, but can readily be achieved by imploding-liner flux compression.
By trapping magnetic flux in electrical conductors, we can compress it to megagauss field levels.

Magnetic flux conserved inside imploding shell

\[ B_1 A_1 = B_2 A_2 \]

The implosion of the conducting shell converts kinetic energy into magnetic energy.

Plasma carries trapped magnetic flux

\[ \frac{B}{n_e r} = \text{constant} \]

Initial experiments (c. 1960) used explosive action to obtain the kinetic energy of the imploding shell. Later work used electromagnetic and pneumatic techniques.
Operation at megagauss field levels to achieve controlled fusion at the low-cost minimum has many detailed problems, but three principal challenges.

**Challenges:**

Compression needs to be stable

- Plasma target must survive compression
- Avoid mixing of high-Z material with fuel

“Kopek” problem

- For economical, pulsed reactor, need to re-establish conditions each shot for price of coke bottle
- To enable development of low-cost fusion, need hundreds of plasma shots (several shots per day vs several weeks per shot)

Ferocious fluence of high-energy neutrons

- 100 MW(e) means $10^{20}$ n/s vs $10^{15}$ n/cm² for insulator damage

If a scheme, however conceptually pretty, fails one of more of these challenges, it cannot lead to low-cost fusion power.
First challenge: Successful compression of fusion plasma to megagauss field levels depends on stability, both of the plasma target and the liner.

Plasma Stability

Magnetic field

Plasma

Unstable

Stable

Many other stability problems, including microinstabilities that affect particle loss.

Liner Stability

Gravity

Unstable

Stable

Acceleration (slowing front surface)

This is Rayleigh-Taylor instability. Many other ways liner surface can be distorted.

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If the high atomic-number liner material mixes with the plasma, the plasma may cool below fusion temperatures.
Over several decades, many plasma arrangements have been explored. This exploration continues for megagauss fusion.

Early notions for fusion plasma – the so-called “magnetic bottle” – sought plasma pressure about equal to magnetic pressure:

$$\beta = \frac{p}{(B^2/2\mu)} \approx 1$$

Many attempted arrangements were unstable; others leaked. Efforts then emphasized $\beta << 1$ (once known as ‘hydromagnetics’).

More recently, high $\beta$ possibilities are being pursued:

- Field-Reversed Configuration (FRC)
- Flow-stabilized z-pinch
- Magnetically-insulated plasma ($\beta >> 1$)

These high-beta concepts are pulsed, so the implosion event must be repeated in an economic fashion.
Proper liner behavior is critical for compression of plasma target and efficient transfer of energy.

Behavior depends on type of liner material (solid, liquid, plasma) and geometry of implosion (cylindrical vs spherical)

Initially solid-density shell

Shell yields to external pressure and implodes
Retains plastic strength, so buckling occurs
Hinging, colliding and spraying of material
Explosion as shrapnel and droplets

Growth of perturbations in fluid shells of liquid or plasma

“Secular”
Rayleigh-Taylor
Rayleigh-Taylor with rotation

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Substantial deceleration for efficient energy transfer to plasma target, means effective “gravity” points inward. Rotation can reverse this for stability.
Experiments at the Naval Research Laboratory demonstrated the complete stabilization of liquid liner implosions, including efficient reversible motion.

Basic arrangement for stabilized liner compression (in NRL experiments)

Implosion/expansion of rotating liquid liner compressing trapped-gas payload (NRL, c.1978)

Such stabilized implosions enable multi-megajoule experiments to develop the plasma target, and lead to low-cost reactor embodiments because the required nuclear gain is reduced.
Second challenge: The cost of electricity is determined in part by the initial cost of the reactor “core”. This depends on the size to obtain the required nuclear gain Q.

For confinement based on inertia, e.g., the surrounding liner, the dwell time at fusion conditions scales as the characteristic dimension x divided by a speed v \sim (p/\rho)^{1/2} \sim B, \tau \sim x/p^{1/2}.

With p \sim nT, nuclear gain Q \sim n\tau \sim n^{1/2}x, so x \sim Q/n^{1/2}

Reactor size and energy then scale as x^3 \sim Q^3

How much gain is needed?

This depends on the reactor cycle, especially the fraction of output energy that must be circulated back to the reactor for operation:

CPF = circulating power fraction

If CPF = 1, no electrical output (very expensive electricity); CPF = 25% may be OK.

Some schemes (e.g., Linus, Helion) might be able to use the alpha-particle energy to counter losses before thermal energy is processed by electrical generator. Others, however, cannot and need higher Q-values.
Suppose a fractional loss $f_L$ of liner energy $W_T$ is replaced by energy fraction $f_\alpha$ due to $\alpha$-particle energy and by energy circulation fraction $C$, then the energy cycle requires

$$f_L \ W_T = f_\alpha \ f_p \ f_F Q \ W_T + C \left[ f_t \left( f_p \ f_F Q(1-f_\alpha) + f_L \right) \right] \ W_T$$

with $f_p = \text{fraction delivered to payload}$, $f_F = \text{fraction of payload for fusion reactions}$, and $f_t = \text{thermal generator efficiency}$.

The required gain relative to plasma energy is:

$$Q = f_L \ (1 - C \ f_t) / f_p \ f_F [ f_\alpha + C \ f_t \ (1-f_\alpha)]$$

For $f_L = 0.2$, $f_p = 0.4$, $f_F = 0.3$, $f_t = 0.33$, and $f_\alpha = 0.156$, a circulating power fraction $C = 25\%$ needs $Q = 6.8$.

If $f_L = 1$ and $f_\alpha = 0$, $Q = 46.3$, (with $f_p = 0.8$, a larger value because rotational energy is not required).
In addition to cost due to the basic size, there are issues with repeated preparation and maintenance.

Larger energy can imply greater number of components, more mass for re-manufacture, and higher initial cost of the supporting systems for the installation. These all depend on the details of technology choices:

**“Conventional” Approach**

--- High currents in direct drive of implosion require minimum diameters for connections (e.g., about one meter “cassette” for 60 MA implosion)

--- Thirty-year operation at 1 Hz repetition rate is a billion shots. High grade, energy storage capacitors (c.1972) had life-time of $10^5$ shots, so energy-density must be reduced by factor of $\sim 14$, increasing size and cost for pulsed electrical power.

--- Electrodes (e.g., in gas-discharge switches, pulsed plasma sources) can erode at $>100 \ \mu$gram/coulomb requiring replacement of parts.

**Alternatives**

--- Induce currents in liner and plasma by using magnetic flux compression

--- Store and use energy at much higher densities than capacitive energy: $85 \ \text{MJ/m}^3 \ vs \ 10 \ \text{kJ/m}^3$

--- Use strong adiabatic compression to reduce energy of initial plasma

--- Use solid-state switches

--- Use “theta-pinch” inductive plasma sources

In some cases, there are no alternatives to the components of a scheme, so costs must be accepted.
Third challenge: High-energy neutrons from D-T reactions can damage reactor components, such as the high-voltage insulators in the plasma production systems.

At 20 MeV per D-T reaction, an output of 100 MW(e) corresponds to $1.25 \times 10^{20}$ n/s, \textit{~independent of the scheme.}

The threshold for damage to insulation of the sort used in high-voltage capacitors is about $10^{15}$ n/cm$^2$ for energies $> 2-3$ MeV; sapphire may be higher.

The damage threshold would be reached in two weeks of operation for an unshielded area of a sphere 2.2 km in diameter. To reduce this to 10 m, we need to deplete the neutrons ($> 2$ MeV) by $\sim 48,000$.

Delivery of electromagnetic or plasmadynamic energy requires open channel (vacuum or insulator)

Hydrodynamic compression of flux allows thick liner to block neutrons

Baffles are used to shield power flow channels from UV. Neutrons are much more penetrating. A thick liner may work, but other schemes may not.
Conceptual example based on stabilized liner implosion compressing elongated FRC answers the three challenges: Stability, Cost, Neutrons

Even this arrangement needs to include additional shielding for the axial flux of neutrons (~1%) near the axis. Strong adiabatic compression techniques greatly reduce the necessary capacitive energy storage.
A significant minimum in size and cost for controlled fusion appears to exist between the mainline schemes, but requires operation at megagauss field levels. Such fields are available by magnetic flux compression.

While various notions may offer demonstrations of fusion, the successful power reactor poses three challenges:

Stability

Perturbations of the inner surface can grow and penetrate the plasma

--- Need very high quality inner surface (position/speed) or growth just by convergence will be too great; scaling as $1/r$ (cylindrical), $1/r^2$ (spherical).

--- Rayleigh-Taylor growth can be avoided by rotation, but only for cylindrical implosions; “polar” regions still unstable in spherical case.

Cost

--- Significant improvement by reversible implosion (size/cost $\sim Q^3$) and strong adiabatic compression to reduce plasma source energy.

Neutrons

--- High-energy neutron fluence can kill reactor quickly unless very, very substantial ($>>10^4$) shielding is provided.

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