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INTERNATIONAL ATOMIC ENERGY AGENCY

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FUSION-FISSION HYBRID STUDIES IN THE UNITED STATES*

ABSTRACT

Systems and conceptual design studies have been carried out on the following three hybrid types: (1) The fission-suppressed hybrid, which maximizes fissile material produced (Pu or ^{233}U) per unit of total nuclear power by suppressing the fission process and multiplying neutrons by (n,2n) reactions in materials like beryllium. (2) The fast-fission hybrid, which maximizes fissile material produced per unit of fusion power by maximizing fission of ^{238}U (Pu is produced) in which twice the fissile atoms per unit of fusion power (but only a third per unit of nuclear power) are made. (3) The power hybrid, which amplifies power in the blanket for power production but does not produce fuel to sell. All three types must sell electrical power to be economical.

A series of studies led to a reference design of a fission-suppressed breeder that used liquid-lithium cooling of beryllium balls with thorium snap rings. Another series of studies considered a fission-suppressed, helium-cooled, molten-salt breeder design. Safety improvements for use in fast-fission designs were also identified. Low-burnup metal balls, which can be drained out of the blanket to passively cooled holding tanks, would be used in several of the above design concepts.

Blanket designs not requiring reprocessing, called direct enrichment, were also studied. Experiments were carried out on neutron multiplication in beryllium, beryllium radiation damage, corrosion, and pebble flow. Breeding blanket designs for tokamak and tandem-mirror configurations were based on liquid-lithium, water, and helium cooling. Solid (U, Th, $LiAlO_2$, Li_2O) and liquid breeders (Li, LiF+ThF_4) were considered.

Studies indicate that as the predicted cost of the fission-suppressed fusion plant drops from twice a light-water reactor's (LWR) cost, the calculated breakeven price of uranium from the fusion breeder drops from $100/pound. A fusion plant costing 1.5 times an LWR is calculated to produce fuel at an equivalent price of $70/pound. Even lower prices are predicted as fusion costs drop. An overall conclusion is that the deployment of fusion technology can cap the price of uranium.

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1. INTRODUCTION

In this paper, we discuss the U.S. progress on the hybrid concept since the last meeting held in Tokyo in 1981. At that meeting, we gave a paper on the fission-suppressed blanket.[1] Since 1981, we have made significant progress in developing systems and conceptual designs for the fission-suppressed hybrid.

2. HYBRID TYPES

The typical characteristics of the three hybrid types are shown in Table I. For comparison, we also show a pure-fusion or fusion-electric case in Table I. The power amplifier uses 14-MeV neutrons to drive a subcritical assembly. The fusion neutron kinetic energy is multiplied (or amplified) by fast fission of ^{238}U (or Th) and fission of Pu (or ^{233}U). A fast-neutron blanket assembly where the Pu is removed at relatively low concentrations has a neutron energy multiplication of about 10 times 14 MeV. By using beryllium or another nonfissioning neutron multiplier, we can suppress fast-fission of Th or ^{238}U and, by removing the bred ^{233}U or Pu, we can also suppress thermal neutron fissioning. We prefer breeding ^{233}U, which can be mixed with ^{238}U and then used in almost exactly the same way ^{235}U + ^{238}U is used today with no thorium in the fission fuel. Other options include: mixing bred ^{233}U with thorium (in this case, no Pu exists in either fuel cycle) or breeding plutonium and mixing it with ^{238}U. Effectively, this bred fuel can place a ceiling on the escalating price of mined U_3O_8.

The three hybrid types are called power, fast-fission, and fission-suppressed hybrids. The three types have strongly different characteristics as shown in Table I. The fission-suppressed design has the highest allowed capital cost, but it perturbs the fission industry and power utility industry the least because it is a fuel factory that supports about 14 fission plants (e.g., LWRs) of the same thermal power. The fission-suppressed hybrid type requires the most from fusion technology ($Q \geq 10$) and it also has a capital cost twice that of a fusion-electric power plant. Lowering capital cost will result in lower-cost bred fuel.

The fast-fission type is primarily a power plant with a secondary product--fuel for sale. This type supports far fewer fission reactors.

The power hybrid relaxes fusion requirements the most ($Q \geq 1$), but can also cost the least ($\leq$1.2 times an LWR's cost). Safety considerations with both the power and fast-fission types are a major design constraint.

3. ECONOMICS

In the last few years, significant new economic analyses on fusion breeders were performed. The question addressed in these analyses is as follows: "At what price of uranium would the operator of an LWR or other reactor type incur the same costs over a 30 year period as the costs he would incur from operating a fusion breeder to supply his fuel needs over a 30 year period. If one fusion breeder fueled 14 LWRs, then he would be a 1/14 owner/operator of the fusion breeder." An example of the results from Ref. [2] are given in Fig. 1.

In Fig. 1, the power generation cost in mills/kW•h in 1983 dollars averaged or levelized over 30 years is plotted vs the price paid for uranium in 1983 constant dollars. The solid line is the LWR. The line labeled (a) shows a lithium-cooled, fission-suppressed hybrid [3] and its supported LWRs. For this particular example, the hybrid costs 2.3 times the LWR cost per unit electricity, and the levelized electricity generation cost for the hybrid-fueled LWR is less than an LWR using uranium priced greater than $102/lb. The breakeven uranium price in constant 1983 dollars is $102/lb. The line labeled (b) is a high-cost liquid-metal fast-breeder reactor (LMFBR), which is assumed to cost 1.37 times an LWR and has a breakeven uranium price of $179/lb. The line labeled (c) is a low-cost LMFBR, which is assumed to cost 1.1 times an LWR and has a breakeven uranium price of $65/lb. Figure 2 and Table II summarize the results for several cases including molten-salt hybrids [4] and with the high-temperature gas reactor (HTGR) and molten-salt reactor (MSR) as burners of the hybrid fuel. The designating MS (1.6) and MS (2.5) indicate systems with blanket energy multiplication (M) factors of 1.6 and 2.5, respectively. The MS hybrids [3] cost 2.3 [MS (2.5) case] and 3.0 [MS (1.6) case] times the LWR cost per kW_e and result in breakeven uranium prices of $110/lb and $118/lb, respectively. Clearly, if fusion costs are reduced significantly, the breakeven uranium price can also be reduced significantly below \$100/lb. Refer to Ref. [2] for economic analyses details.

Figure 3 illustrates the insensitivities to capital cost of the hybrid and shows that the LMFBR is very sensitive to capital cost.

4. U.S. URANIUM RESOURCES

This section presents a calculation of adequacy of U.S. uranium resources that is similar to earlier calculations by S. I. Abdel-Khalik [5], D. H. Berwald [6], and C. E. Max [7]. We chose the following scenario 100 GW_e of LWRs in 1985, rising to 140 by the year 1990 with no new units until after the year 2000. The growth for the years 2000 to 2025 is 5% per year until 2025, at which time the number of new units reaches and is limited to 20 GW_e per year. We assume a total electrical capacity of 718 MW_e in 1985, increasing at 2% per year until 2025, at which time we assume it increases only 1% per year. The nuclear fraction of the total capacity is 14% in 1985, 15% in 2000, 26% in 2020, 42% in 2040 and 52% in 2050. Figure 4 shows the above deployment scenario for light water (or other) reactors.

Assuming each LWR uses 210 (short) tons of U_3O_8 per year at 80% capacity until 2 million tons are consumed, and then 147 tons per year thereafter and assuming full recycle, the cumulative uranium consumption starting in 1985 is given in Fig. 5.

Next, the forward cost (roughly defined as the future cost to be incurred, not counting exploration, mine development, mill construction, income tax, or cost of money) of uranium vs cumulative uranium mined is taken from Ref. [7], using a 50% probability of finding a given amount of uranium. This was converted from 1981 dollars into 1986 dollars by each year's dollar-deflator factors (1.063 × 1.038 × 1.038 × 1.038 × 1.04 = 1.236). The price at which a supplier would <u>like</u> to sell in order to pay forward costs and to recover some sunk costs, taxes, and profit is more by a factor of about 1.8. Of course, the market price will vary widely due to many factors. The price in the sense described above vs cumulative consumption is plotted in Fig. 6.

Using these assumptions, Fig. 7 shows the price and forward cost projected into the future. The price rises to $50/lb in 2007, $100/lb in 2027 and $125/lb in 2035, $206 in 2045, and $410 in 2055. Some strategies could push these dates into the more distant future (e.g., building fewer LWRs and importing foreign uranium). Some events could also bring these dates into the nearer future (e.g., cartels; embargos; more expensive mining safety requirements; increased electricity use, resulting in higher nuclear fraction to mitigate environmental factors; or new electricity uses such as transportation). For comparison, Fig. 7 includes the historic price of uranium in constant 1986 dollars from 1950 to 1982. This analysis was done only for the U.S. It would be useful to have the data to analyze a world-wide uranium resource/consumption scenario.

We conclude from this U.S. scenario of fission power-plant construction that some very important changes may be necessary in the middle of the next century. Being able to provide fuel to LWRs from the fusion hybrid may be a valuable option.

5. UPDATED REFERENCE DESIGN OF A LIQUID-METAL-COOLED TANDEM-MIRROR FISSION-SUPPRESSED FUSION BREEDER

An updated version [3] of a reference design for a liquid-metal-cooled tandem-mirror fusion breeder (fusion-fission hybrid reactor) is shown in Fig. 8. This revised design incorporates the results of several recent studies that have attempted to resolve key technical issues associated with an earlier reference design [8] completed in 1982. The issues addressed in this new reference design relate to the following areas: nuclear performance, magnetohydrodynamic (MHD) pressure loading, beryllium-multiplier lifetime, structural efficiency and lifetime, reactor safety, corrosion/mass transfer, and fusion-breeder capital cost.

The updated blanket design provides increased performance and reduced technological risk when compared with earlier fission-suppressed hybrid-blanket designs.[9] This blanket should achieve a net fissile-breeding ratio (per fusion) of 0.84, with a tritium breeding ratio of 1.06, and an average blanket energy multiplication of 2.44. In addition, this blanket would operate at a relatively-low neutron wall loading (1.7 MW/m^2) with a low lithium coolant outlet temperature (425°C). These features provide for a very low beryllium swelling (~0.3% $\Delta V/V$) over the operating cycle. Similarly, the irradiation lifetime of the ferritic-steel blanket structure is expected to exceed 10 calendar years (180 dpa). Despite this increased blanket-energy multiplication and reduced lithium-coolant outlet temperature, we estimate an acceptable first-wall MHD pressure of 1.7 MPa for the reference flow conditions. The updated design continues to provide for a mobile, pebble-shaped, beryllium/thorium fuel element that can be loaded and discharged to a dump tank without removing the blanket. The dump tank can be passively cooled to provide attractive reactor safety features.

In addition to the blanket design revisions, we have also completed a plant concept, cost, and fuel-cycle economics assessment. Assuming that the fusion breeder uses the same 2600-MW_f fusion-plant design developed for the 1983 Mirror Advanced Reactor Study (MARS),[10] the total plant cost and net electrical production should be \$6.3 billion and 1990 MW_e, respectively. In comparison with the MARS fusion-electric plant estimates, both of these numbers are ~1.7 times higher. However, the fusion breeder would also produce 6660 kg/y of ^{233}U fuel for consumption in fission-burner reactors. Specifically, the 6660 kg/y would be sufficient to provide makeup for about 25 LWRs operating on a denatured thorium-fuel cycle. Economic studies that reflect this high level of market leverage indicate that the reference fusion breeder would be economical if the price of mined uranium were to increase to only about 100 $lb. The key design features of this updated breeder are given in Table III.

In summary, we have completed an updated liquid-metal-cooled blanket design for a tandem-mirror fusion breeder. Several prior feasibility issues have been addressed and the design continues to promise attractive levels of performance as an economical producer of fissile fuel for many client LWRs.

6. DESIGN OF A HELIUM-COOLED MOLTEN-SALT FUSION BREEDER

A new conceptual blanket design, based on the use of molten salt for a fusion reactor, produces fissile material for fission power plants (Figs. 9 and 10). Fission is suppressed by using beryllium, rather than uranium, to multiply neutrons and also by minimizing the fissile inventory. The molten-salt breeding media ($LiF+BeF_2+ThF_4$) is circulated through the blanket and on to the online processing system where ^{233}U and tritium are continuously removed. Helium cools the blanket, including the steel tubes containing the molten salt. We chose austenitic steel because of its ease of fabrication, adequate radiation-damage lifetime, and low corrosion rate by molten salt. Some of the plant parameters are given in Table IV. Removal of bred ^{233}U is easily accomplished using the low-cost fluorination process, estimated to only cost a few dollars per gram of product. We estimate that the breeder, having 3000 MW of fusion power, produces 6400 kg of ^{233}U per year at an 80% capacity factor, which is enough to provide makeup for 20 GW_e of LWRs per year (or 14 LWR plants of 4440 MW_t) or twice that many HTGRs or CANDUs. Safety is enhanced because the afterheat is low and the blanket materials do not react with air or water. Important technical issues that still need to be resolved include tritium containment and the feasibility of using beryllium. In addition, barriers to tritium permeation from the helium stream to the steam generators must be developed. Beryllium-beryllium self-welding and beryllium-steel welding at the contact points are issues needing experimental investigation. The ability of the beryllium balls to withstand neutron radiation is maximized by design (small size); however, irradiation data are needed. Beryllium swelling--leading to jamming, cracking, chipping, and flying missiles that might damage circulators--also needs to be investigated. The fusion breeder based on a pre-MARS tandem mirror is estimated to cost $4.9 billion or 3.0 times an LWR of the same electric power. The estimated breakeven price of uranium is $118/lb in 1983 dollars as discussed in the Sec. 3, Economics.

7. NUCLEAR ANALYSIS

Our refined nuclear analysis,[11] including the treatment of resonance and spatial self-shielding coupled with an optimization procedure, has resulted in improved performance estimates for two conceptual fission-suppressed blankets.

The first blanket has a pebble bed of composite beryllium and thorium (Be/Th) metal spheres cooled by liquid lithium. The liquid lithium is also the tritium-breeding medium. The Be/Th spheres are replaced without blanket disassembly to facilitate quick refueling. We found that specific fissile breeding (F_{net}/E) in this blanket had a broad maximum around a thorium volume fraction of 0.15 with a net fissile breeding ratio (F_{net}) of 0.84 and a tritium breeding ratio of 1.06. The average blanket energy multiplication (M) is 2.5, given a discharge ^{233}U/Th ratio of 1% [M = E(blanket)/14 MeV].

The second blanket also uses a beryllium pebble bed for neutron multiplication, but its fertile elements (lithium and thorium) are in a molten salt (70 mol% LiF + 12 mol% BeF_2 + 18 mol% ThF_4) contained in tubes within the beryllium pebble bed. The blanket is cooled by helium. Molten salt (MS) is an attractive fuel form because it allows online refueling, low-cost processing, and because it does not require thorium-fuel fabrication. With 3 vol% steel structure, in addition to the salt tubes, specific breeding in this blanket maximized at a salt volume fraction of 0.33 with net fissile breeding (F_{net}) of 0.62 (T breeding is 1.06). Blanket energy multiplication (M) is 1.9, at a ^{233}U/Th ratio of 0.11%.

Specific breeding (F_{net}/E) in these two blankets is nearly the same, 0.024 vs 0.023 (atoms/MeV). We predict that the specific breeding in fusion breeders using these blankets will be well over an order of magnitude higher than in fission breeders.

8. THE FISSION-SUPPRESSED DIRECT-ENRICHMENT (FSDE) FUSION BREEDER

The fission-suppressed direct-enrichment (FSDE) fusion-breeder concept breeds fissile fuel employing a fission-suppressed blanket in a fusion reactor. This fuel is subsequently used directly in fission reactors (e.g., water or gas-cooled) without any reprocessing. No reprocessing of fission reactor fuel, however, implies a low support ratio and a rather high breakeven U_3O_8 price. Therefore, we propose reprocessing spent fuel only in the client reactors. In the near-term development of fusion breeders, the FSDE breeder will probably receive minimum sociopolitical impact because of this reprocessing issue. This concept will also benefit the development of advanced fission reactors because of the availability of enriched fuel such as ^{233}U.

The FSDE fusion breeder blanket [12] proposes the use of fertile fuel (^{232}Th) or (^{238}U) in the form of about 3-mm oxide particles suspended in a lithium-lead eutectic ($Li_{17}Pb_{83}$), which can be the tritium breeding material as well as coolant. After about 3% fissile (^{233}U or ^{239}Pu) enrichment, the fuel particles can be extracted from the blanket and then be directly fabricated into fuel elements without chemical reprocessing. The fabrication technologies are state of the art, and are very similar to pellet or the more advanced sphere-pac fuels technologies.

A typical beryllium fission-suppressed blanket such as the one conceived in 1982 and studied in detail by the U.S. fusion breeder development program [13] can be modified for the FSDE blanket. Beryllium balls are employed in the blanket for neutron multiplication and energy-moderation purposes. The blanket can be cooled by either liquid-lithium or lithium-lead eutectic for low pressure operation. The fertile rings on the beryllium balls as described in 1982 will be eliminated. Instead of these ring components, tubes of about 3-cm diameter, containing fertile oxide microspheres suspended in lithium-lead eutectic will be introduced in the blanket.

The breeding performance of an FSDE breeder blanket described above will be similar to the 1982 reference blanket. However, the effect of resonant self-shielding requires increasing the thorium fraction by about a factor of two. The enrichment rate is so high, as a unique feature of the fertile-dilution design, that this blanket takes only about 120 days for these fertile particles to reach 3% fissile enrichment, assuming the neutron wall loading is 4 MW per meter square. For the Th-U cycle, some of the bred fuel at this enrichment time is still in the form of nonfissile ^{233}Pa. The blanket average ^{233}U concentration will be about 1% in the fertile material, only 33% of the total U+Pa inventory. This phenomenon substantially reduces the fissioning power in the blanket while producing enriched particles at adequate fissile enrichment levels. Moreover, the active fissile content in the blanket can be reduced further if more than one size of particle is employed. For example, if the three sizes of particles are introduced in the blanket, when No. 1 particles reach 3% fissile enrichment, the Nos. 2 and 3 particles are enriched only to 2 and 1%, respectively. The average fissile enrichment in the blanket is 2%, which is a 33% reduction of the fissile inventory compared to the one-size particle design.

9. BERYLLIUM NUCLEAR DATA EXPERIMENTS

Thick beryllium assemblies (~20-cm full density) proposed for fission-suppressed fusion breeders have a considerable data base uncertainty relevant to neutron multiplication. Measurements by Basu [14] reported 25% less multiplication than calculated. This result was alarming, especially since the reduction in net breeding after 1 neutron is allocated to replenishing the burned triton, in which case the 25% can more than double to over a 50% reduction in predicted breeding. Doyle and Lee [15] in consultation with Basu reduced the discrepancy to 15% with significant uncertainty, still a rather large reduction in breeding. In addition, they analyzed a previously unreported experiment on a large beryllium assembly carried out in the early 1950s, and they found that the experimental value of neutron multiplication less than calculated by about 10%, which results in a predicted net breeding decrease of over 20%. As a result of this considerable discrepancy, pulsed neutron measurements using time-of-flight techniques were carried out by Wong et al. [16] Calculations of this pulse sphere experiment using the latest cross-section evaluations [17] agree within 10%. [16]

Whereas the infinite media breeding ratio was 2.7, with the new evaluation it is 2.5. To resolve the Be multiplication question, an accurate integral experiment such as using the Mn bath method should be carried out on the existing Be spherical shells of 19.9 cm thick or a similar assembly. Such an experiment is possible at the facility at Idaho National Engineering Laboratory (INEL) in which multiplication can be measured with an accuracy approaching ±1%.

10. FAST-FISSION DESIGN

We made a preliminary scoping study of a tokamak with a fast-fission blanket.[18] The previous fast-fission designs were developed in the 5 years before hybrid work in the U.S. shifted to fission-suppressed designs. A number of ideas, stimulated by safety considerations in the fission-suppressed designs, resulted in major improvements in the fast-fission design. For example, one improvement over previous fast-fission blanket concepts is the use of a mobile fuel (pebbles) with helium cooling. A second and redundant path for decay heat removal is accomplished by circulating a liquid tritium-breeding media through tubes in the pebble bed. In loss of coolant cases, the mobile fuel can be gravity-dumped to a separately cooled dump tank before excessive temperatures are reached. The pebble bed allows removing fuel on a different schedule than the blanket removal schedule, so that the increased power multiplication due to Pu buildup can be minimized by removing the fuel pebbles often. At a blanket exposure of 2 MW y/m^2, the average Pu concentration in ^{238}U at discharge is 1%, whereas the blanket energy multiplication of 14-MeV neutrons only increases from 9.1 to 10.5. Employing metal fuel facilitates use of pyroprocessing, which is predicted to significantly lower cost compared to using the aqueous (PUREX) processing. The tokamak parameters used in the calculations were: major radius 5.2 m, average plasma beta 5%, toroidal field 5.6T, and an average neutron wall loading of 1.3 MW/m^2. With the ignited tokamak plasma producing 620 MW of fusion power, the net electric power is 1600 MW_e from 4600 MW of thermal power. The annual fissile production exceeds 3 tonnes. The direct capital cost is estimated at $2652 million (1985). In the future, low-cost tokamak designs should be developed using, for example, higher beta and optimal plasma shaping.

11. RECOMMENDED FUTURE WORK

As fusion technology continues to progress, a continual up-to-date economic analysis should be carried out to assess the fusion breeder application. Worldwide uranium resources should be studied to better predict when resource depletion will cause the price of uranium to rise to the point where hybrid-bred fuel would be competitive. A design and system study of a fast-fission blanket should be performed with special emphasis on safety. For both fast-fission and fission-suppressed designs, detailed neutronics analyses should be made for a realistic tokamak device and blanket configuration. Experimental work should be done on feasibility issues such as tritium barriers and materials unique to fusion breeders (e.g., beryllium). An example of a near-term development program for the liquid-metal and the molten-salt fusion breeders is given in Figs. 11 and 12.

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TABLE I. Various characteristics of fusion hybrid blankets.

	Power amplifier	Fast fission	Fission suppressed	Pure fusion
Blanket energy multiplication (M_{av})	25	10	2	1.3
Required gain for efficient electricity production (Q)	1	2	10	16
Net fissile breeding per fusion (F)	1	1.2	0.7	-
Fuel production rate (kg/MW·y)	0.2	0.6	1.9	-
LWR consumption rate (kg/MW·y)	0.2 (Pu)	0.2 (Pu)	0.14 (U)	-
LWR support ratio (R)	1	3	14	-
Dominant afterheat source	Fission products	Fission products	Actinides	Structure
Dominant mode of operation	Power plant	Power plant	Fuel factory	Power plant
Capital cost goal relative to LWR	1.2	1.4	2.5	1.3
Fuel reprocessing cost impact	Low	Low	High	-

TABLE II. Breakeven uranium price for fission/fusion hybrid systems and for LMFBRs.

	Fission reactor[a]		
	LWR	HTGR	MSR
Hybrid			
Opt-Li	102[b]		
MS (1.6)	118	74	79
MS (2.5)	110	69	77
LMFBR			
High	179		
Low	65		

[a] DU3(TH) for hybrids, Pu(u) for LMFBR.
[b] Assumes pyrochemical reprocessing at $126/kg and design improvements subsequent to Ref. [2].

TABLE III. Key design features for the liquid-metal-cooled tandem-mirror fission-suppressed fusion breeder.

	Performance parameter
Tandem-mirror fusion driver	
MARS performance with lower wall loading	
Fusion power (MW)	2600
Plasma power gain (Q)	26
Neutron wall loading (MW/m^2)	1.7
Breeding blanket	
Average blanket energy multiplication	2.4
Net ^{233}U breeding ratio	0.84
Tritium breeding ratio	1.06
Overall performance	
Maximum thermal power (MW)	5700
Average thermal power (MW)	5075
Average net electric power (MW_e)	1990
Capacity factor (%)	70
^{233}U production (kg/y)	6660
Number of 1-GW_e LWRs fueled	25

TABLE IV. Plant parameters.

P_{nuclear} (MW)	4440
P_{fusion} (MW)	3000
$P_{\text{alpha particle}}$ (MW)	600
P_{blanket} (MW)	3840
P_{electric} (MW_e)	1380
$P_{\text{wall load}}$ (MW/m^2)	2
Blanket length (m)	127
First-wall radius (m)	1.5
F_{net}	0.6
M[a]	1.6
Fissile production (kg ^{233}U/y at 80% capacity factor)	6380
Total cost ($ million)	4867

[a] F_{net} is fissile atoms bred/triton consumed; M is the energy released in the blanket per triton consumed divided by 14 MeV.

FIGURE CAPTIONS

FIG. 1. Power generation cost for selected systems, including the Li-cooled fission-suppressed hybrid.

FIG. 2. Power generation cost for selected systems, including the helium-cooled fission-suppressed molten-salt hybrid.

FIG. 3. Breakeven uranium price vs reactor capital cost for fusion breeders and LMFBRs.

FIG. 4. Projected number of 1-GW_e LWRs.

FIG. 5. Cumulative uranium consumption. Assume 210 tons per 11-GW_e LWR per year until 2 million tons are reached, and 147 tons thereafter.

FIG. 6. Cumulative uranium consumption vs price.

FIG. 7. Historical and projected uranium price.

FIG. 8. The reference liquid-metal-cooled, fission-suppressed, tandem-mirror fusion-hybrid blanket features direct cooling of a bed of beryllium-thorium pebbles.

FIG. 9. One module of a helium-cooled molten-salt blanket. Helium under 5-MPa pressure flows from the rearmost ring header to the apex of each pod, then radially outward through the blanket to the forward ring header, and thence to heat exchangers for generating electricity.

FIG. 10. Cross section along the axis of one segment of a helium-cooled molten-salt blanket, showing arrangement of helium flow and of beryllium spheres and tubing for the molten salts.

FIG. 11. Near term development program for liquid-metal fusion breeder.

FIG. 12. Near term development program for molten-salt fusion breeder.

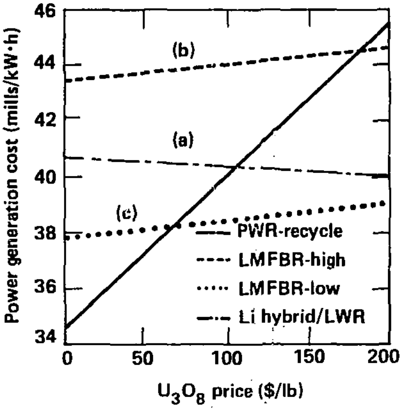


FIG. 1. Power generation cost for selected systems, including the Li-cooled fission-suppressed hybrid.

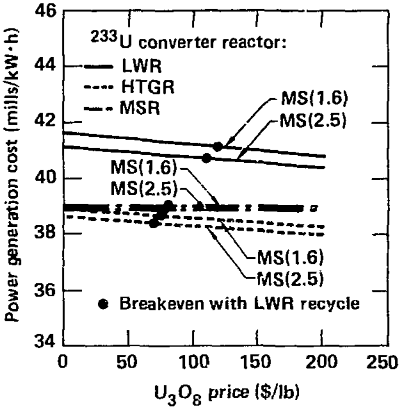


FIG. 2. Power generation cost for selected systems, including the helium-cooled fission-suppressed molten-salt hybrid.

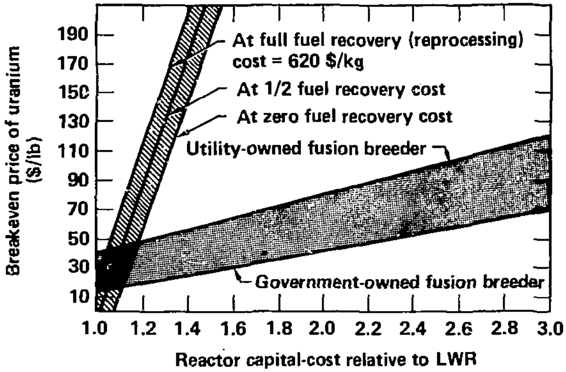
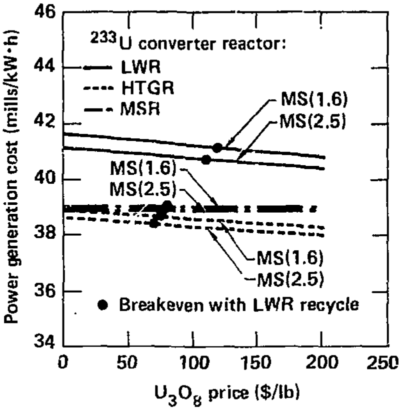


FIG. 3. Breakeven uranium price vs reactor capital cost for fusion breeders and LMFBRs.



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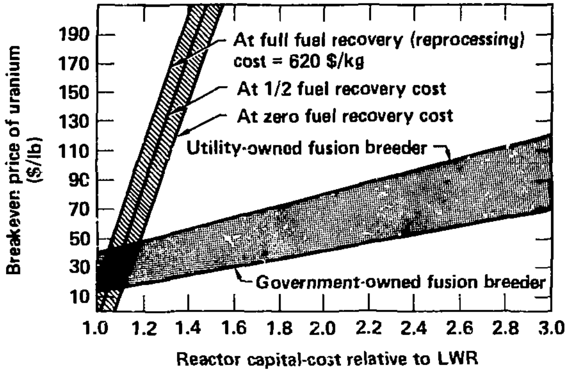

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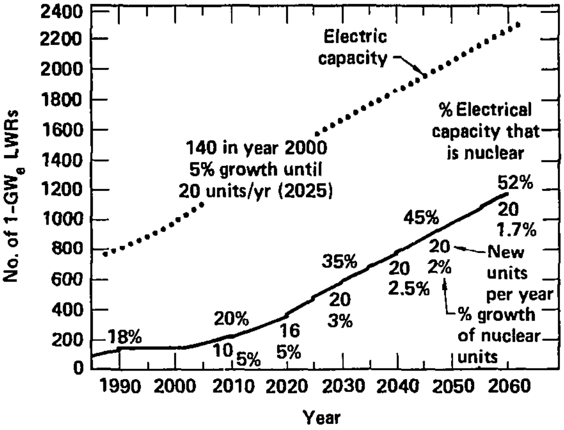

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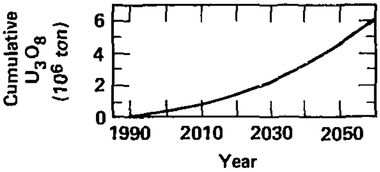

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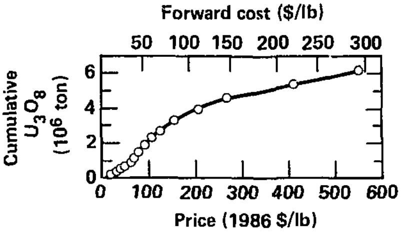

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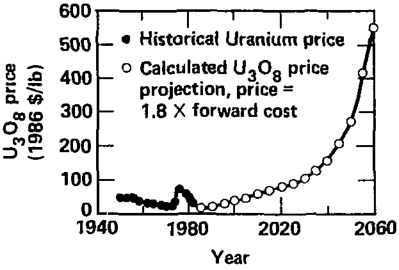

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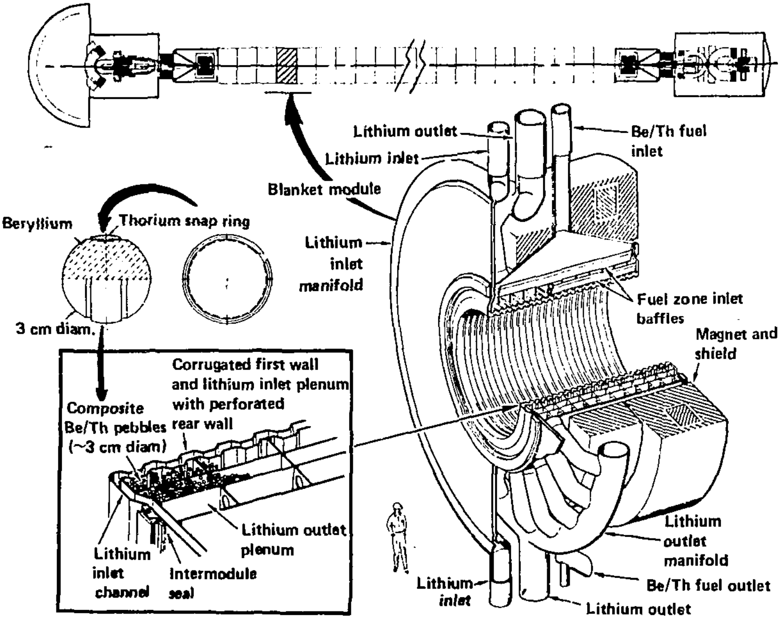

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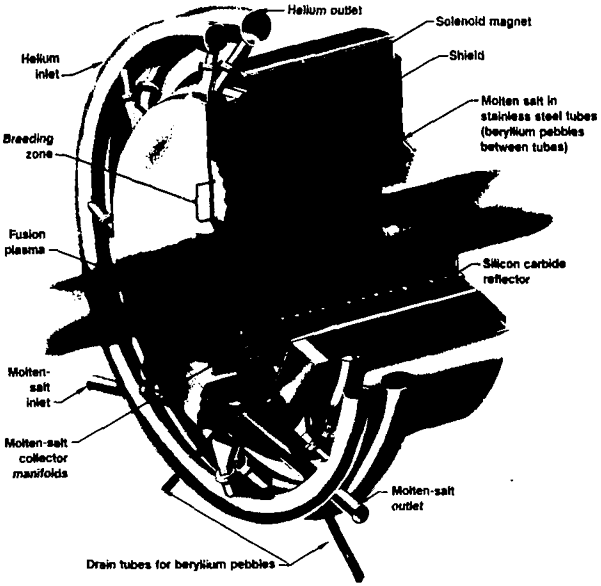

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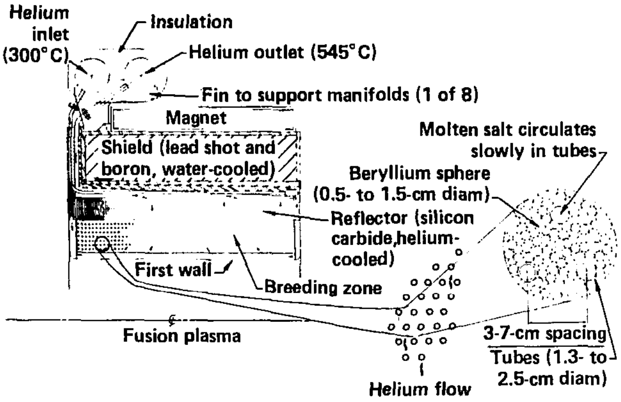

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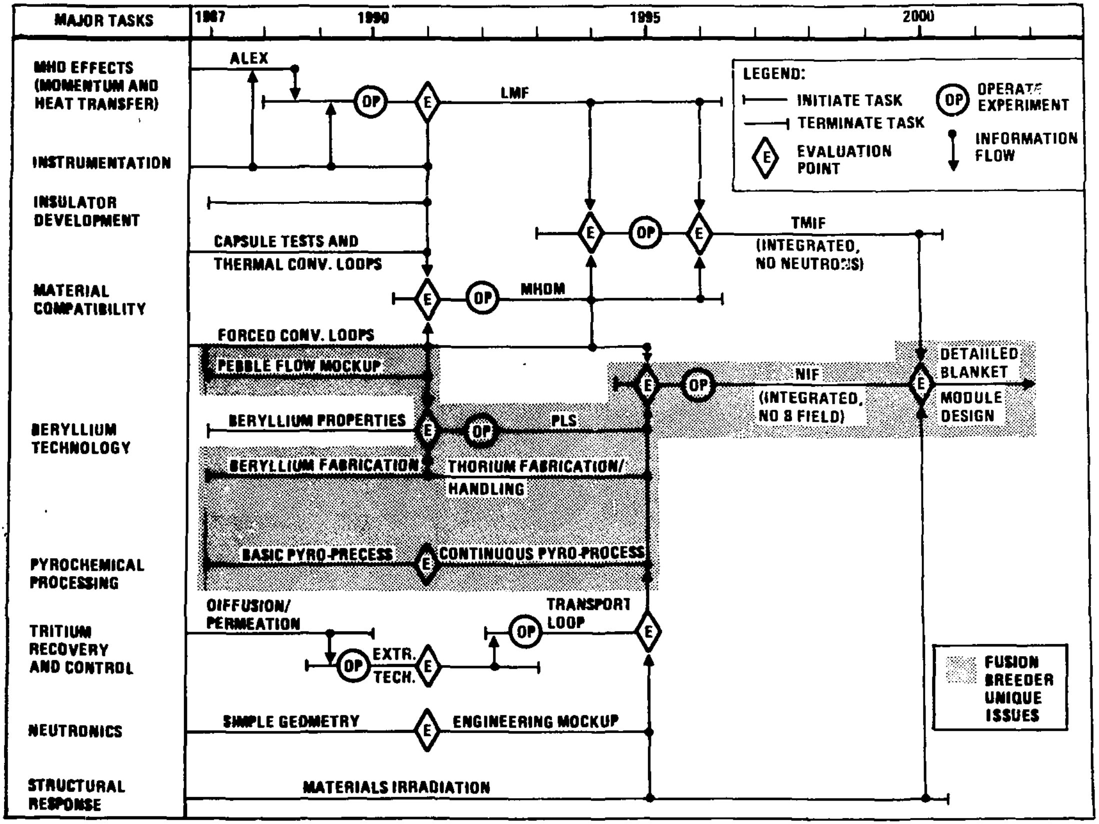

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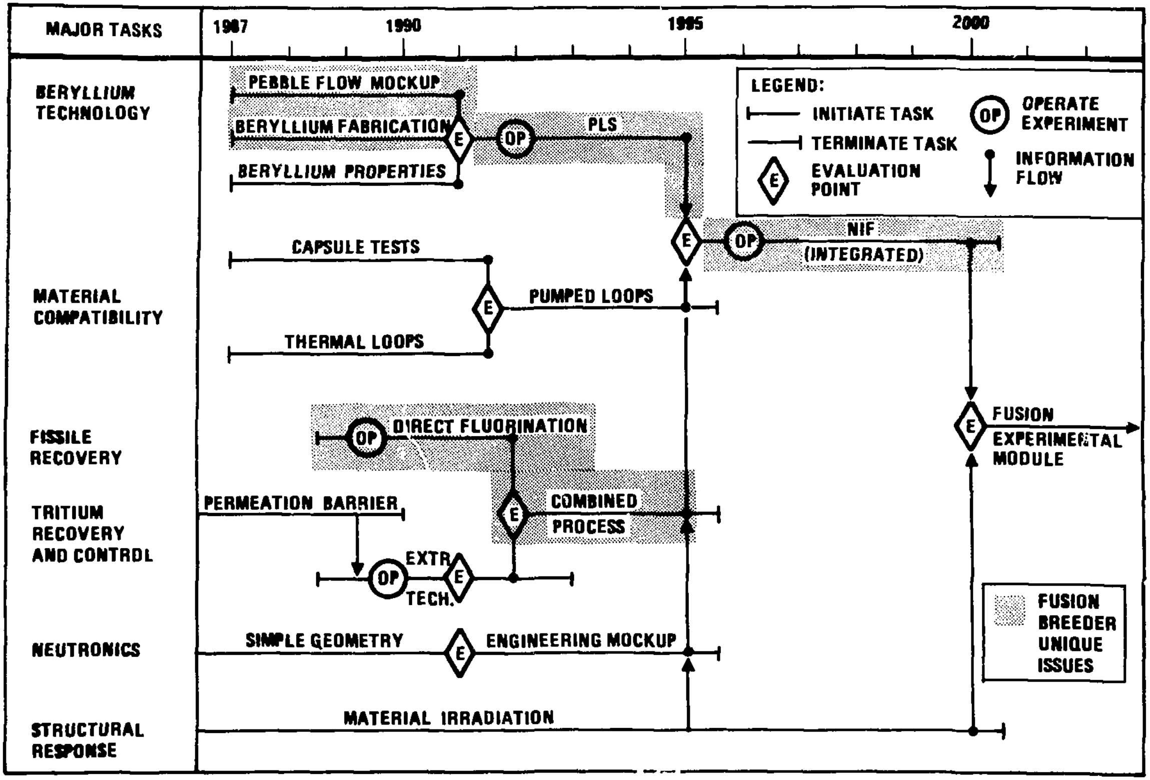

FIG. 12. Near term development program for molten-salt fusion breeder.