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FUSION MICROEXPLOSIONS, EXOTIC FUSION FUELS, DIRECT CONVERSION: ADVANCED TECHNOLOGY OPTIONS FOR CTR*

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SUMMARY

In the past few years, several new technological options related to controlled fusion have been developed that promise to dramatically improve the long term prospects for the production of inexpensive electrical energy with minimal environmental impact. This paper very briefly describes three of these options: laser-initiated fusion microexplosions, exotic fuel usage, and new forms of conversion of fusion energy directly to electricity. While these technologies do not depend on each other for their useful realization, they rather naturally combine to form an extremely attractive fusion reactor system.

LASER FUSION

The basic concept of the laser-initiated fusion microexplosion, in which an intense, carefully time-shaped laser pulse serves to compress and ignite a pellet of fusion fuel, is depicted in Figure 1. The sequence of events presented there is described in more detail in Appendix A, and is based upon extremely sophisticated computer modelling calculations. To date, such computer codes have been successful in accurately modelling a variety of plasma phenomena and their predictions are thus regarded with a reasonably high degree of confidence. The typical microexplosion described here requires a 1 megajoule, 10^{-10} second duration

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*Research performed under the auspices of the United States Atomic Energy Commission.

†Also Fannie and John Hertz Foundation Fellow, Physics Dept., University of Calif., Berkeley.

laser pulse, and produces 25 kilowatt-hours of thermal energy, with the expenditure of 1-3 kwh to excite the laser. Figure 2 shows a conceptual model of an early-type DT-burning laser-fusion power plant. Such a plant would accomodate 10-100 "typical" microexplosions a second and would thus produce 1000-10,000 time-averaged megawatts of thermal power. As it stands, the capital cost of this reactor is believed to be comparable to conventional power plants, with operating costs significantly less. (See Table 6.) Further possible improvements will be described below.

The present status of laser fusion research efforts is sketched in Table 1. The major emphasis at present is on the development of the required high power, short pulse lasers, with a total US effort of $\sim$ \$33 million/yr. The "moderate"-power lasers needed for decisive experimental verification of the microexplosion theory are expected to be available in 2-3 years. If the outcome of such experiments is basically favorable, then the fundamentally different laser-induced microexplosion approach to controlled fusion will have dramatically outpaced the development of the magnetic confinement approaches.

Figure 3 shows an idealized advanced fusion power plant, and serves to indicate its potential characteristics and the technologies required for implementation. While a fusion microexplosion-based plant is depicted, the concepts and technologies are applicable to other controlled fusion approaches. Only the exotic fuels and direct conversion techniques will be discussed in detail here, but the others also deserve serious attention.

EXOTIC FUSION FUELS

The necessary and desirable characteristics of fusion fuels are detailed in Table 2, while Table 3 lists the most promising exotic fuel candidates. The apparently superior candidate is the $p + B^{11} \rightarrow 3He^4$ reaction (denoted by pB^{11}), whose characteristics are given in Table 4 and Figure 4. The most salient features are the exceedingly clean burn ("ashes" $\lesssim$ 0.1% neutrons or radioactive particles), combined with a reasonably high burn rate and a fairly large fractional energy output in charged particles. Thus, problems involving neutron wall damage and activation, radioactive material handling and waste disposal, radiation shielding, and efficient neutron energy conversion are essentially eliminated in advanced CTR reactors fueled by pB^{11}.

DIRECT CONVERSION

The required scope of direct fusion-electric conversion devices along with a listing of the more promising approaches is given in Table 5. Figure 5 depicts the AC MHD method of extracting electrical energy from plasma expansion. Figure 6 sketches possible means of direct conversion to electricity of x-ray and neutron energy, via scattering of charged particles. Figures 7 and 8 depict reactors using these conversion devices. Methods of x-ray and neutron direct conversion have to date received virtually no experimental attention, despite their obvious importance to the efficiency of fusion systems, and indeed the proposals presented here are apparently the first outlines of possible approaches to the problem. (It has apparently been assumed hitherto that neutrons and x-rays couldn't be directly converted to electrical energy because they were electrically uncharged.) Much more work in these areas is clearly required. If such direct conversions systems can be constructed, $\gtrsim$ 60% overall conversion efficiencies seem plausible for advanced fusion reactors. Figure 9 shows the fusion energy "pig" partitioning--typical conversion processes for early DT- and advanced pB^{11}-burning CTR power systems. Virtually all energy forms appear to be directly convertible, except for a soft x-ray "squeal".

Table 6 summarizes various estimates of the capital cost per installed kilowatt, electrical conversion efficiency, and operating cost which have been reported or projected for various conventional, fission, and fusion power plants.

The technological outlines of an "nearly ideal" advanced fusion reactor system thus seem to be emerging at present. It appears that a vigorous program of technological development to fill in these outlines is called for. The realization of such an advanced power system and its attendant substantial cost and environmental advantages would seem to be a high priority concern of forward-looking power technologists.

APPENDIX

Caption to Figure 1: Typical Laser Fusion Microexplosion:

a) Atmosphere formation

Initially weak laser beams symmetrically strike a $\sim$ 1 mg frozen deuterium-tritium pellet from many directions, vaporizing and ionizing 1% of its skin to form an atmosphere around the pellet. This atmosphere enhances (through lower pellet reflectivity) and symmetrizes (by multiple scattering--the overcast, cloudy-sky effect) the pellet's absorption of the subsequently inputted laser light.

b) Compression

Laser light intensity is increased and much more material is heated up and violently blown off the pellet "surface". The escaping material expands radially outward, resulting in an inward-directed reaction force on the pellet (exactly analogous to a number of rockets, all pointed directly toward the same point). The time variation of the laser beams' intensity is carefully adjusted so that this reaction force compresses the pellet in a barely subsonic fashion (to avoid creating shock waves that would heat the pellet and thus hinder its further compression).

c) Ignition

At this stage 70% of the pellet has been ablated away, and the remaining core compressed to 10,000 times its original density. A final, abrupt pulse of laser light then strikes the pellet, resulting in a strong compressional wave that steepens into a shock wave just before it reaches the center of the pellet. This shock wave heats the pellet's central region to 100 million °C, initiating thermonuclear reactions there that quickly spread throughout the rest of the pellet.

d) Thermonuclear Burn

The laser light has been turned off, and the pellet continues to burn until its increasing internal pressure blows it apart. The rate of burn is proportional to the square of the pellet's density and the time the pellet stays together is approximately equal to its radius divided by the sound speed in the hot plasma. Since the pellet was so extremely compressed before ignition, its burn rate is so large that external containment (i.e. via magnetic fields) to prolong its burn time is not necessary to achieve a release of fusion energy very large compared to the inputted energy.

e) Energy Conversion

The plasma remnant of the pellet then expands, perhaps compressing a magnetic field in the process to directly convert its energy into electricity. (For DT, however, $\lesssim$ 75% of the fusion energy is carried away as high energy neutrons, which escape from the plasma as it burns. Another 5% comes out as x-rays.)

REFERENCES

The concepts reported here have been described in more detail in the following papers and reports:

Laser Fusion:

1) "Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications", J. Nuckolls, L. Wood, A. Thiessen and G. Zimmerman, Nature, 239, 139 (1972).

Exotic Fuels:

1) "Prospects for Exotic Fuel Usage in CTR Systems I. $B^{11}(p,2\alpha)He^4$: A Clean, High Performance CTR Fuel", T. Weaver, G. Zimmerman and L. Wood, UCRL 74191/ UCRL 74352 (November 1972).

2) "Exotic CTR Fuels for Direct Conversion-Utilizing Fusion Reactors", T. Weaver and L. Wood, UCID 16230 (March 1973).

3) "Concerning Electron-Ion Coupling and Charged Particle Energy Deposition During Vigorous Thermonuclear Burn", G. Lee, G. Zimmerman and L. Wood, UCRL 74192 (1972).

Direct Conversion:

1) "Some Direct Conversion Possibilities for Advanced CTR Systems", L. Wood and T. Weaver, UCID 16229 (March 1973).

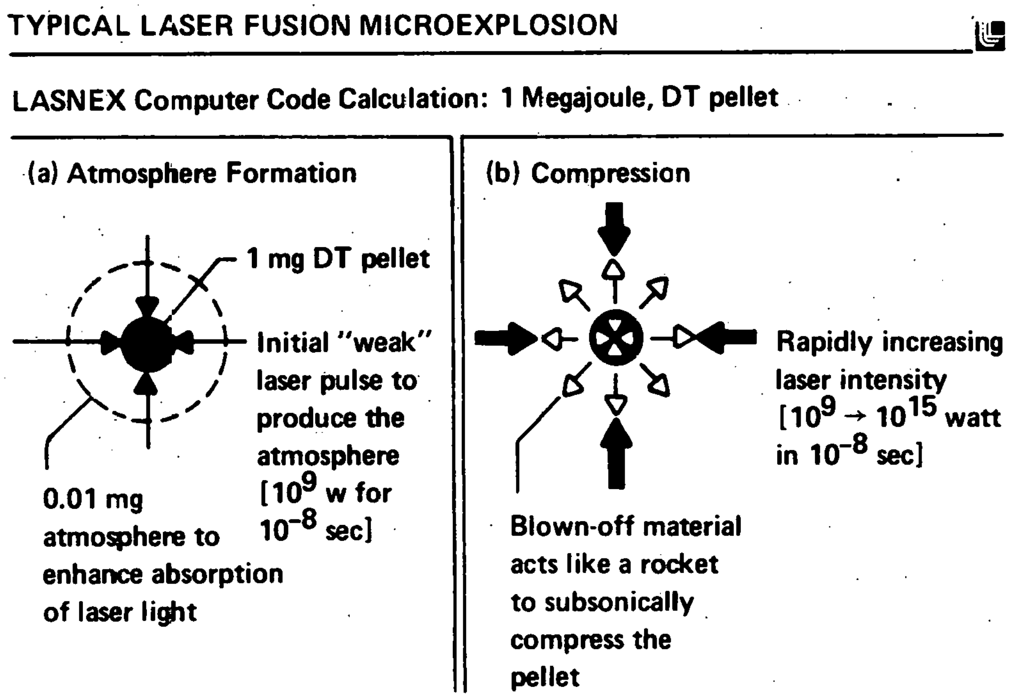
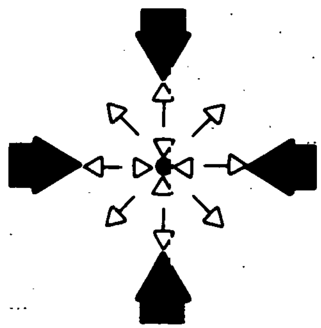

TYPICAL LASER FUSION MICROEXPLOSION
LASNEX Computer Code Calculation: 1 Megajoule, DT pellet
(a) Atmosphere Formation
1 mg DT pellet
Initial "weak" laser pulse to produce the atmosphere [10^9 w for 10^{-8} sec]
0.01 mg atmosphere to enhance absorption of laser light
(b) Compression
Rapidly increasing laser intensity [$10^9 \rightarrow 10^{15}$ watt in 10^{-8} sec]
Blown-off material acts like a rocket to subsonically compress the pellet

FIGURE 1

FIGURE 1
cont'd

TYPICAL LASER FUSION MICROEXPLOSION (Con't)

(c) Ignition

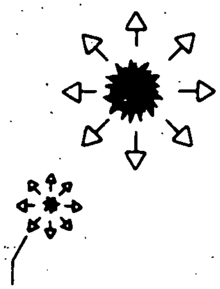


Final large pulse of laser light [3×10^{15} watt for 10^{-10} sec]

70% of pellet has been ablated away. Remainder compressed to 10,000 X its original density

Final laser pulse shock-compresses pellet center to thermonuclear ignition temperature (100 million °C)

(d) Thermonuclear Burn



Laser off

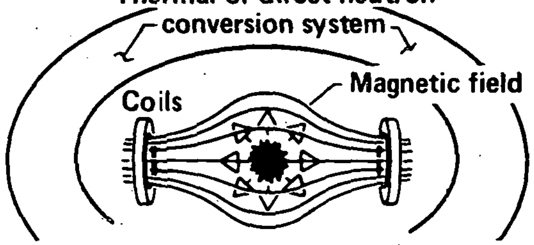
Thermonuclear burn spreads from center throughout pellet

Burn rate proportional to $(\text{density})^2$

Burn time proportional to $\dfrac{\text{pellet radius}}{\text{sound speed}}$

TYPICAL LASER FUSION MICROEXPLOSION (Cont'd)

(e) Energy Conversion



Expanding plasma compresses magnetic for direct conversion of plasma energy to electricity

Energy output
75% neutrons
20% expanding plasma
5% radiation

Cycle Specifications:

Total laser energy:
1 megajoule (1/4 kwh)

Total electrical energy input:
3-10 megajoule (1-3 kwh)

Total thermonuclear energy output:
100 megajoule (25 kwh)

Total electrical energy output:
35-70 megajoule (9-18 kwh)

Repeated 10-100 times/sec
for a 1-10 million kilowatt (thermal) power plant

FIGURE 1
concluded

CONCEPT OF LASER FUSION ELECTRICAL POWER PLANT WITH DIRECT CONVERSION

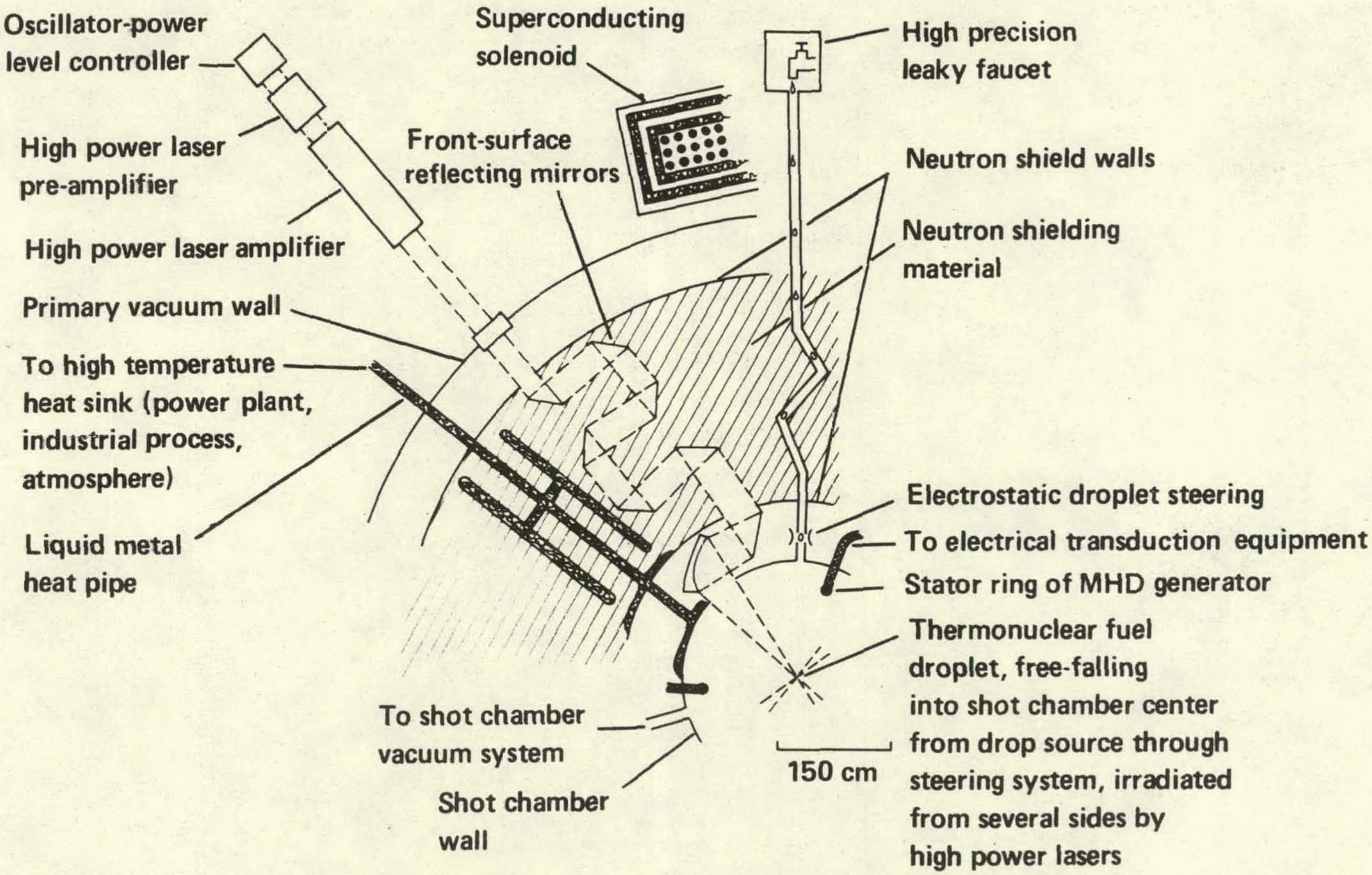


FIGURE 2

TABLE 1

LASER FUSION PROGRAM

Major efforts in US (Livermore, Los Alamos, U. Rochester, KMS), France, Germany, Japan and USSR

- $30 million annual funding (US); comparable level of effort abroad
- ~ $3 million (known) annual private funding
- Approx. yearly doubling of effort since 1969 in US

Present AEC Program:

- Development of high power, short pulsed lasers (~ 80% effort)
- Elaborate computer modeling of laser fusion microexplosion and related theoretical studies (~ 10% effort)
- Laser-plasma interaction experiments (~ 10% effort)

Present Status:

Laser Development

- 1 kilojoule (1/4000 kwh) laser pulses are state-of-the-art
  - ~ 0.1 kilojoule pulses of the required time duration (10^{-10} sec) have been obtained
- 1 kilojoule, 10^{-10} sec pulses needed for "scientific breakeven" DT fusion experiments projected in 1-2 years (laser light energy = fusion energy produced)
- 0.1 - 1 megajoule pulse, moderate efficiency (~ 10%), high rep rate (10-100 per second) lasers for power plant applications projected in 5-10 years

TABLE 1 concluded

Present Status Cont'd

Theoretical/Calculational Studies

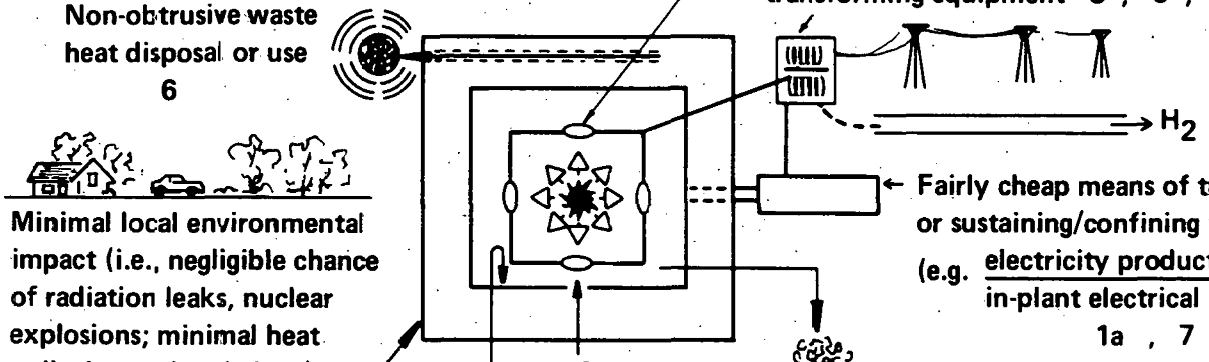
- Use of very sophisticated computer simulation codes
  - Extensively checked against laser-matter interaction experiments, other verified computer codes, and analytically solved problems
  - Exploitation of world's most powerful computers
- "Energetic breakeven" predicted for $\lesssim 10^3$ joules of optimally used laser light
- "Electrical breakeven" calculated for $\simeq 10^5$ joules of pulsed-shaped laser energy

fusion only

- "Electrical breakeven" computed at 10^3 - 10^4 joules of laser energy for 10% - 1% efficient laser
  - Hybrid system—fission blanket around fusion combustion chamber
  - Burn natural/depleted uranium or thorium to completion—no plutonium cycling
  - Intermediate technological stage?
  - Feature common to all DT-burning CTR systems

IDEALIZED ADVANCED FUSION POWER PLANT

Emphasis on • low capital cost • negligible fuel cost • minimal environmental impact



Technology	
1	Controlled fusion
1a	Laser fusion; advanced magnetic confinement systems
2	Exotic fuels (e.g., pB^{11})
3	Plasma/neutron/x-ray direct conversion
4	Refractory materials and isotope separation
5	Pulse → 60 Hz transformers
6	High temperature radiators; heat transport systems
7	Superconductor technology

Virtually none of the above characteristics can be realized with presently proposed fission systems.

FIGURE 3

TABLE 2

DESIRED EXOTIC CTR FUEL CHARACTERISTICS

- 1) Reactions involving virtually no neutrons or radioactive elements.
- 2) Fuel reactants cheaply and inexhaustably available.
- 3) Principal energy output in charged particles to allow efficient direct conversion.
- 4) Non-prohibitive $n\tau$ requirements:

  i.e.: $E_{\text{Thermonuclear}} \times \text{Conversion Efficiency} > E_{\text{External Heating}}$

  generally requiring:

  $\dot{E}_{\text{Thermonuclear}} > \dot{E}_{\text{Brems}} + \dot{E}_{\substack{\text{Other}\\ \text{Losses}}}$ [Fuel Ignition Condition]

- 5) Energy generation possible under technically accessible conditions.

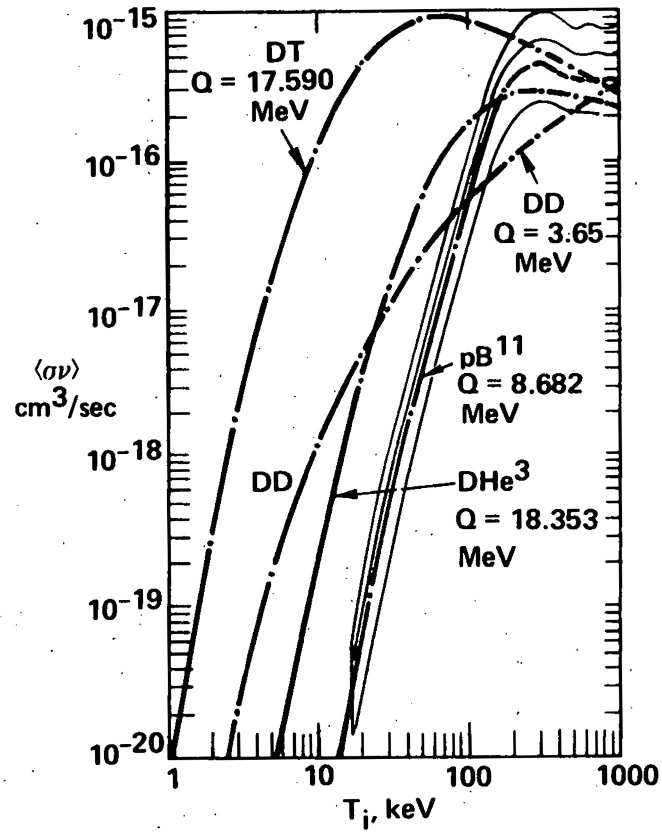
TABLE 3

PROPOSED EXOTIC FUEL CANDIDATES

- $p + B^{11} \rightarrow 3He^4 + 8.7$ MeV (WZW): Essentially meets all above conditions.
- $p + Li^6 \rightarrow He^3 + He^4 + 4.0$ MeV (Post): Meets 1-3, but apparently not 4 and 5 (under quasi-thermal conditions).
- $p + Be^9 \rightarrow \alpha + Li^6 + 2.1$ MeV (McNally)
  - $\rightarrow D + Be^8 + 0.6$ MeV
    - $\rightarrow D + D \rightarrow D + T$

  Meets 2 and 3, but not 1
  Also not 4 and 5 under quasi-thermal conditions
- $D + Li^6 \rightarrow He^4 + He^4 + 22.3$ MeV
  - $\rightarrow p + Li^7 + 5.0$ MeV
  - $\rightarrow T + Li^5 + 0.6$ MeV
    - $\rightarrow D + T$

  Tritium Breeding Reaction
- Fusion Chains (Jetter, Post, McNally): Potentially meet 2, 3, 4; 1 and 5 in doubt.



From: WZW (UCRL Report #74191/74352

FIGURE 4

TABLE 4

pB^{11} FUEL SYSTEM CHARACTERISTICS

- $p + B^{11} \rightarrow 3He^4 + 8.68$ MeV
- $>$ 99.9% of reaction "ashes" are safe, non-radioactive helium nucleii
- $\langle \sigma v \rangle$ at $T_i > 150$ keV* greater than all other CTR fuels; optimal $n\tau$ requirements less than DD and comparable to DHe^3 (for $T_{i_{opt}} \sim 200$ keV)
- Ignition criteria* satisfied for 125 keV $\leqslant T_i$ for $\ell n\Lambda = 5$ (typical of laser-fusion systems) and $150 \leqslant T_i \leqslant 600$ keV for $\ell n\Lambda = 20$ (typical of mirror-machine systems).

*Critically cross-section-dependent.

continued

TABLE 4 cont'd

pB^{11} FUEL SYSTEM CHARACTERISTICS, continued

- Very small contaminating side branches

Reaction	Q MeV	Occurrence relative to $p + B^{11} \rightarrow 3He^4$ at 250 keV	Radioisotope inventory of 1000 MWt plant, Curies	
$p + B^{11} \rightarrow C^{12} + \gamma$	16.0	5×10^{-5}	200 (Steady state)*	97% 12 + 4 MeV γ's 3% 16 MeV γ's
$p + B^{11} \rightarrow n + C^{11}$	- 2.8	1.5×10^{-5}	4×10^5 (Steady state)	Thermal neutrons, $t_{1/2}(C^{11})$=20min.
$\alpha + B^{11} \rightarrow n + N^{14}$	0.2	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^5$ (Nb structural activity — short-lived)	Non-thermal generation
$\alpha + B^{11} \rightarrow p + C^{14}$	0.8	$\lesssim 10^{-4}$	$\lesssim 10^3$ (Annual production)	$1 \lesssim (E_n, E_p) \lesssim 4$ MeV $t_{1/2}(C^{14})$=6000yr.
DT Fusion Reactor	—	—	$\sim 10^8 - 10^9$ (Steady state)	
Fission reactor	—	—	$\sim 10^{10}$ (Steady state)	

*O^{15} from activation of water shielding ($t_{1/2}$ = 2 min)

pB^{11} FUEL SYSTEM CHARACTERISTICS, continued

- Cheaper and more abundant than standard fuels:

Reactant	ppm by weight of Earth's crust	Estimated recovery or production cost*
B^{11}	8	10–20 ¢/g
Li^6	4	20 ¢/g
D	0.5	20–30 ¢/g
He^3/H^3	negligible [projected production from D and Li^6]	\$10,000/g† \$1/gm (?) (CTR economy)

*available technology applied to large scale (CTR) production

†present AEC official price

- Energy output in potentially directly convertible form:
  - Charged particles (~ 70% of E ~ 300 keV)
  - Hard X-rays (~ 30% of $E_{phot} \simeq$ 50–70 keV)
  - MHD conversion efficiency of $\gtrsim$70% of charged particle energy
  - Compton generator efficiency of 10–30% of hard x-rays

TABLE 5

DIRECT FUSION-ELECTRIC ENERGY PRODUCTION

Importance is to reduce

- waste heat
- capital cost

per unit of electrical output, by improving conversion efficiency.

Fusion Energy Output Mode	DT	DHe^3	pB^{11}
Expanding plasma	15%	20%	70%/50%
Neutrons	80%	30%	$<$ 0.1%
X-rays and other EM radiation	5%	50%	30%/50%

- Efficient direct conversion should utilize all these energy forms
- Most efforts to date have been aimed at plasma energy conversion
- Conversion of x-ray and neutron energy by other than thermal means has received virtually no attention

TABLE 5 concluded

DIRECT FUSION-ELECTRIC ENERGY PRODUCTION, continued

Direct Plasma Energy Conversion Approaches

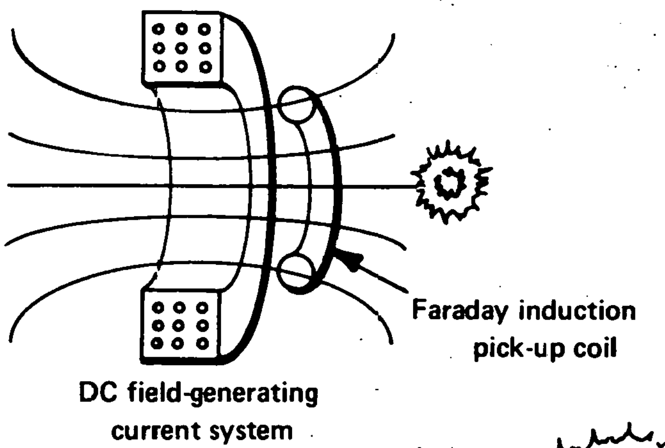
- Electrostatic: Ions and electrons separated, and ions are decelerated against an electrostatic field (Post, et al)
- MHD duct: Plasma components replace conventional generator rotor
- AC MHD: Expanding plasma compresses a magnetic field through induction coils

Direct Neutron Energy Conversion Approaches

- Neutronic Compton generator
  Neutrons scatter protons, whose energy is then extracted electrostatically

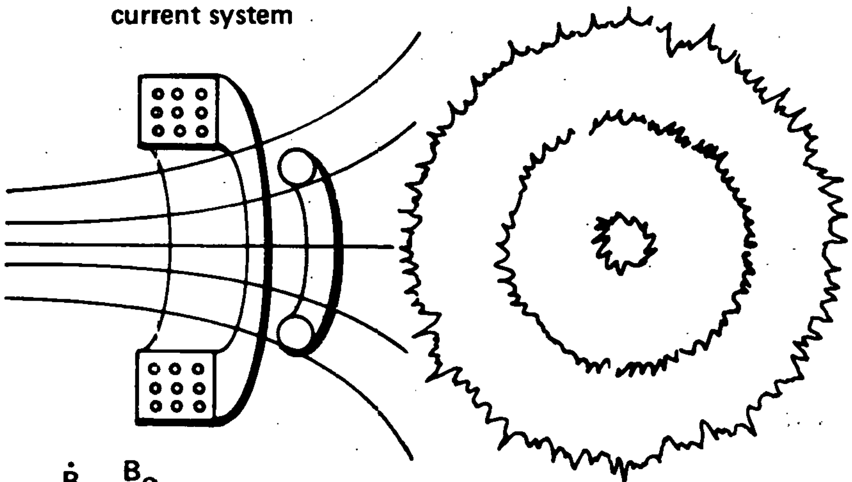
Direct X-ray Energy Conversion Approaches

- Plasma absorption
  High Z material is injected around reacting plasma to absorb x-rays and convert their energy to plasma kinetic energy
- Compton generator
  X-rays scatter electrons, whose energy is then extracted electrostatically



Features

- Basic feasibility demonstrated – $\gtrsim$ 70% of KeV fireball internal energy converted to compressed magnetic field energy (Haught, et al, 1970)
- Low magnetic field intensities suitable – 2-4 Tesla for 10^7 joule microexplosions
- 500-5000 kν, $\simeq$ 1 μsec rise time pulses available for direct transmission line excitation, or for transformation



$$V \propto \frac{\dot{B}}{C} \simeq \frac{B_o}{C} (\nu_{plasma}/\ell_{scale})$$

$$p \propto \left(\frac{\dot{B}}{C}\right)^2 \frac{1}{Z} \lesssim 10^{13} \text{ watts}$$

$$(p_{TN} \simeq 10^{18} \text{ watts})$$

FIGURE 5

PHOTON- AND NEUTRON-DRIVEN COMPTON GENERATOR MECHANISMS

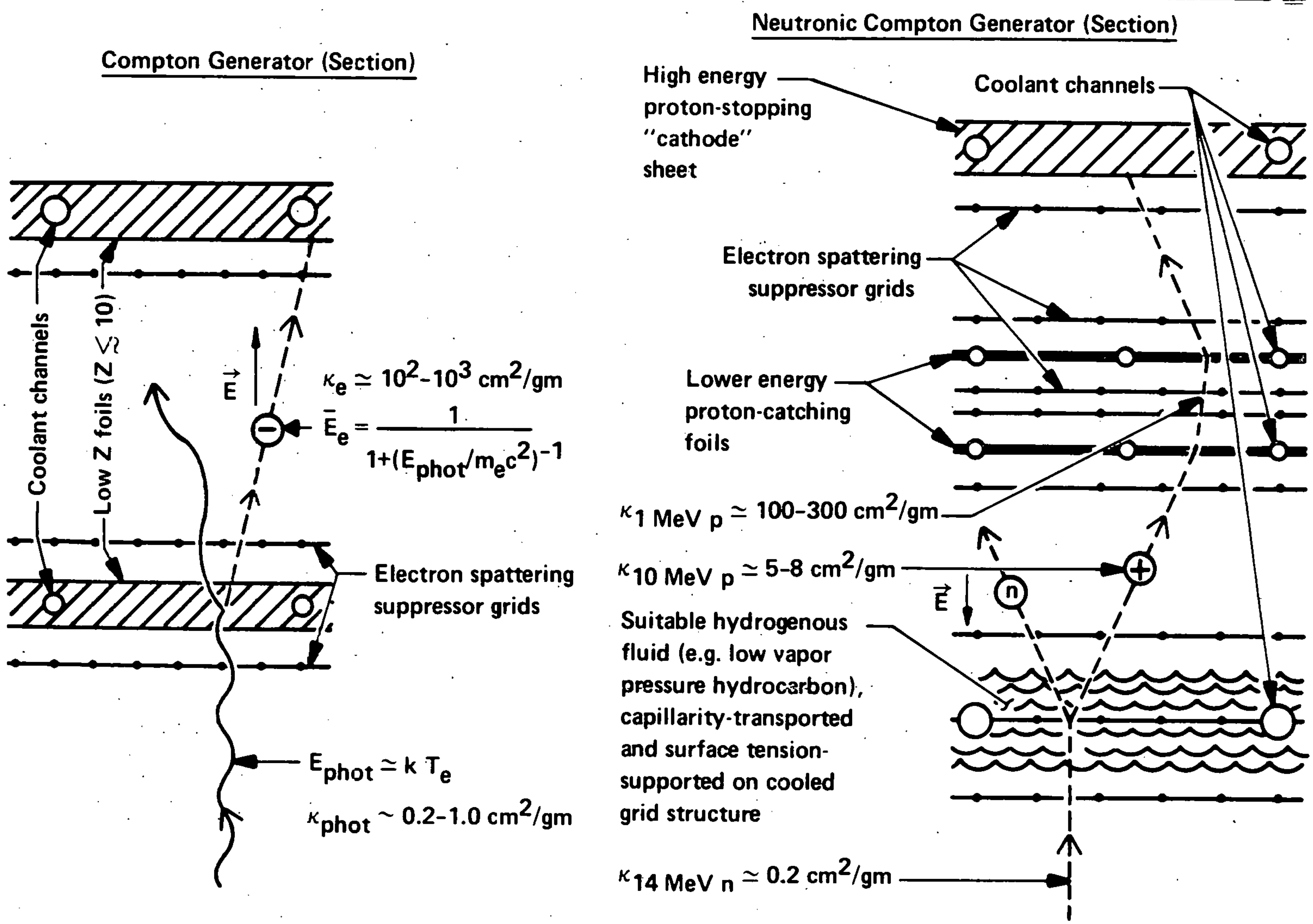


FIGURE 6

DIRECT CONVERSION OF MULTI-MEV NEUTRON ENERGY TO ELECTRICITY

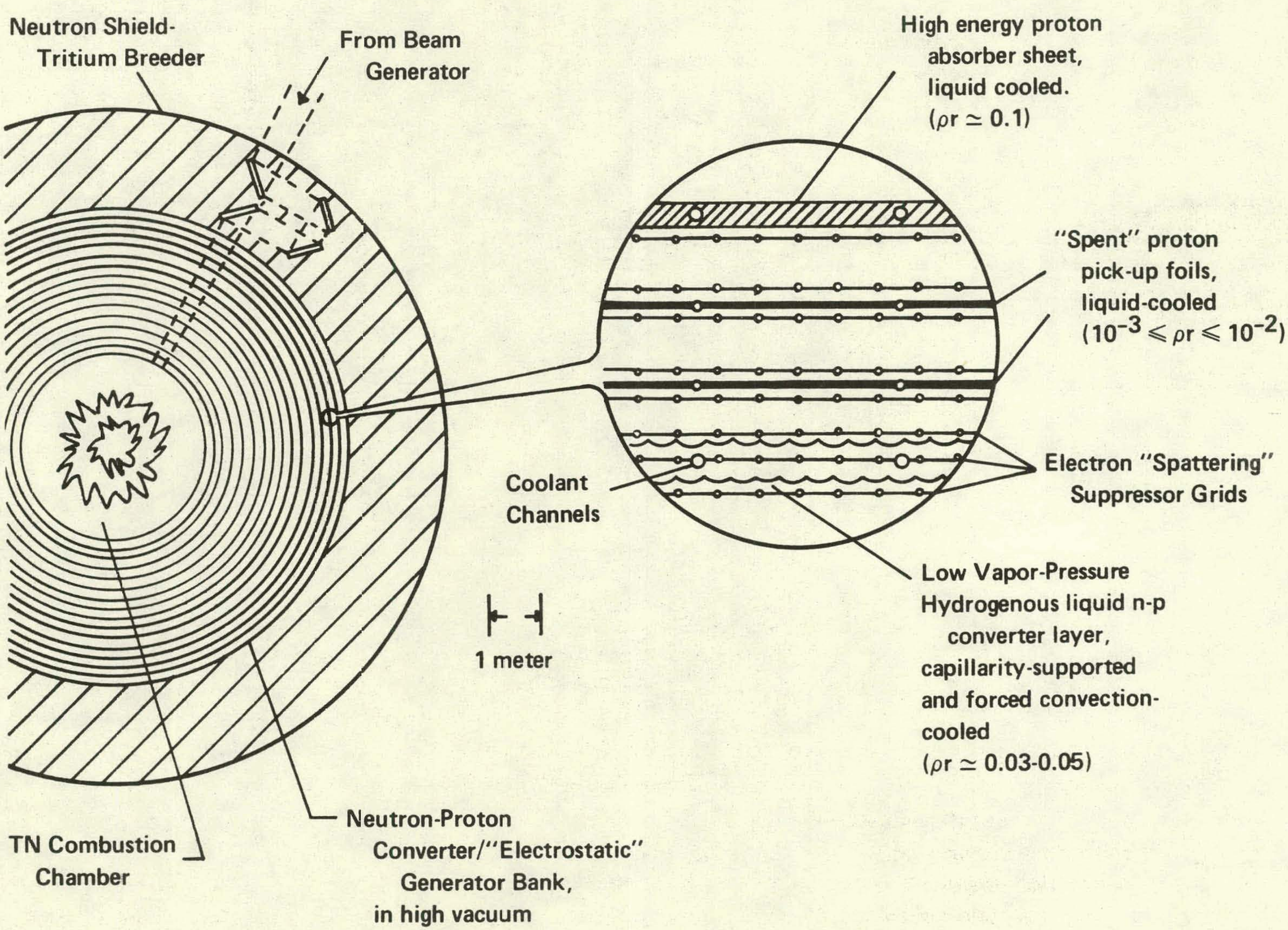
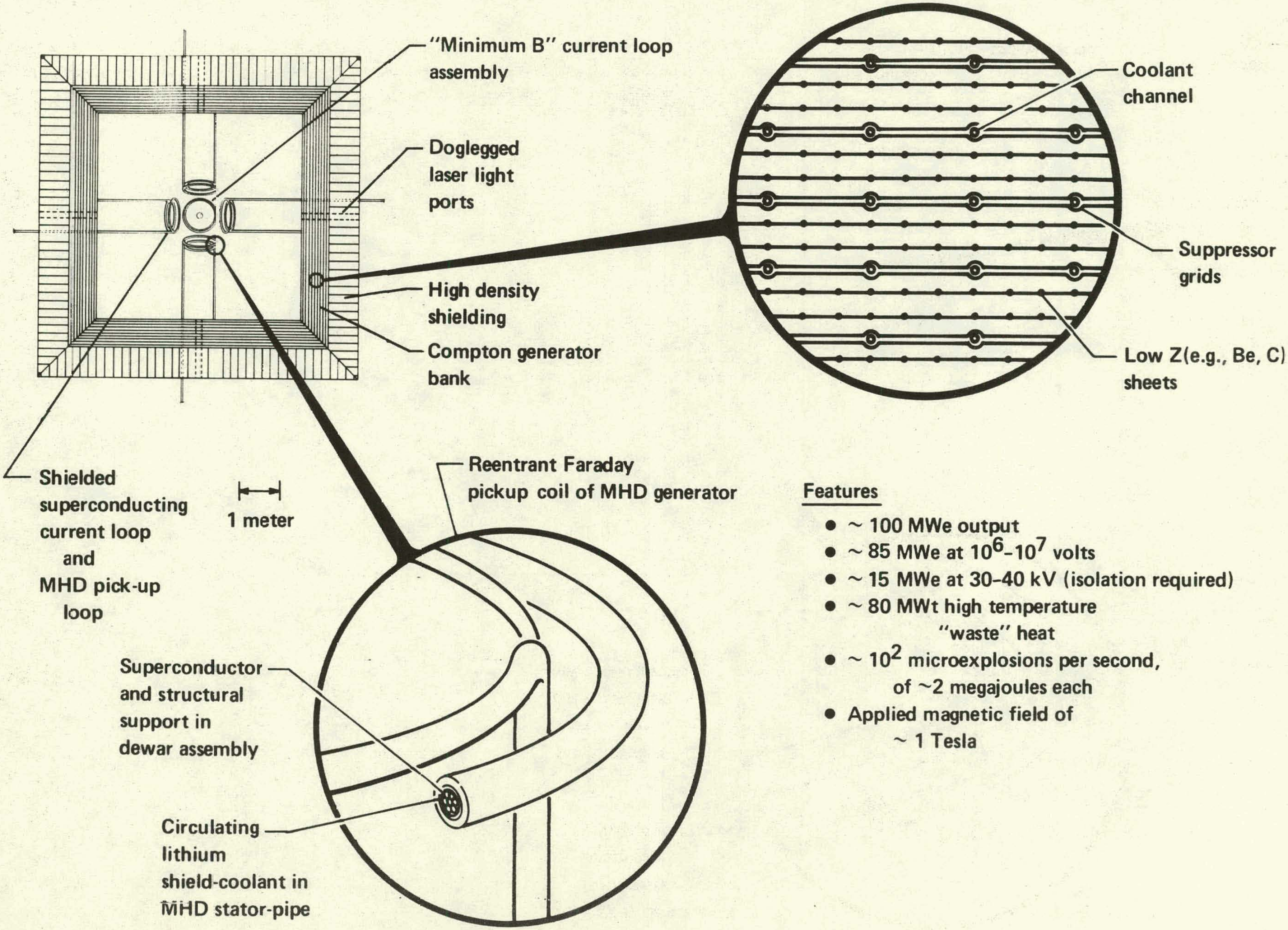


FIGURE 7

CONCEPTUAL DESIGN OF MHD CONVERTER-COMPTON GENERATOR MODULE (100 MWe) OF pB^{11}-BURNING PULSED FUSION POWER PLANT



Features

- ~ 100 MWe output
- ~ 85 MWe at 10^6–10^7 volts
- ~ 15 MWe at 30-40 kV (isolation required)
- ~ 80 MWt high temperature "waste" heat
- ~ 10^2 microexplosions per second, of ~2 megajoules each
- Applied magnetic field of ~ 1 Tesla

FIGURE 8

DIRECT CONVERSION PARTITIONING OF THE FUSION POWER PIG

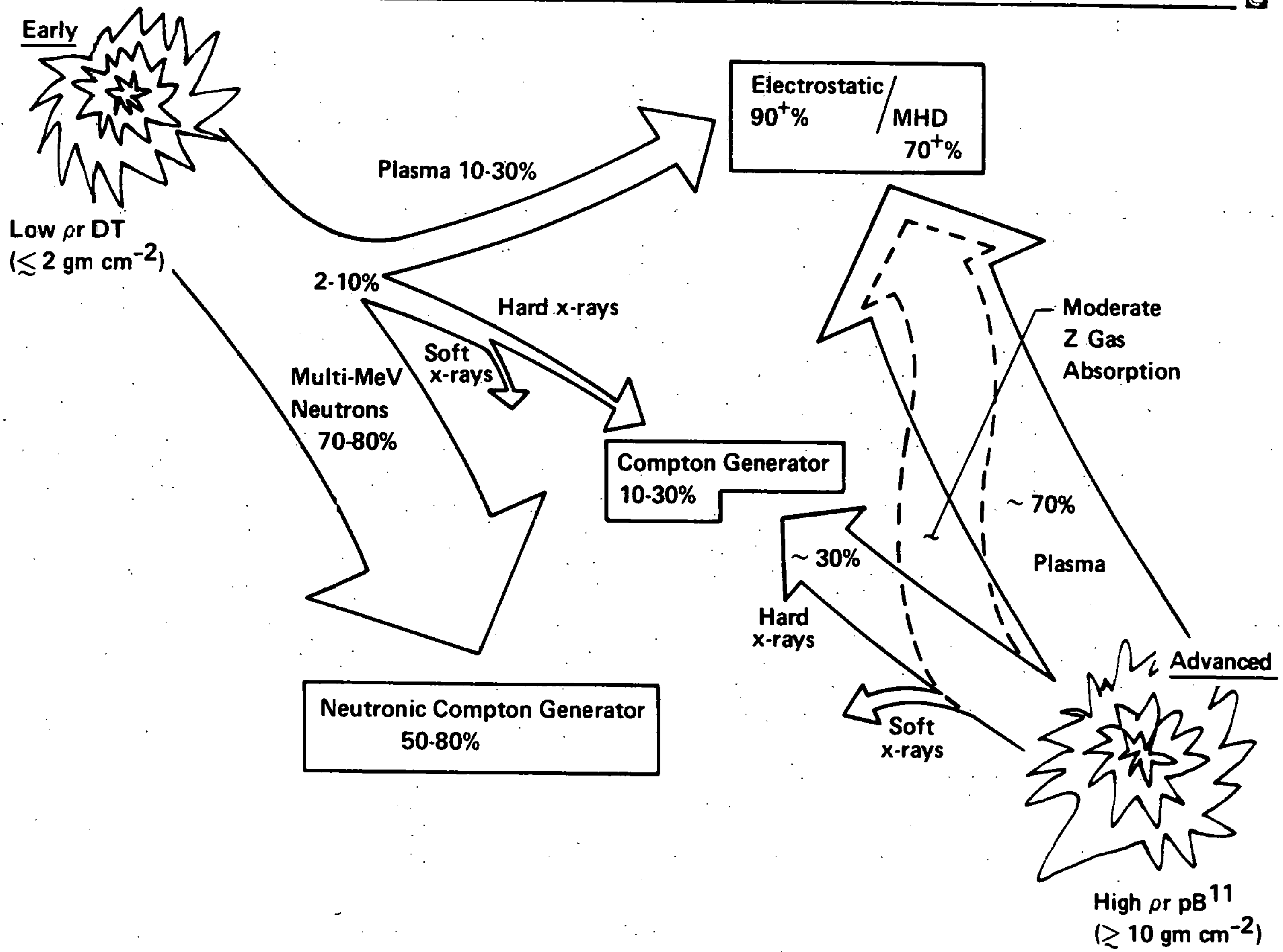


FIGURE 9

TABLE 6

PROJECTED REACTOR COSTS AND EFFICIENCIES

Reactor Type	$ per kwe	Efficiency	Operating cost (total), mills/kwh
Conventional	$150-250	30-45%	7
Conventional. with MHD	$100-250	40-60%	4
Nuclear (non-breeder)	$200-400	25-35%	2-3
Nuclear Fast Breeder	$250-500	30-40%	1.5-2.5
Fusion/Thermal Conversion	$200-400	35-45%	1.5-2.5
Advanced DT Fusion Reactor w/Direct Conversion	$150-300	50-70%	1-2
Advanced pB^{11} Fusion Reactor w/Direct Conversion	$100-200	50-70%	1-2

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