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THE FUSION BREEDER:
ITS POTENTIAL ROLE AND PROSPECTS

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J. D. Lee

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The Fusion Breeder: Its Potential Role and Prospects*

J. D. Lee
Lawrence Livermore National Laboratory
Livermore, CA, USA

The fusion breeder is a concept that utilizes 14 MeV neutrons from $D + T \rightarrow n(14.1 \text{ MeV}) + \alpha(3.5 \text{ MeV})$ fusion reactions to produce more fuel than the tritium (T) needed to sustain the fusion process. This excess fuel production capacity is used to produce fissile material (Pu-239 or U-233) for subsequent use in fission reactors. We are concentrating on a class of blankets we call fission suppressed. The blanket is the region surrounding the fusion plasma in which fusion neutrons interact to produce fuel and heat.

The fission-suppressed blanket uses non-fission reactions (mainly $(n,2n)$ or $(n,n't)$) to generate excess neutrons for the production of net fuel. This is in contrast to the fast fission class of blankets which use (n,fiss) reactions to generate excess neutrons. Fusion reactors with fast fission blankets are commonly known as fusion-fission hybrids because they combine fusion and fission in the same device.

Motivation

The motivation for the fusion breeder is basically the same as the fission breeder -- to tap the enormous energy potential of the world's abundant U-238 and Th-232 resources. While the basic motive is the same there are important differences that make the fusion breeder concept most

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intriguing. For example:

1. The fusion breeder requires no fissile inventory and the doubling time for the fissile inventory (T) is measured in weeks, not years.
2. The fusion breeder can produce many times (up to ~ 30) more net fissile product per unit of power.
3. Power densities are 10 to 100 times less.
4. The fusion breeder adds flexibility to the long-term fission energy option. All sorts of fission reactors can be considered, not just fast breeders, by virtue of an inexhaustible, prolific source of fissile material from fusion breeders.
5. The fuel production and energy production roles are performed in separate devices.

From fusion's viewpoint a motivation for the fusion breeder is the potential for an earlier, competitive application of fusion that in turn would advance fusion technology towards its goal of a stand-alone energy source. For example, consider a scenario in which the following conditions exist:

- o One or more fusion concepts have had a successful engineering demonstration.
- o Fission reactor (thermal, such as LWR's, HTGR's) capacity has expanded but now all uranium reserves are committed. Fuel recycle (reprocessing) and advanced isotope separation have already been exploited.
- o The fission fast breeder has been developed but not yet deployed because of its higher cost.

- o The relative energy cost position, in ascending cost, of the major options for additional and replacement capacity is: thermal fission fueled by fusion breeders; fission breeders; coal; fusion.

With this scenario economics would dictate that fission plus fusion breeder reactors would be deployed. If fusion breeder specific technology were not developed, the fission breeder and/or coal would be the logical choice and fusion would not benefit from early deployment. And the economic and environmental costs for power would be higher.

The above scenario, while only an example, does point to the conditions that must exist for fusion breeder deployment. They are:

1. The fusion program must succeed and field an engineering demonstration of fusion.
2. Fission, with reprocessing, must be accepted and have assumed its logical place in the energy mix.
3. Fusion breeder specific technology (blankets and fuel cycles) must be developed and demonstrated.

The fusion breeder could quickly become an important element in the energy system. This is possible because one fusion breeder could support the makeup fuel needs of many fission reactors, 15 or more of similar nuclear power. In addition to quick introduction another advantage of high support ratios is that system economics are quite insensitive to performance and cost uncertainties of the fusion breeder.

The lower power density inherent in the fission-suppressed fusion breeder should simplify design and licensing compared to systems with high fission power densities.

The timely development of the fusion breeder could be considered an insurance policy, insurance to protect against a uranium resource shortfall, and uranium cartels, environmental limitations on coal, economic and deployment limitations on alternatives such as conservation, solar, or fusion. Preliminary economic analysis suggests the fusion breeder could be competitive with mined uranium when U_3O_8 reaches about 100 \$/lb, about twice the cost uranium was selling for a few years ago. The mere existence of a demonstrated fusion breeder technology should put a cap on uranium prices.

The fusion breeder could be beneficial to fission breeder deployment by providing some or all of their initial fission inventories and thus overcome their doubling time constraints. But at the same time the fission breeder will have to be competitive with non-breeders for there to be an incentive for deployment. Thus the fusion breeder adds a new dimension to fission and fusion by providing the flexibility of making non-net breeding fission reactors renewable (long-term) energy options, and by allowing fission breeders to be deployed independent of their doubling time. This in turn provides an application for fusion that is economically viable, earlier in its development when fusion alone may be 2 to 3 times more expensive.

The national magnetic fusion program is aiming for an engineering demonstration of fusion by the late 1990's. A successful demonstration of

fusion coupled with development of fusion breeder specific technology would then allow a fusion breeder demonstration in the 2000-2010 time frame. This is fortuitous because this is about the time frame when a uranium shortfall is predicted to curtail commitment to further conventional nuclear construction.

We believe the fusion breeder could play an important role in our energy future and its economic benefits should far outweigh its overall additional development cost relative to the main line magnetic fusion development program.

History

The idea of marrying fusion and fission was first considered at Livermore by Imhoff¹ in the early 1950's at the beginning of the fusion program. But the idea was not pursued because large uranium deposits were discovered and fusion was found to be far more difficult to achieve than first perceived. In the early 1960's Weale² performed integral experiments with a natural uranium pile and a DT neutron source and measured nuclear reaction rates of 14 MeV neutrons in uranium. In the late 1960's Lidsky at MIT did some studies on fusion-fission and presented the concept of fusion-fission "symbioses."³

At about the same time Lee at Livermore started looking at fusion neutron-induced fission of U-238 as a way to improve the power balance of low Q fusion systems.⁴ This work culminated with Livermore collaborating with General Atomic in the conceptual design of a "standard mirror" hybrid

reactor.⁵ This reactor used a minimum B mirror fusion driver and a fast fission U-238 blanket. The fusion driver operated at 400 MW fusion, driving the blanket at 3400 MW. Net output from this reactor was 600 MWe and 2000 kg Pu-239 per year (at a capacity factor of 0.74).

At this point in Livermore's fusion-fission program, emphasis switched from standard mirror to higher performance tandem mirror fusion drivers⁶ and we also began investigating the fission-suppressed class of fissile-breeding blankets.^{7,8} In 1979 Livermore, Bechtel, General Atomic, and General Electric worked together on a conceptual design study of tandem mirror hybrids. This was the first year of a proposed, multi-year study. The first year of this study had two principle purposes. One was to examine the applicability of a low technology ($Q \sim 2$) tandem mirror as the driver for fusion-fission; the second was to develop and compare conceptual designs of U-233-producing blankets. The result was two conceptual designs, one based on fast fission of thorium, the other on the fission suppression concept.⁹ Conclusions reached were that the tandem mirror should make a good driver and that both blanket types resulted in similar attractive economics but had grossly different operating characteristics and feasibility issues. The fission suppression blanket case produced 3 times more fissile fuel (U-233) per unit of nuclear power and its peak fission power density and fission product after heat was ~ 100 times less for a given fusion neutron current. The high specific fissile production, low fission power density, and low fission product inventory made the fission suppression blanket very attractive.

While the potential performance of fission suppression blankets is

attractive their feasibility is less certain. The specific blanket concept examined in the 1979 study used Be for neutron multiplication, and a molten salt ($\text{LiF-BeF}_2\text{-ThF}_4$) as a mobile fuel and heat transfer fluid from which the U-233 (as well as T) could be removed economically at low concentrations. The feasibility issues of concern are how to protect the Be from the molten salt (MS), how to deal with Be swelling, and what structural material(s) to use to contain the MS. The structural material must also stand up to the fusion neutron environment and not overly reduce breeding. In this design graphite was used to contain sintered Be powder and TZM was chosen for the structure. Graphite is known to be compatible with MS but its radiation resistance is of concern. TZM is known to be compatible with MS and is expected to be reasonably resistant to radiation damage, but there are feasibility issues with TZM fabrication.

Another concern is molten salt preprocessing technology. It is thought to be feasible but a large-scale development effort will be required for commercialization. Tandem mirror drivers and fission-suppressed blankets were also found to compare favorably to other drivers and blanket types in a 1980 EPRI-sponsored Westinghouse-lead feasibility assessment of fusion-fission.¹⁰

The attractive performance of the FY79 fission-suppressed case, tempered by its feasibility and other concerns, set the stage for our FY81 work. The principle objective of this work is to develop fission-suppressed blanket design concepts that performed about as well as the FY79 case but that did not have its feasibility and development concerns. A secondary objective is to

look at higher performance tandem mirrors as drivers, since with the development of a new tandem concept (thermal barriers) higher performance could be achieved without pushing technology to extremes.

The history described above is intended to summarize how the Livermore fusion breeder concept has evolved. For a more general review of fusion-fission, Refs. 11-13 are recommended.

Fusion-Fission System

A fusion-fission system consists of fusion breeders providing fissile inventory and/or make up fuel to fission reactors. The fusion breeder has three major elements:

1. The fusion driver (neutron source)
2. The blanket (for breeding)
3. The fuel cycle (reprocessing and refabrication).

The world-wide fusion research effort is pursuing both magnetic and inertial confinement approaches to commercialize fusion. At present the tokamak and the tandem mirror, both magnetic approaches, are considered the top contenders. All are potential candidates for drivers for fusion-fission. The latest in a series of tokamak commercial reactor design studies is Starfire.¹⁴ The 3500-MW fusion Starfire design (shown in Fig. 1) is representative of how a tokamak fusion breeder might look. The tandem mirror has an open-ended axial geometry as opposed to tokamak's closed toroid. The

conceptual 3000-MW fusion tandem mirror driver shown in Fig. 2 shows the tandem's major features.¹⁵

Blankets for fusion breeders (or fusion-fission hybrids) can have nuclear characteristics that range from fast fission of U-238 for neutron multiplication to fission-suppressed cases that use Be or Pb (n,2n) or ${}^7\text{Li}(n,n'\text{T})$ reactions for the generation of excess neutrons. The breeding ratio and energy release from 14 MeV neutrons with various multipliers is given in Table 1. These are idealized cases in that no blanket engineering requirements are included, i.e., no structure or coolants, etc. U-238 is the most prolific multiplier per 14 MeV neutron while Be gives the highest net fissile production per unit power. Performance estimates for three blanket types, where conceptual engineering design requirements are included, are given in Table 2. For an example, the mechanical layout of a conceptual central cell module for a tandem mirror with a beryllium/molten salt (Be/MS) blanket is shown in Fig. 3.

At this point in the evolution of the fusion breeder concept we believe the fission-suppressed class of blankets has the most potential. This belief is based on the fact that the fission-suppressed blanket has the lowest fission power density and after heat, and the lowest fission product inventory which should simplify design and licensing. It also gives the highest support ratio which should facilitate deployment. Utilities could buy fissile fuel from fusion breeders like they do today from enrichment plants.

A successful fission-suppressed blanket requires that:

1. Fast fission of fertile material must be suppressed by limiting its exposure to fast neutrons.
2. An effective non-fission neutron multiplier must be used to generate significant neutrons in excess of those needed to breed tritium to fuel the DT fusion reaction.
3. Breeding must not be compromised by parasitic neutron capture.
4. Fissile material must be removed at low concentrations to inhibit in-situ fission reactions.
5. *Fuel reprocessing and fabrication must be low-cost.*
6. Tritium inventory must be kept low to limit its loss due to radioactive decay.
7. Wherever possible, conventional technology should be used to minimize the cost, risk, and time for the necessary development program.

The types of fission reactors that could be fueled (initial inventory and/or makeup) by fusion breeders span the entire spectrum from conventional thermal reactors (LWR, HWR, etc.) to advanced thermal (HTGR, LWBR, etc.) and fast breeders. Conventional fuel cycles can be used as is or modified to make better use of fissile materials. The fusion breeder could provide the U-233 needed for large-scale use of the Th/U fuel cycle in conventional or advanced reactors.

Now for a specific example of a fusion-fission system. The fusion breeder part of the system has a tandem mirror for the fusion driver, and a beryllium fission-suppressed blanket with a molten salt fuel cycle. This fusion breeder supplies makeup fuel to LWR's operating on the Th/U-233 with

thorex reprocessing and recycle. This fusion breeder has a fusion power of 2700 MW resulting in a total nuclear power of 4000 MW. Net electrical and fissile production by this fusion breeder is 1000 MW and 6200 kg U-233 per year at 70% capacity factor. The U-233 produced supports 24,000 MWe of LWR capacity. System power levels are listed in Table 3. Note that 96% of the system's net electric production is by the fission reactors.

Results of our economic evaluation of this example fusion-fission system are given in Table 4. While our ability to estimate fusion breeder economics is primitive, economics is still an important aspect of our studies. Note that in this case the fusion breeder cost is quite high (4.4 B\$) but when divided by all the LWR's supported, the system capital cost is only 20% higher than the LWR's alone. The resulting system electricity cost is 43 mills/kw-hr which is only ~ 15% higher than if the LWR's were using U-Pu recycle and U_3O_8 at 90 \$/kg. We estimate that this fusion breeder is competitive with U_3O_8 at about 180 \$/kg.

The uncertainty in our estimate of fusion breeder economics is large but because it can support many fission reactors, the uncertainty in system electricity cost is much smaller. For example, a 100% increase in U-233 cost leads to only about a 25% increase in electricity cost, while a 50% decrease in U-233 cost results in a 10% decrease in electricity cost. This insensitivity to uncertainties in fusion breeder economics has been referred to as its "robustness."¹⁷ For more details on this example fusion-fission system, see Ref. 18.

What type of blanket is best? While we at Livermore believe the fission-suppressed blanket is best, it is still an unanswered question. One of the goals of EPRI's assessment¹⁰ was to compare blanket types. System economics for a tandem mirror fusion breeder with three blanket types vs net breeder power are compared in Fig. 4. The three blanket types are thorium metal-fast fission (Th-FF), uranium carbide-fast fission (UC-Ft), and the Be fission-suppressed blanket designated here as Th-FS. The Th-FS blanket was found to have some economic advantage over the other two but this advantage is reduced as breeder net electric power increases. On the other hand when other characteristics are compared, at 800 MWe, for example (Table 5), we see striking differences in LWR power supported (21,000 down to 6000 MWe), fusion power (2400 down to 700 MW), and breeder capital cost (4.1 down to 2.7 B\$). The highest values are with the fission-suppressed blanket, the lowest with the uranium fast fission blanket.

What type of fusion driver is best? This question was also addressed in the EPRI study.¹⁰ As a representative economic comparison, Fig. 5 shows that all three major fusion approaches could make economically competitive drivers.

Major conclusions and recommendations of the 1980 EPRI Feasibility Assessment of Fusion-Fission are listed below.

1. U_3O_8 resource limitations are only a question of time.
Fusion-fission could eliminate the shortfall.
2. Fusion breeders could provide a ceiling on U_3O_8 real cost escalation

in the 100 to 400 \$/kg range.

3. Commercial introduction needed in the 2000-2020 time frame.
4. Has potential for near-term impact on utility decision making.
5. The three confinement approaches considered--tokamak, tandem mirror and laser ICF--resulted in similar economics.
6. Cost and performance differences were due more to blanket/fuel cycle choices.
7. A tokamak commercial demo could be operational by 2000 with the tandem mirror and ICF demos following 5 years apart.
8. Blanket development may be the pacing element.
9. Fusion-fission should be made a viable energy option for the time when UO_8 shortfall is anticipated.
10. Increasing conceptual design activity is needed.
11. Increased attention should be devoted to fission-suppressed blanket concepts.
12. In-depth development scenarios are needed.

The U.S. fusion-fission funding in 1981 is ~ 1.0 M\$, 0.7 from the Department of Energy (DOE), and 0.3 from the Electric Power Research Institute (EPRI). The DOE funding supports Livermore and four subcontractors (TRW, General Atomic Co., Westinghouse, and ORNL) working on the Tandem Mirror Hybrid (Breeder) project with major emphasis on development of fission-suppressed blanket concepts. The EPRI funding supports Combustion Engineering Co. on a project appraising past blanket designs.

Fusion breeder development is dependent upon the success and timetable of

fusion development. Fusion development in the U.S. is scheduled to: demonstrate physics feasibility in the 1980's with TFTR and MFTF-B; demonstrate engineering feasibility in the 1990's with the fusion engineering device, FED; and have a demo electric power plant operational by 2000. The objectives and timetable for the U.S. fusion program are called for in the Magnetic Fusion Energy Act of 1980. The FED could be a test bed for fusion breeder blankets as well as fusion driver technology. The demo could be a fusion breeder demo, assuming blanket and fuel cycles are developed.

Deployment

A major advantage we see of fusion-fission is its ability to support a much faster and more timely growth in nuclear capacity than fission or fusion could alone. Conventional fission (LWR, etc.) will run out of fuel. The fission breeder (LMFBR's) will be limited first by the historical limitation on the introduction of a new technology than by its doubling time when the Pu stockpile is exhausted. Fusion electric deployment will also be limited by introduction constraints.

So even with the successful commercial introduction of fission breeders and fusion electric, an energy shortfall is very likely as oil, gas, and uranium resources are exhausted. The fusion breeder, by virtue of its high support ratio, could provide the stepping stone needed to bridge the energy gap (shortfall) while the fission breeder and/or fusion electric are being introduced.

For example, consider the following U.S. scenario.

Nuclear generation goals

250 GW (electric) of LWR in 2000 (21% of demand)

1900 GW (electric) nuclear in 2060 (50% of demand)

Requires nuclear growth of 3.4%/yr

LWR assumptions

U_3O_8 resource limit of 3 million tonnes

Utilities must see 30-yr U_3O_8 supply to commit to a new LWR

Plutonium is recovered and stockpiled for use in LMFBR's

LMFBR assumptions

First commercial plant in 2005, 8 GW (electric) in 2020

25%/yr growth after 2020 until 20 plant/yr limit is reached

20 plant/yr until growth = 10%/yr

10%/yr until plutonium stockpile consumed then limited to 18-yr doubling time

Fusion breeder assumptions

First commercial plant in 2015

Initial introduction rate same as LMFBR

30 plants on line in 2037 (each 4000 MW-nuclear, 6200 kg fissile/yr)

The projected effect of 30 fusion breeders on U.S. nuclear capacity is substantial. As shown in Fig. 6, without these fusion breeders, LWR expansion would stop in 2020 and LMFBR construction is not sufficient to keep nuclear's market share from dropping back to ~ 20% in ~ 2035. By 2060 LMFBR construction has increased nuclear's market share to ~ 37% but this is

~ 500 GW short of the 50% nuclear goal.

With the fusion breeder, LWR expansion could continue until LMFBR expansion could catch up and continue to expand independent of its doubling time constraints. For this example, 30 fusion breeders would allow nuclear to meet 60% of the demand in 2060, 1000 GW more than fission could alone. If fission breeders were not deployed, additional fusion breeders could be used to provide fuel for LWR's to meet the nuclear goal.

If fusion development is successful and deployment is like the LMFBR except 10 years later, but the fusion breeder option is not exercised, fusion + fission breeders could meet the long-term nuclear goal (after ~ 2055). But in the shorter term nuclear would miss its goal by a much wider margin. For this example, in 2040, there is ~ 700 GWe less nuclear with fusion but without the fusion breeder.

While the deployment scenario just described is speculative, it is a good example of the fusion breeder's potential deployment advantages.

Summary

In summary the fusion breeder:

1. Could have a significant role in nuclear power development and deployment, both fission and fusion, for it allows fission to meet the demand with a variety of reactor types and is an earlier commercial

mission for fusion.

2. Could be ready in time to help avert serious energy or environmental problems in the 21st century if fusion's development time table is met.
3. Is showing favorable economics, < 30% increase in energy costs, based on preliminary studies and is very robust. It would put a cap on U_3O_8 price.
4. Gives utilities the option of just buying fissile fuel, like they do now from enrichment plants.
5. Could have a very high benefit/cost ratio.
6. Is a near-term application; serious development should start now.

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TABLE 1
IDEAL BREEDING RATIO AND ENERGY RELEASE
WITH VARIOUS NEUTRON MULTIPLIERS

<u>MULTIPLIER^A</u>	<u>BREEDING</u>		<u>FISSILE ATOMS</u>
	<u>RATIO^B</u>	<u>ENERGY (MEV)^B</u>	<u>PER MEV^C</u>
U-238	4.2	190	.017
Th232	2.4	50	.028

Be	2.7	22	.077
Li	1.8	16	.050
Pb	1.7	19	.037

(A) PLUS FERTILE MATERIALS

(B) ATOMS OR ENERGY PER 14 MeV DT FUSION NEUTRON

(C) (BREEDING RATIO - 1)/ENERGY

TABLE 2
PERFORMANCE ESTIMATES FOR ENGINEERED BLANKETS

BLANKET TYPE	FAST FISSION		FISSION SUPPRESSED
	U-238	Th	Th
TRITIUM BREEDING	1.0	1.0	1.0
FISSILE BREEDING RATIO ^A	1.5	0.8	0.8
ENERGY MULT. (M) ^B	11	5	1.6
FISSION POWER DENSITY, PEAK (W/CM ³)	350	100	10
FISSILE PRODUCTION RATE (KG/Y) ^C	2700	2900	9600
FISSION REACTOR POWER SUPPORTED (MW) ^D	19,000	30,000	99,000
NUCLEAR SUPPORT RATIO ^E	5	9	25

(A) NET ATOMS PER DT FUSION

(B) M = ENERGY/14 MeV

(C) BREEDER POWER = 4000 MW_N

(D) LWR MAKEUP 142 KG PU OR 97 KG U-233 PER GW-Y

(E) RATIO OF FISSION REACTOR POWER TO FUSION BREEDER POWER

TABLE 3

EXAMPLE FUSION-FISSION SYSTEM POWER LEVELS

FUSION BREEDER

FUSION POWER	2700 MW
NUCLEAR POWER LEVEL	4000 MW
ELECTRIC POWER, GROSS	2400 MW
ELECTRIC POWER, NET	1000 MW
FISSILE (U-233) PRODUCTION, NET (@ 70% CAPACITY FACTOR)	6200 KG/Y

FISSION REACTOR (LWR) POWER SUPPORTED (ANNUAL U-233 MAKEUP = 255 KG/GW _E @ 70% CAPACITY FACTOR)	24,000 MW _E
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TABLE 4

EXAMPLE FUSION-FISSION SYSTEM ECONOMICS (1980 \$)

TOTAL CAPITAL COST OF FUSION BREEDER	4.4 B\$
TOTAL CAPITAL COST OF LWRs	870 \$/kWe
CAPITAL COST RATIO (LWRs + FB/LWRs)	1.20
SYSTEM ELECTRICITY COST	43 MILLS/KW-HR
FISSILE MATERIAL (U-233) TRANSFER COST	45 \$/g
EQUIVALENT U_3O_8 COST	180 \$/kg

NOTE: CAPACITY FACTORS = 70%, CAPITAL CHARGE = 15% PER YEAR

TABLE 5

PARAMETERS FOR AN 800 MW_e NET BREEDER
WITH 3 BLANKET TYPES

<u>BLANKET TYPE</u>	<u>UC-FF</u>	<u>TH-FF</u>	<u>TH-FS</u>
FUSION POWER, MW	655	980	2350
CENTRAL CELL LENGTH, M	22.5	34	81
NET FISSILE PRODUCTION, KG/YR	2120(PU)	2600(U)	5410(U)
LWR SUPPORT, GW(E)	6.0	10.5	21.1
TOTAL CAPITAL COST OF BREEDER, \$B	2.69	2.76	4.1
SYMBIOTIC SYSTEM COE, MILLS/KW-HR	46.5	49.0	43.4
TRANSFER COST OF FISSILE MATERIAL \$/G	52.9	87.5	51.0
EQUIV. COST OF U ₃ O ₈ \$/KG	260	310	200

FIG. 1. STARFIRE REFERENCE DESIGN

FIG. 2. 3000 MW_f TANDEM MIRROR DRIVER

FIG. 3.

The Blanket for the Tandem Mirror Consists of Cylindrical Modules

FIG. 4. SYSTEM POWER COST Vs FUSION BREEDER NET POWER
FOR 3 BLANKETS

FIG. 5.

Estimated Economics Vs Fusion Driver:
(with thorium fission suppressed blanket)

FIG. 6

U.S. NUCLEAR ELECTRICITY GENERATION PROJECTIONS

- WITHOUT FUSION BREEDER (3×10^6 TONS U_3O_8)
- WITH 30 FUSION BREEDER (HYBRIDS) DEPLOYED BETWEEN 2015 & 2037

TRW

72-742-0