A Fusion Hybrid Reactor Based On the Gasdynamic Mirror (GDM)

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Presented at:
ICENES-2011 Conference
San Fransisco, CA
May 16-19, 2011

1. World population by 2050 = 10 billion
2. Power need 10-30 TW carbon-free
3. Estimate of world energy resources

Source	Energy (TW yrs)
Fossil	7500
Coal	5000
Oil	1250
Gas	1250
Mined Uranium	60-300

4. Nuclear Power = major component of carbon-free power
5. Breeding fissile material ⇒ multiply available energy by more than a factor of 100.
6. Breeding can be done via fission, fusion, or accelerator-produced fast neutrons.
7. Two breeding cycles of interest:
   i) Pu^{239} from U^{238}
   ii) U^{233} from Th^{232}

From proliferation standpoint, we choose ii)
i.e. U^{233} from Th^{232}

8. Price of neutrons?

Thermal Reactor	6×10^{-3} neutrons/MeV
Fast Reactor	7.5×10^{-3} neutrons/MeV
Accelerators	1.5×10^{-2} neutrons/MeV
Fusion	5.7×10^{-2} neutrons/MeV

9. Fusion device ⇒ Gasdynamic mirror (GDM)

i) plasma density and temperature ⇒ ion-ion collision mean free path << L/R_M

ii) plasma behaves like a continuous medium – a fluid.

iii) its escape from device is analogous to flow of a gas into vacuum from a vessel with a hole.

iv) plasma confinement time τ is given by

$$\tau = R_M L / v_{th} \tag{1}$$

R_M = mirror ratio

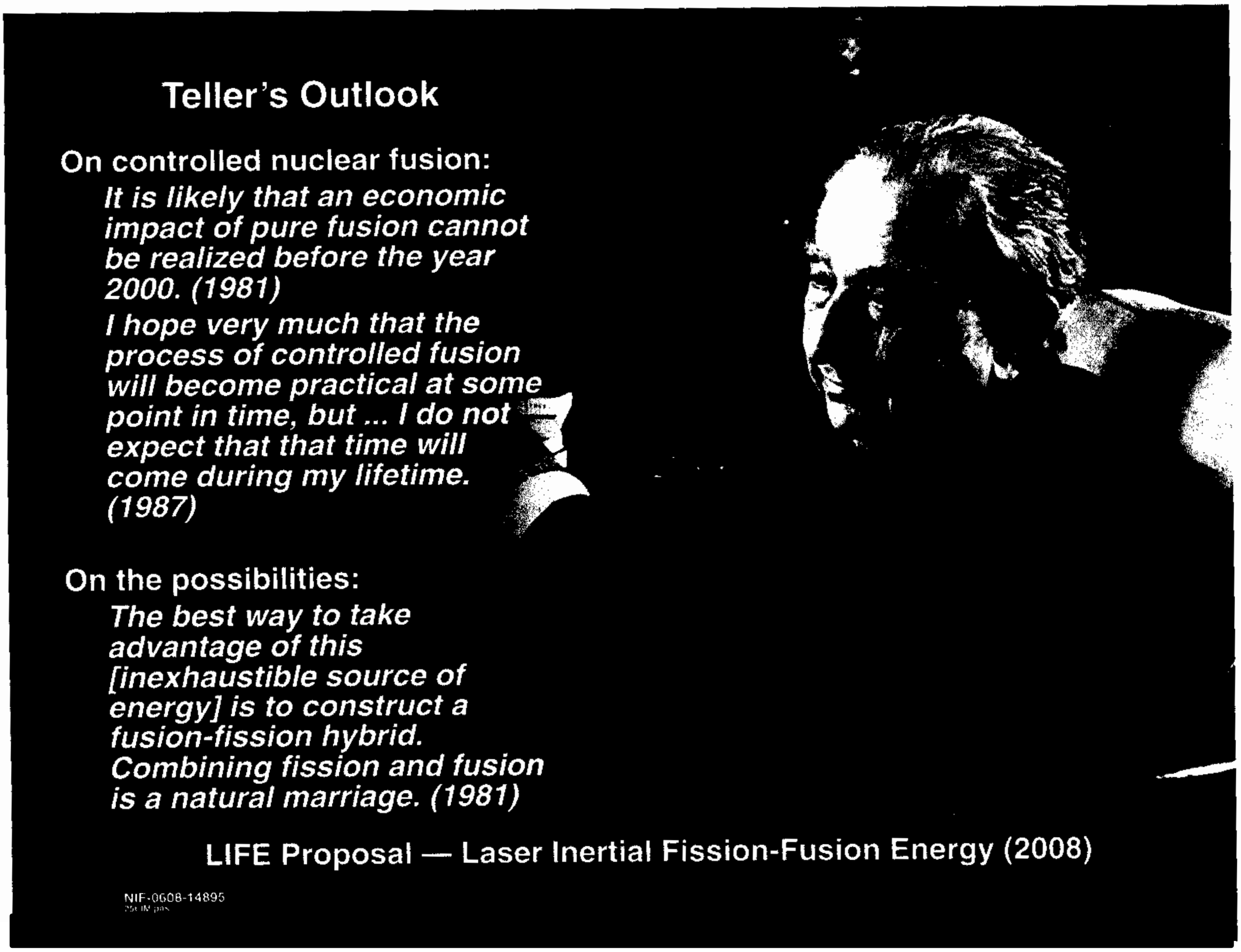
L = length of device

v_{th} = mean (thermal) velocity of ions

10. High aspect ratio GDM, i.e. $L/r_p \gg 1$, where r_p = plasma radius, is MHD stable for large R_M and β

$$\beta = \frac{\text{plasma pressure} = n_p kT}{\text{B field pressure} = B^2/(8\pi)} \tag{2}$$

Edward Teller saw the promise of fusion-fission hybrid systems more than three decades ago



Teller's Outlook

On controlled nuclear fusion:

It is likely that an economic impact of pure fusion cannot be realized before the year 2000. (1981)

I hope very much that the process of controlled fusion will become practical at some point in time, but ... I do not expect that that time will come during my lifetime. (1987)

On the possibilities:

The best way to take advantage of this [inexhaustible source of energy] is to construct a fusion-fission hybrid. Combining fission and fusion is a natural marriage. (1981)

LIFE Proposal — Laser Inertial Fission-Fusion Energy (2008)

NIF-0608-14895
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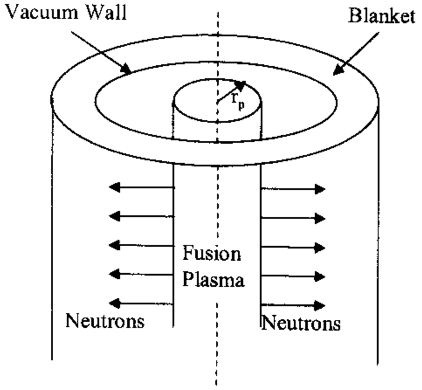
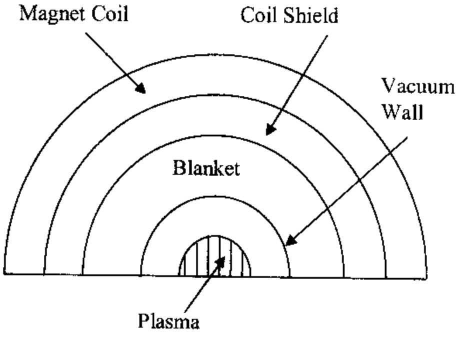
System Geometry



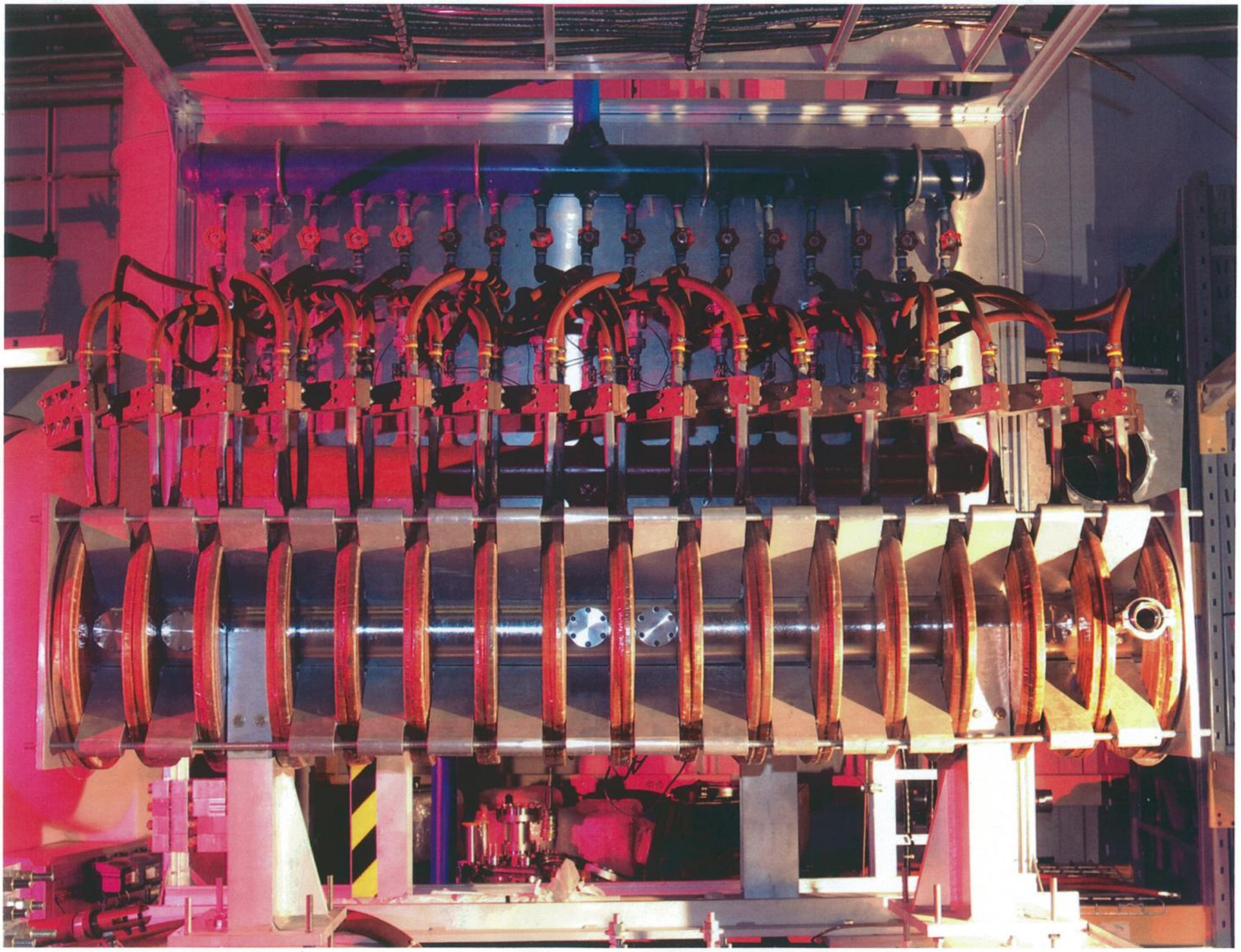
Upright View



Cross Section View

$$Th^{232}(n,\gamma)\,Th^{233} \xrightarrow[22\ m]{\beta^-} Pa^{233} \xrightarrow[27.4\ d]{\beta^-} U^{233}$$

<u>Breeding</u> <u>Reaction</u>



Analysis

Ion-ion collision mean free path "λ"

$$\lambda = 1.253 \times 10^{18} \frac{T^2(keV)}{n_p(cm^{-3})} \qquad (3)$$

n_p = plasma density

T = temperature

For $n_p = 10^{16}$ cm^{-3} and T = 10 keV

λ = 1.253x10^4 cm

Gasdynamic condition:

$\lambda/R_M << L$

R_M = plasma mirror ratio → optimum 55

$\boxed{L > 2.28\text{m}}$

must reconcile this with "L" given by the confinement time "τ" in Eq. (1)

$$\tau = \frac{R_M L}{v_{thi}} \qquad (1)$$

Multiple Eq. (1) by n_p

$$n_p \tau = n_p \frac{R_M L}{v_{thi}} \qquad (4)$$

If $n_p\tau = n_p\tau)_{BE} = 10^{14}$ for D-T

Then L = 182 m, Too large

So use npτ = 10^{-1} $n_p\tau)_{BE}$ = 1013

Then $\boxed{\text{L = 18.2 m}}$ reasonable!

Breeding Equation

$$\frac{dN^{33}}{dt} = \varphi\sigma_\gamma N^{32} - \varphi\sigma_f N^{33} = 0 \qquad (5)$$

N^{32} = Thorium-232 particle density

N^{33} = U-233 particle density

φ = fast neutron flux

σ_γ = Thorium microscopic capture X-section

σ_f = fast neutron Uranium fission X-section

Note that

$$N^{33} = \frac{\overline{\sigma_\gamma}}{\overline{\sigma_f}} N^{32} \tag{6}$$

where $\overline{\sigma_\gamma}/\overline{\sigma_f}$ are averaged over neutron spectral distribution (Ala MCNP)

Neutron flux distribution in Blanket

$$\frac{dn}{dt} = D\nabla^2\varphi - \left(\sum_{at} - \nu \sum_f\right)\varphi - S = 0 \tag{7}$$

or

$$D\nabla^2\varphi - \left(\sum_{at} - \nu \sum_f\right)\varphi = S\delta(r - r_p) \tag{8}$$

or

$$\boxed{\nabla^2\varphi - \alpha^2\varphi = \frac{S}{D}\delta\left(r - r_p\right)} \tag{9}$$

with

$$\alpha^2 = \frac{\left(\Sigma_{at} - \nu\Sigma_f\right)}{D} \tag{10}$$

Σat = total absorption macroscopic X-section

Σf = fission macroscopic X-section

ν = neutrons produced per fission (~2.5)

Solution to Eq. (9) subject to appropriate Bounday Conditions leads to the power generated per unit length, P_l, of the proposed hybrid reactor i.e.

$$P_l = \frac{4\pi^3 {r_p}^4 S}{\alpha D^2} N^{33} \sigma_f E K_1(\alpha r_p) \qquad (11)$$

where S = fusion produced neutron source, namely

$$S = \frac{{n_p}^2}{4} \langle \sigma v \rangle \qquad (12)$$

for (D-T) at 50-50%

E = energy produced per fission

$K_1(\alpha r_p)$ = modified Bessel function

<u>Numerical Result</u>

$S = 0.25 \times 10^{16}$ neutrons/cm^3/sec

$N^{33} = 0.1 N^{32} = 3 \times 10^{21}$ #/cm^3

E = 200MeV

D = 3cm; r_p = 5cm

σ_f = 2.343 barns

$K_1(\alpha r_p) = 16.81$

Fast fission (@ several MeV) = 15%
Coolant ducts = 70% of cross section

$$P_l = 61 \text{ MW/cm} \qquad (13)$$

In presence of moderator e.g. H_2O fast neutrons thermalize in about 10 µsec's. Power estimate for Thermal neutrons

$$P_l = \pi {r_p}^2 S \left(\frac{1}{1 - k_{eff}} \right) E \frac{\Sigma_\mathrm{f}}{\Sigma_\mathrm{t}} \qquad (14)$$

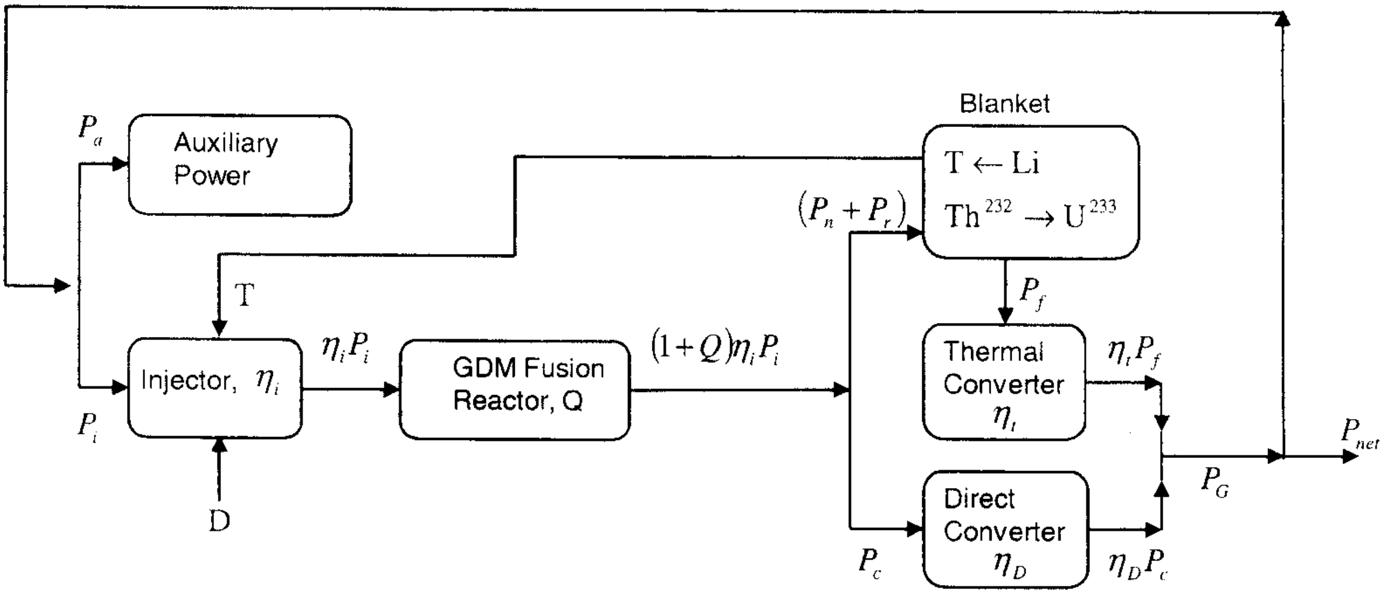
where

$$k_{eff} = \frac{\Sigma_\mathrm{f}}{\Sigma_\mathrm{at} + D{B_g}^2} = 0.99 < 1 \qquad (15)$$

i.e. subcritical!, $\Sigma_f/\Sigma_t = 0.4$

$$P_l = 75 \text{ MW/cm} \qquad (16)$$

assuming coolant ducts = 70% of cross section note that one fusion neutron yields $\left(\frac{1}{1 - k_{eff}} \right) \approx 100$ thermal neutrons!



Power Flow Diagram

Fusion Driven Fission Power Producer

P_a = auxiliary power
P_i = injection power
Q = fusion power / P_i
P_c = charged particle power
P_r = radiative power
P_n = neutron power

P_G = gross electric power
P_{net} = net electric power
P_f = fission power
η's = efficiencies
D = deuterium
T = tritium

Conclusions

1. The Fusion-Hybrid Reactor Based on the Gasdynamic Mirror (GDM) can produce large amounts of power “safely” because it is “subcritical”, and “securely” because of the thorium fuel-cycle which is known to be “resistant” to “proliferation” and “clandestine operation”
2. Since the Fusion component (i.e. The GDM) serves primarily as a neutron source, it can operate at or near “breakeven” condition, which is much less stringent than that required for pure fusion reactor
3. The hybrid can breed its own fuel and simultaneously burn it to produce power. With proper design, it can operate for a long time without refueling.
4. The D-T fusion fuel is not particularly desirable since the 14.1 MeV neutrons cause very little fission but large amount of actinides in the blanket

5. Lower energy neutrons such as those from D-D are more suitable since they reach “thermalization” much faster, and thus produce much less actinides (al MCNP)
6. At $n_p\tau = 10^{-1}$ (BE) → Injection Power (P_{inj}) ~ 10 fusion power (P_f). Early estimates show that P_{inj} ~ 1-2% of the gross power produced by the reactor.
7. Since the reactor is “driven”, and not “critical”, its control can be achieved through manipulation of the fusion-produced neutrons!