THE FUSION-BREEDER PROGRAM

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Ralph W. Moir
Lawrence Livermore National Laboratory

**Fusion could produce an assured
fissile-fuel supply for fission**

Fusion breeder

Early economic application
of fusion

Fissile
fuel

6 tonnes
per yr

Fission
reactors

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. The fusion breeder could be a backup to the fission breeder by providing fuel assurance to LWR's while the fission breeder is being deployed.

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 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 would be an earlier payoff for fusion R&D and help advance fusion technology towards its goal of a stand-alone energy source.

The timely development of the fusion breeder could be an insurance policy, insurance 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 U₃O₈ reaches 100 to 200 \$/lb. The mere existence of the fusion breeder should help put a cap on uranium prices.

The fusion breeder could be beneficial to fission breeder deployment by providing some or all of their initial fissile 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 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.

Our studies of the fusion breeder have shown the possibility of fusion producing large quantities of fissile materials at a marketable cost with rather low performance of fusion components, i.e., $qQ = 2$ to 4, and cost three to four times an equal-size, light-water reactor where q is the heating efficiency. As fusion performance improves, the cost of the bred fuel decreases. We conclude that when an alternate source of fissile fuel is needed, the fusion breeder might fill that need.

A modest level of effort now could save much time and money later if fusion is called on in the future for this role. The fusion part of fusion-fission hybrid studies since FY79 was based on the tandem mirror. Starting in FY82 we considered tokamak fusion drivers as well. In FY83 the tokamak blankets are being emphasized. The studies emphasized fission-suppressed blankets and generic fuel cycle issues.

Our fusion breeder work is determining technical and economic feasibility. Issues being addressed relate to reactor design fuel handling, safety, fuel cycles, balance-of-plant designs, etc. Our FY81 work concentrated on fission-suppressed blankets and showed the breeding with beryllium to be significantly better than with ^7Li . The liquid-metal cooled blanket was more feasible than the helium cooled design. Due to good performance and relevance of extensive technology from the liquid metal reactor program, a liquid-metal-cooled beryllium design was chosen as the FY82 reference design. Reprocessing costs using conventional aqueous solution processes, Purex or Thorex, although high (~ 25 \$/g of fissile), were deemed low enough to permit processing of the very low burnup fuel (0.5% Pu in ^{238}U or 0.5% ^{233}U in Th). Pyrochemical reprocessing technologies should result in lowering the reprocessing cost to ~ 3 \$/g fissile. The U.S.S.R. is working on fusion breeder designs and has made fissile breeding a major objective of their fusion program.

A national lab-industry team conducts the fusion breeder program

The design of the fusion breeder (fusion-fission hybrid reactor) has progressed to a level of conceptual design detail which requires a multi-disciplinary and inter-organizational team approach. The present study includes the participation of the following organizations:

Organization

Lawrence Livermore National Laboratory (LLNL)

R. W. Moir, J. D. Lee, M. S. Coops,
F. J. Fulton, W. S. Neef

TRW Energy Development Group (TRW)

J. A. Maniscalco, D. H. Berwald, R. B. Campbell,
D. Flanders, J. K. Garner, J. R. Ogren, R. H. Whitley

General Atomic Company (GAC)

K. R. Schultz, E. T. Cheng, C. P. C. Wong,
G. Benedict, R. L. Creedon, I. Maya

Westinghouse Electric Corporation (WEC)

R. P. Rose, J. S. Karbowski

Oak Ridge National Laboratory (ORNL)

J. H. DeVan, P. Tortorelli

Princeton Plasma Physics Laboratory (PPPL)

D. L. Jassby

Idaho National Engineering Laboratory (INEL-EG&G)

L. G. Miller, P. Y. S. Hsu

Energy Technology Engineering Center (ETEC)

N. J. Hoffman

University of California, Los Angeles (UCLA)

N. Ghoniem

Principal Roles

Program Management, Tandem Mirror Physics
and Technology, Nuclear Design, Beryllium,
Fabrication, Pyrochemical Fuel Reprocessing

Technical Integration, Tandem Mirror Plasma
Engineering and Technology, Reactor Systems
Modeling, Design Support

Fluid Mechanics and Heat Transfer, Fuel
Management System, Reactor Safety Systems,
Aqueous Fuel Reprocessing

Mechanical Design, Reactor Systems Layout,
Operation and Maintenance

Chemical Engineering and Materials
Compatibility

Tokamak Plasma Engineering and Technology

Radiation Damage and Nuclear Performance
Testing

Consultant

Consultant

One fusion breeder could fuel many fission reactors

For example, 17 LWRs (17,000 MWe)

For a specific example, consider a fusion breeder with a tandem mirror fusion driver, and a beryllium, fission-suppressed blanket with a thorex fuel cycle. This fusion breeder supplies makeup fuel to LWRs operating on the U-233/U-238 fuel cycle with purex reprocessing and recycle. This fusion breeder has a fusion power of 3100 MW resulting in a total average nuclear power of 5100 MW. Net average electrical and fissile production by this fusion breeder is 1700 MWe and 5700 kg U-233 per year at a 70% capacity factor. The U-233 produced supports 17,000 MWe of LWR capacity. Note that 91% of the system's net electric production is by the fission reactors.

If the U-233 produced by this breeder is used as makeup to LWRs operating on the denatured uranium/thorium fuel cycle with thorex processing and recycle, 21,000 MWe is supported. For this case, 93% of the system's net electric power comes from the LWRs.

A fusion-fission system would have a few fusion-based fuel centers

Fusion breeders can be best understood and evaluated in the context of a symbiotic fusion breeder-fission burner electricity generation system. In this concept, the fusion breeder is typically incorporated into a fuel cycle complex along with a fuel reprocessing plant, a fuel fabrication facility, and possibly a waste disposal facility. The entire fuel cycle complex is located within a safeguarded area. The fissile fuel produced in the fusion breeder is mixed with fertile fuel, fabricated into fuel rods and shipped to the burner reactors. The spent fuel from the burner reactors is shipped back to the safeguarded fuel cycle complex where the remaining fissile fuel is separated from the radioactive waste material that is processed for disposal. If desired, some of the fissile fuel in the system can be used within the safeguarded energy park.

Interest in fusion breeders has increased significantly over the past five years because substantial progress has been made in fusion research and workers now believe that the performance needed to breed fissile fuel will be demonstrated within this decade, perhaps as early as 1985. If so, fusion driven breeders will have the potential to begin to make significant contributions to our energy needs shortly after the turn of the century. In comparison to any new power producer, be it fission breeder, fusion, or solar, fusion breeders can more rapidly be deployed from the demonstration phase to significant commercial utilization. This results because their initial growth is not bound by fissile inventory requirements. Each fusion breeder will be supplying fuel for several already existing power plants.

The fusion breeder can have a large, positive impact on both the nuclear industry and the success of the national fusion program. Its potential to be an inexhaustible supply of fuel for conventional LWRs will help to preserve the nuclear industry's investment and experience in these economical fission systems. In addition, fusion-breeder-fueled electricity generation systems offer a flexibility of fissile fuel cycle options that can lead to a more proliferation-resistant nuclear economy. The fusion breeder can have a positive impact on the fusion program because it represents an early application of fusion featuring relaxed fusion gain, reduced technology development, and/or improved economics. In addition, it can allow fusion technology to be gradually introduced into the commercial sector by providing an earlier date for commercial introduction.

The specific number of fueled fission reactors depends on three factors

1 Breeder type

2 Fission reactor type

3 Fuel cycle

Thermal support ratio
(fission reactors per fusion breeder)

Several figures of merit are important for evaluating the fusion breeder-fission burner system. They include thermal support ratio, equivalent U_3O_8 cost, fusion breeder cost, and the system electricity cost. The thermal reactor support ratio is defined as the number of equivalent thermal power fission reactors that can be fueled by the fusion breeder. For a specific example, a 5100-MW (thermal) fusion breeder with a suppressed-fission blanket produces 5700 kg of ^{233}U per year. This is enough ^{233}U to satisfy the makeup fuel requirements of twenty-one, 3000-MW (thermal) LWRs operating on the denatured uranium-thorium fuel cycle. Thus, the thermal support ratio is 13. A high thermal support ratio is advantageous because only a small fraction of the symbiotic system's total cost and energy generation comes from the fusion breeder. Therefore, system electricity costs can be relatively insensitive to uncertainties in the performance and cost of the fusion system. Also, because a large fraction of the existing nuclear electric grid can be fueled from a small amount of fusion breeder capacity, fusion breeders with high support ratios will have larger commercial impacts at early dates. Finally, a symbiotic system with high support ratio breeders may be more proliferation-resistant, because only a small fraction of the system energy needs to be generated in safeguarded areas where the fissile fuel is produced and processed. The majority of the electricity is generated in LWRs using denatured, proliferation-resistant fuel.

Shown are typical thermal support ratios for several generic fusion breeders in symbiosis with either LWRs or advanced converter reactors (ACRs) [e.g., high-temperature gas-cooled reactors (HTGRs) or Canadian deuterium uranium (CANDU) heavy water reactors]. The thermal support ratios range from 4 to 52, depending on the choice of fusion breeder and thermal converter. The cross-hatched areas represent variations in thermal support ratios that are dependent on the specifics of both the fusion breeder blanket designs and fuel cycle choices. Blanket design choices that significantly influence fissile fuel breeding include blanket coverage, first-wall thickness, fuel burnup, and the relative concentrations of fuel, coolant, structure, moderators, and parasitic absorbers.

The lowest thermal support ratios (four to six) are obtained with uranium fast fission breeders, which produce plutonium for LWRs, while the highest (30 to 50) are obtained with thorium suppressed-fission breeders, which support ACRs such as HTGRs and CANDUs. These thermal support ratios can be put in perspective by comparing them to those of a liquid-metal fast breeder reactor (LMFBR). An LMFBR can produce enough excess fissile fuel to support 0.7 to 1.4 LWRs of equivalent thermal power.

A fusion breeder produces more than 10 times the fissile material produced by a fission breeder

Fusion breeder

12 LWRs
(1000 MWe
each)

$$\frac{0.59 \text{ net atoms}}{29 \text{ MeV}} = 0.02$$

All reactors have
equal nuclear power

Fission
breeder

Less than
1 LWR

$$\frac{0.3 \text{ net atoms}}{190 \text{ MeV}} = 0.0016$$

The fusion breeder can be primarily a fuel producer. The fission breeder is primarily an energy producer. For example, net breeding in the fusion breeder is about 0.6 atoms per reaction, while in the fission breeder about 0.3. Energy release per basis event is about 30 MeV per fusion, and 190 MeV per fission. Thus, for this example, the fusion breeder produces 13 times more fissile material per unit of energy than the fission breeder.

Fusion breeders operate at much lower power densities

	Peak power density (W/cm³)	Peak after-heat power density: 1 min after shutdown (W/cm³)
Fusion breeder	< 20 (< 5 from fission)	< 0.3
Fission breeder	> 500	> 20

Fusion breeders employing fission suppressed blankets will have low operational and afterheat power densities. We anticipate these low power densities will reduce the time and cost of development compared to systems having much higher power densities. Passive or near passive afterheat cooling may even be possible. Specifically, for our reference design, peak afterheat power density (at $t_0 + 1 \text{ min}$) is less than 0.3 w/cc, 2/3 from actinide decay (^{233}U and ^{233}Pa), 1/3 from fission product decay.

THE FUSION BREEDER APPEARS TO OFFER SIGNIFICANT SAFETY ADVANTAGES

- REDUCED BIOLOGICAL HAZARD POTENTIAL (BHP) AND AFTERHEAT COMPARED TO FISSION BREEDER.

	FUSION BREEDER	FISSION BREEDER
BHP	$\sim 10^9$	$\sim 10^{10}$
AFTERHEAT w/cc	< 0.3	> 20

- THE LOWER AFTERHEAT LEVELS OF SUPPRESSED FISSION BLANKETS CAN POTENTIALLY AVOID STRUCTURAL MELTING/FAILURE DURING LOSS OF COOLING EVENTS AND INCREASE THE EFFECTIVENESS OF PASSIVE BACKUP SAFETY SYSTEMS.

Safety Considerations of a Fusion Breeder Reactor

At the current level of design of the fusion breeder, safety evaluations are limited to deterministic/consequence analyses. Preliminary work in this area identified three safety characteristics which have been used to compare alternative blanket designs. These characteristics include activity level, Biological Hazard Potential (BHP), and time-to-melt/failure during loss-of-coolant conditions.

Early blankets were based on uranium and thorium fast fission. Evaluations of the radioactive inventory and isotopics showed that reactors based on these blankets would be comparable to fission reactors in curie level and BHP based on comparable thermal power. Under loss-of-coolant conditions, these blankets would exhibit times-to-melt estimated to be on the order of 15-20 minutes.

More recently, blanket designs have been directed toward the goal of enhanced fuel production. These designs are characterized by a conscious attempt at suppressing fission events within the blanket to enhance fuel production. The techniques used to achieve fission suppression result in significant qualitative and quantitative safety advantages, including reduced actinide and fission product hazard (by factors of 10-100), and reduced decay afterheat levels. The magnitude of the decrease in the decay afterheat rate in suppressed-fission blankets is sufficient to potentially preclude structural melting in postulated loss-of-coolant events. The decay heat levels are sufficiently low to permit passive cooling systems, such as natural circulation of liquid lithium, to serve as viable backup safety systems.

The fusion breeder, with its suppressed-fission blanket, thus appears to offer significant safety advantages compared to fissioning systems.

These nuclear reactions are the
basis for our fusion breeder concept

The fundamental nuclear reaction sequence employed in this fusion breeder starts with the fusion of deuterium and tritium nuclei producing a 3.5 MeV alpha particle and a 14.1 MeV neutron. The alpha remains in and heats the plasma. The neutron leaves the plasma and enters the blanket where it causes $n, 2n$ reactions in Be. The resulting neutrons then undergo $\text{Li6}(n,\alpha)\text{T}$ reactions producing the tritium needed to fuel the DT fusion reaction, and $\text{Th}(n,\gamma)$ reactions producing the desired product U-233. It is interesting to note that the 'waste' from these reactions is only helium.

**An ideal infinite medium of mostly beryllium
produces a breeding ratio of 2.7**

Composition of
infinite medium

	Atom %
Be	95
^6Li	1
Th	4

First
wall

14-MeV neutrons

DT plasma

Breeding ratio $\left(2.67 \frac{\text{atoms}}{\text{fusion reaction}} \right)$

Blanket energy multiplication

$$M = \frac{28 \text{ MeV}}{14 \text{ MeV}} = 2.0$$

Calculated Breeding Ratios (atoms per 14 MeV neutron) and Energy Release (MeV per 14 MeV neutron)
Are Listed Below for Infinite Media of Various Homogeneous Mixtures of Multiplying and Fertile Materials:

Medium	Product Atoms	Energy Release (MeV)
$^{238}\text{U} + 7.6\% \text{ } ^6\text{Li}$	$3.1 \text{ } ^{239}\text{Pu} + 1.1 \text{ T}$	193
$^{232}\text{Th} + 16.0\% \text{ } ^6\text{Li}$	$1.3 \text{ } ^{233}\text{U} + 1.1 \text{ T}$	49
$^9\text{Be} + 5.0\% \text{ } ^6\text{Li}$	2.7 T	22
$^9\text{Be} + 5.0\% \text{ } ^{232}\text{Th}$	$2.7 \text{ } ^{233}\text{U}$	30
$^9\text{Be} + 1.0\% \text{ } ^{238}\text{U}$	2.4 Pu	29
$^9\text{Be} + 3.0\% \text{ Th} + 2.0\% \text{ } ^6\text{Li}$	$1.6 \text{ } ^{233}\text{U} + 1.1 \text{ T}$	27
$^9\text{Be} + 1.0\% \text{ U} + 0.4\% \text{ } ^6\text{Li}$	$1.6 \text{ Pu} + 1.1 \text{ T}$	~ 28
$^7\text{Li} + 0.8\% \text{ Th} + 0.02\% \text{ } ^6\text{Li}$	$0.7 \text{ } ^{233}\text{U} + 1.1 \text{ T}$	18
$\text{Pb} + 5.0\% \text{ Th}$	$1.6 \text{ } ^{233}\text{U}$	21

% $\equiv$ atomic percent

We chose beryllium because it's the best nonfissioning multiplier

The fusion breeder program is examining tandem mirrors and tokamaks for the plasma cores

Tandem mirror

Tokamak

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 the core of a fusion breeder. The latest in a series of tokamak commercial reactor design studies is Starfire (ref: ANL/PPP-80-1). The 3500 MW fusion Starfire design producing 1200 MW of net electric power is representative of how a large scale commercial tokamak might look. The tandem mirror has an open-ended axial geometry as opposed to tokamak's closed toroid. The ongoing Mirror Advanced Reactor Study (MARS) is developing a conceptual design of a commercial tandem mirror comparable to Starfire. The MARS design also operates at 3500 MW-fusion and produced 1550 MW of net electric power (ref: UCRL-53333). The principle difference between these fusion electric designs and their fusion breeder variants are their blankets. For the breeder application the fusion neutrons are used to produce fissile material as well as tritium and heat.

**The central cell of a tandem mirror
breeder would have many blanket modules**

The central cell of the tandem mirror is made up of many identical modules. For this particular design, 6 sets of 8, 4 meter modules make up the central cell. Each set is serviced by a coolant pump and an intermediate heat exchanger. The pumps and heat exchangers are interconnected for redundancy.

**This blanket module concept is
the one we're currently developing**

The blanket structure is ferritic steel (HT-9 or 2-1/4 Cr -1 Mo) operated in the range of 350-500°C. Lithium coolant flows to the first wall plenum through a thin coolant annulus and is distributed to the packed bed through perforations in a corrugated intermediate wall which, in combination with a corrugated first wall and radial stiffeners (tied to the back of the blanket), provides structural support.

The coolant flows radially outward through two fuel zones (separated by a perforated wall), exits the bed through a perforated wall outside of the second fuel zone, and exits the blanket through 20 large outlet pipes. A critical parameter, the MHD induced coolant pressure at the first wall is estimated (we believe conservatively) to be ~ 250 psi. The blanket was designed on this basis, but an experimental confirmation is needed. The fuel pebbles (beryllium pebbles with thorium inserts) are loaded in the top of the blanket and discharged at the bottom in a frequent batch process (i.e., fuel residence time < 90 days) without requiring blanket disassembly to get the bred U-233. Tritium is bred in and removed from the lithium coolant.

This design offers several attractive features. Most importantly, the nuclear performance is good for two reasons. First, the pebble beds have a high volume fraction of good neutron multipliers, 57% beryllium, and 40% lithium. Secondly, both fast and thermal fission are suppressed. Fast fissions are effectively suppressed due to neutron moderation in the beryllium and the low thorium volume fraction (3%). Thermal and epithermal fissions in the bred U-233 are suppressed due to fuel discharge at low concentration (< 1%) in the small volume of thorium and the presence of Li-6.

Another advantage that should be highlighted is that this design can tolerate beryllium swelling since the beryllium pebbles are removed and replaced frequently and can be refabricated as needed.

We face five technical issues with the beryllium ball blanket cooled by liquid lithium

1. Verification of predicted neutron multiplication in Be
2. Radiation damage in Be
3. Be, Li, Th, Fe compatibility

4. MHD pressure drop due to liquid Li flow in magnetic field through packed bed

Technical Issues with this Design Concept

1. Verification of predicted neutron multiplication in Beryllium.

Integral neutronic experiments are needed to verify Monte Carlo computer code predictions of breeding performance.

2. Radiation damage in Beryllium.

He production by $(n,2n)$ reactions leads to embrittlement and swelling. Samples irradiated in EBR-II are being analyzed.

3. Compatibility, Be-Li-Th-Fe.

Static capsule tests are underway which will determine allowable operating temperatures. Convective loop proof tests will be required.

4. MHD pressure drop due to liquid Li flowing in magnetic field through packed bed.

Experiments are needed to check analytic predictions of MHD pressure drop through a packed bed and through various orifices.

5. Removing U-233 from Th by the Mg dissolution pyroprocess.

Small scale proof-of-principle tests could put this concept on a sound basis. Reprocessing by this method could save more than \$20/g of fissile material produced.

With this blanket design, the breeding ratio is 1.6

Nuclear performance

Breeding ratio (T + F) = 1.61 atoms/fusion

Net breeding (F_{net}) = 0.59 atoms/fusion

Blanket energy
multiplication (M) = 1.25 to 2.5

Pebble bed composition

Mat'l	v/o	a/o
Be	57	78
⁷ Li	39.6	21
⁶ Li	0.4	0.2
Th	3	1

Structure, coolant plena, finite thickness, heterogeneous effects and end effects all must be considered when calculating the nuclear performance of a realistic reactor/blanket. For our present design the reactor breeding ratio is 1.61 giving a net or excess breeding ratio of 0.59. Blanket energy multiplication varies between 1.25 and ~ 2.5 as the U-233 content in the thorium varies between 0 and 1 a/o during each fuel management cycle.

We're adapting a similar blanket concept to tokamak geometry

The blanket for the tandem mirror was adapted to the tokamak of the INTOR class intended for operation about 2015. Liquid lithium was not used due to the high magnetic field on the inside of the torus causing high MHD pressure drop and, therefore, high pressure on the first wall. Instead, the molten salt FLiBe (LiF + BeF) is proposed as the coolant.

Differences Between Tokamak and Tandem Mirror Reference Blanket

<u>Differences</u>	<u>Reason</u>
Change coolant	Higher magnetic field
Separately cooled first wall may be necessary	Higher wall loading, higher surface heat flux
More than one type of blanket module	Penetrations for neutral beams
Irregular shaped modules (wedge shaped)	Toroidal geometry instead of straight central cell
More complicated piping to blanket	Less access to inner zone of blanket
Potentially more coolant circuits per module	Longer coolant paths, higher pressure drop

The U.S. fusion program is developing the tandem mirror and tokamak concepts

**Mirror Fusion
Test Facility (MFTF)**

**Tokamak Fusion
Test Reactor (TFTR)**

The U.S. magnetic fusion program is spending about \$500 M per year mainly on two mainline concepts: the tandem mirror and tokamak. The tandem mirror lead project is MFTF-B, expected to operate in 1986 at LLNL. Other smaller tandem mirror experiments are underway or under construction in Novosibirsk, Japan, the University of Wisconsin, and MIT.

The TFTR (Tokamak Fusion Test Reactor) being built at PPPL should go into operation in 1983. Scientific break-even where as much fusion power as heating power absorbed is expected during its tritium burning phase where 20 MW of fusion power is expected. Many tokamaks are operating or under construction, most notably: JET (Culham, U.K.), JT-60 (Japan), T-15 (Moscow), and TOR-II (France). The later two are especially significant in that they are superconducting like MFTF-B. Jet will also burn tritium.

The principle objectives of these mainline experiments are to demonstrate the scientific feasibility of fusion with the tokamak and tandem mirror approach.

The MFTF central cell must be scaled up for demonstration and commercial fusion breeders

The fusion driver for the demo breeder could be the Fusion Power Demonstration (FPD) presently being studied for possible operation in the late 1990's. The commercial breeder is based on the MARS tandem mirror design. We are planning for the first commercial breeder to operate in 2015.

The TFTR major radius must be scaled up for demonstration and commercial fusion breeders

**System capital cost is only 10%
higher than the cost of LWRs alone**

$$\text{System capital cost ratio} = \frac{NC_{LWR} + C_{FB}}{NP_{eLWR} + P_{eFB}} \bigg/ \frac{C_{LWR}}{P_{eLWR}} = 1.1$$

Assumptions

$$C_{LWR} = \$1.6 \text{ B} \quad P_{eLWR} = 1 \text{ GW}_e$$

$$C_{FB} = \$6.7 \text{ B}$$

$$N = 17 \quad P_{eFB} = 1.7 \text{ GW}_e$$

A demo breeder similar to the FED-R, with a major radius of 3.9 m, could be operational in the 1990's. The commercial breeder is similar to the INTOR and Starfire designs. We are planning for the first machine to operate in 2015.

Fuel from a fusion breeder adds only 20% to the electricity cost

Fusion breeder

Fissile
fuel

LWRs

Mining
and
enriching

Fissile
fuel

1982 \$

= 36 mills/kw-h (projected cost)

$\frac{36}{30}$

=

1.2

cost
ratio

= 30 mills/kw-h (today's cost)

FUSION BREEDER ECONOMICS OVERVIEW

Our analysis of fusion breeder economics involves three steps: 1) estimation of the fusion breeder plant performance and capital, fuel cycle and operating costs; 2) development of similar parameters for the LWR client reactors which consume the fuel produced in the breeder; and 3) integration of these quantities into a description of the economics of a symbiotic electricity generation system consisting of the breeder and all of its clients. The fusion breeder performance and cost data derive from the output of our Tandem Mirror Reactor Design Code, a cost and performance estimating program which is continually updated with the results of detailed design and costing studies. The LWR performance and cost data derives from a variety of sources; most notably the DOE NASAP study for advanced fuel cycle performance data and updated estimates of the LWR cost (about 1650 \$/KWe in this analysis).

The economics analysis for the symbiotic system assumes utility ownership and tracks three types of cost (capital costs, fuel cycle and O & M costs, and fissile inventory costs) for each year in a 30 year period representing the financial lifetime of the symbiotic system. Fuel cycle and O & M costs are escalated each year according to an assumed general inflation rate (7%/yr in this analysis) while capital charges are assumed to be fixed on a year-by-year basis. An average present value of the symbiotic cost of electricity is calculated by discounting the cost of electricity in each year n by the factor $1/(1.07)^n$ and averaging over 30 years to obtain an equivalent 1982 cost of electricity.

The average present value of the cost of electricity is calculated to be 36.3 mil/KWe-H. In comparison, an LWR which uses mined U_3O_8 costing 40 \$/lb would produce electricity for 30.3 mil/KWe-H when the same methods of accounting are used. Therefore, we conclude that despite the large cost of the fusion breeder (about 2.7 times the LWR cost on a unit thermal power basis), the symbiotic electricity cost is only about 20% above that of conventional LWRs at the current price of yellowcake.

THE COST OF ELECTRICITY FOR A FUSION-FISSION ELECTRICITY GENERATION SYSTEM IS LOWER AND LESS SENSITIVE TO PERFORMANCE THAN THE PURE FUSION ELECTRICITY COST

FUSION BREEDER/FUSION ELECTRIC ECONOMICS COMPARISON

This vugraph provides an indication of differences in economics for the fusion breeder and fusion electric missions. The cost of electricity for both options, as a function of the plasma Q value, is shown. Q, the ratio of fusion power to power consumed to sustain the fusion plasma, is the single most descriptive figure of merit for fusion systems.

For high Q values, both systems are insensitive to Q, but the fusion electric application remains more expensive than the conventionally fueled LWR by about 60%. For lower values of Q, the fusion electric plant electricity cost increases more quickly than that of the fusion breeder and its clients. The FY82 fusion breeder Q value is about 20. At this Q value the fusion breeder cost of electricity is less than 20% above that of the LWR while the fusion electric cost of electricity is more than 80% above the LWR cost of electricity.

Another important uncertainty is the fusion plant capital cost. If the fusion electric plant capital cost increases by 50%, its cost of electricity increases to 3.0 times the LWR cost of electricity. The fusion breeder is less sensitive to capital cost uncertainties because of the large number of LWRs supported. If the fusion breeder capital cost increases by 50%, the symbiotic cost of electricity increases less than 15% (to 1.35 times the LWR cost of electricity).

THE COST OF ELECTRICITY FOR A FUSION-FISSION ELECTRICITY GENERATION SYSTEM IS ALSO LESS SENSITIVE TO COST UNCERTAINTIES

FUSION BREEDER DEPLOYMENT CAN RESULT IN CAPITAL COST SAVINGS OF TENS TO HUNDREDS OF BILLIONS

CAPITAL COST REQUIREMENTS FOR ALTERNATIVE NUCLEAR POWER OPTIONS

The capital cost requirements for electricity generation using LMFBRs, Fusion Electric Generation, and a symbiotic system consisting of LWRs and Fusion Breeders were calculated as a function of the total installed capacity. For the purpose of this analysis, LMFBR costs in the range of 1.2 - 1.6 times the LWR cost (1650 \$/GW_e) were considered. Fusion electric and fusion breeder costs of 2 and 2.7 times the LWR cost were assumed.

Taking the 100 GW_e case as an example, the installed capital cost of the symbiotic system is 185 \$B, or 12% above the cost of 100 GW_e of LWR capacity. In contrast, the cost of the LMFBR system when LMFBRs cost 1.4 times the LWR cost is 229 \$B, or 44 \$B above the cost of the symbiotic system. Since only 4.3 fusion breeders are required per 100 GW_e of electrical generation, the cost savings per fusion breeder is 10 \$B in 1982 dollars.

The above cost savings would be used to pay for development of the new technology. If we conservatively postulate that the fusion breeder technology will cost \$20B to develop thru the first commercial scale plant, that the above savings accrue in 2030, that the R&D spending centroid occurs in 2000, and that a 3% discount rate (above inflation) applies, then roughly

$$20 \times (1.03)^{30} = 48 \text{ \$B}$$

of ultimate savings is required to balance the development cost. This corresponds to about 110 GW_e of installed capacity. Ultimately, 1000 GW_e of fusion breeder *supported* field² capacity in the U.S. might be reasonable.

A 10\$ BILLION SAVINGS PER FUSION BREEDER CAN RESULT IF LMFBF COST IS 1.4 TIMES LWR COST

**A 10\$ BILLION SAVINGS PER FUSION BREEDER
CAN RESULT IF LMFBR COST IS 1.4 TIMES LWR COST**

DEPLOYMENT STUDIES INDICATE THAT FUSION BREEDER INTRODUCTION TEN YEARS AFTER LMFBR INTRODUCTION CAN RESULT IN A MUCH LARGER IMPACT AFTER 2025

FUSION BREEDER/LMFBR DEPLOYMENT COMPARISON

The use of fusion to make fuel for existing fission reactors might have a significant impact on our energy supply in an earlier timeframe than the LMFBR, even though fusion technology is less developed than liquid-metal fast-breeder technology. In comparing the two systems with respect to their respective roles in the electricity generation system, we recognize that the primary product of the LMFBR is electricity, while the primary product of the fusion breeder is fissile fuel to be used in fission reactors. This difference in the fuel/power ratio of the two systems delineates the different missions, development time scales, and deployment of the two reactor technologies.

In the case of the LMFBR, commercial demonstration and deployment on an aggressive schedule is needed to positively influence projected electricity generation shortfalls in the post 2000 timeframe. The extent of this positive impact is a strong function of the LWR growth rate, the capital cost differential between the LMFBR and the LWR, the cost of natural uranium, the availability of plutonium produced in LWRs, and the speed at which LMFBRs can be constructed and brought on-line. The Electric Power Research Institute (EPRI) has estimated an ambitious schedule for LMFBR commercial demonstration and deployment. Assuming a decision is made to proceed with an aggressive LMFBR program, the following assumptions were made: the commercial feasibility of an LMFBR could be demonstrated between 1993 and 1996; the first commercial plant could be started as early as 1995 and go into full power operation in 2005; the second through sixth commercial LMFBR plants (1.5 GW_e each) could be ordered between 2006 and 2010 and completed 10 years later. In this mode, the LMFBR by 2020 would account for 9 GW_e (or less than 1% of the total projected capacity in the U.S.).

Similarly, following a 2015 introduction, the first commercial fusion breeder could provide fuel for 20 GW_e of LWR capacity, representing a much larger impact than the 3 GW_e of installed LMFBR capacity which could be operating in the same timeframe. The first 6 fusion breeders could provide makeup fuel for over 120 LWRs in 2030. With a 15%/yr growth rate thereafter, 24 fusion breeders could provide fissile makeup for about 500 GW_e of LWR and fusion breeder capacity in 2040. With the same growth rate, and assuming that plutonium is not more economically recycled in LWRs (but is stockpiled for later use in LMFBRs) there would be 36 GW_e of LMFBR capacity in 2030.

With a fusion breeder, nuclear would achieve 50% of U.S. electricity in 2050

A major advantage we see of the fusion breeder is its ability to support - 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

U3O8 resource limit of 3 million tonnes
Utilities must see 30-yr U3O8 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 GW 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.

**On a moderate basis, we plan for a
commercial fusion breeder by 2015**

THE TANDEM MIRROR DEVELOPMENT PATH CAN ACHIEVE OPERATION OF A COMMERCIAL SCALE PROTOTYPE BEFORE 2015

FUSION BREEDER DEVELOPMENT (TANDEM MIRROR CASE)

Fusion technology, and thus the fusion breeder, is at least 15 years behind the LMFBR in development in the U.S. However, fusion is sufficiently mature that a hybrid engineering test reactor (HETR) could be started in the ^{Late} last 80's and completed by the mid-90's. The HETR can be used to develop nuclear technologies for a demonstration reactor which could operate shortly after 2000. The demonstration reactor would have a mission similar to that of the Clinch River Breeder Reactor (CRBR). That is, the demonstration reactor would provide a near full scale demonstration of all relevant fusion reactor and nuclear technologies. It would also contribute to the qualification of components for a commercial scale prototype reactor which could operate prior to 2015.

In the case of tandem mirror development, the HETR would be based upon the Technology Development Facility (TDF) studied during the past year. Although TDF does not operate in a physics mode which is directly scalable to a demonstration reactor, its physics basis will be demonstrated in the current TMX experiment at LLNL. As an HETR, TDF is reasonably small (< 40 MW) yet provides a large enough wall loading fluence, and test area to demonstrate the operation of full function blanket modules. In combination, the HETR and a long pulse version of the Mirror Fusion Test Facility (designated MFTF-U) would provide high confidence for the step to a demonstration reactor.

THE TOKAMAK DEVELOPMENT PATH UTILIZES AN UPGRADE OF THE HETR FOR DEMO OPERATION

FUSION BREEDER DEVELOPMENT (TOKAMAK CASE)

The tokamak reactor development path might utilize a larger HETR (75 MW) based upon the "Stage-I" operation of the FED-R design studied during the past year. The plasma physics basis for FED-R will be provided by Tokamak Fusion Test Reactor results to be generated during the 1983-6 timeframe. This device would provide a lower wall loading and fluence than its tandem mirror counterpart, but could be upgraded so that a "Stage-II" version (250 MW) might serve as a demonstration reactor. Although FED-R Stage-II cannot serve as a full function DEMO for fusion electric and/or suppressed fission hybrid applications (eg., not ignited and no super-conducting coils), it could be an attractive DEMO for a fast fission hybrid.

For fusion electric and suppressed fission modes of operation, the HETR (FED-R Stage-I) could be followed by a larger DEMO (~ 1000 MW, superconducting coils, ignited plasma) to operate in the 2005 timeframe and a commercial scale prototype to operate in the 2015 timeframe.

Both the tokamak and mirror development paths can lead to efficient SNM production facilities on the same timeframe as the DEMO facilities which are shown (ie., 2000-2005).

An expanded R&D program would allow for a demo program start in 1990

In order to be assured the fusion breeder will be ready when needed, a significantly expanded R & D program will be needed. The feasibility of the fission breeder depends on fusion feasibility itself, but in addition blanket engineering and fuel cycle issues must be resolved both by studies and experiments. To do this job, the present program (\$715K in FY83) must be expanded several fold. The field task proposal submitted for FY83 details such as an expanded program.

SUMMARY OF RATIONALE FOR FUSION BREEDER DEVELOPMENT

Favorable Ultimate Economics

- The fusion breeder can enable electricity production for less than 20% above the current cost of LWR electricity. The ultimate savings can easily pay for its development cost

Attractive to Utilities

- Utilities continue to operate LWRs. Fusion breeders are operated by the government or industry as "enrichment" facilities. Fusion breeders cap U_3O_8 prices at reasonable levels.

Favorable Development Characteristics

- A fusion breeder technology introduced in 2015 can support 120 GW_e of LWR in 2030. Twenty five fusion breeders could support 500 GW_e of LWR capacity in 2040.

International Development Advantages

- An opportunity to pursue a high risk/high payoff option which could leap-frog breeder development internationally and create a new leadership role for the U.S. while reinforcing our role as a fuel supplier to less developed countries

WHY A HYBRID FUEL FACTORY?

- FISSILE FUEL ASSURANCE
- CONTINUED USE OF A PROVEN TECHNOLOGY
- SUPPORT FOR AND BACK-UP TO FAST BREEDER TECHNOLOGY
- ENVIRONMENTAL ATTRACTIVENESS
- LICENSABILITY

FUSION FUEL FACTORY BLANKET CHARACTERISTICS*

CHARACTERISTICS	LMFBR**	FUSION FUEL FACTORIES		PURE FUSION
		FAST FISSION ***	SUPPRES. FISSION ****	
FUEL FORM	STEEL CLAD UO ₂	STEEL CLAD URANIUM	UNCLAD MOBILE FUEL	NA
BLANKET ENERGY MULTIPLICATION	NA	10	1.6	1.2
FIRST WAL FUSION FLUX, $\frac{MW}{M^2}$	NA	1	2	4
BLANKET/CORE POWER DENSITY, $\frac{W}{CM^3}$	600	350	10	10
BLANKET/CORE OPERATING TEMPERATURE	550	500	100-500	500
NET FISSILE FUEL PRODUCTION IN MT (70% CAPACITY FACTOR)	0.20	1.3-2.1	3.4-4.6	NA
IN CORE FISSILE FUEL LOADING, MT	2.1	0	0	0

*ALL BLANKET SYSTEMS NORMALIZED TO 3000 MW OF THERMAL POWER

**LMFBR HAS A BREEDING RATIO OF 1.32

***IT IS ANTICIPATED THAT FUSION DRIVER TECHNOLOGY WILL BE AVAILABLE IN 2000-2010 TIMEFRAME TO SUPPORT FIRST COMMERCIAL FUEL FACTORY

****IT IS ANTICIPATED THAT FUSION DRIVER TECHNOLOGY WILL BE AVAILABLE IN 2010-2020 TIMEFRAME TO SUPPORT FIRST COMMERCIAL FUEL FACTORY.

WHY A HYBRID FUEL FACTORY?

The concept of a fusion electric device operating with relaxed plasma requirements, as a breeder of fissile fuel has received considerable attention of late. It is being widely realized in the nuclear community that, in the absence of a commercially viable fusion device, such a fusion-fission hybrid may well be crucial to the national energy needs beyond the turn of the century if one wishes to maintain the quality of life in the U.S. Among the compelling reasons for this argument are:

- **Fissile Fuel Assurance.** It has been established that national and worldwide Uranium deposits could be significantly depleted during the first quarter of the next century leading to a significant increase in the price of fissile fuel. A single hybrid, deployed as a "fuel factory" would be capable of fueling from 5 to 15 power reactors for an indefinite time period, allowing electricity to be generated at within 15% of current costs.
- **Continued Use of a Proven Technology.** The hybrid would allow the utilities continued use of LWR technology. This would constitute an enhancement of a well-tested, proven technology rather than the introduction of a new one, an important consideration from the utility investors' point of view.
- **Support of and Back-up to Fast Breeder Technology.** As self-fueling reactor technology is brought on line (around the second quarter of the next century) and requires fuel for start-up, hybrids can assure the availability of economic fuel for LWR's through their life-cycle. Among the various advanced breeding technology, the hybrid is the leading alternative in the event breeder deployment is limited by political, economic or technical acceptance considerations on an early enough timescale.
- **Environmental.** The continuing growth of the nuclear generating fraction using proven fission reactor technology minimizes the environmental impacts associated with the use of fossil fuels. Also, the nuclear waste problem is alleviated by use of spent fuel and tailings in the fuel cycle.
- **Licensability.** The hybrid, being an off-shoot of fusion technology, is less affected by the regulatory problems surrounding LWR technology. Development and deployment of this new technology offers a unique opportunity to redefine and rework the entire regulatory process in a manner that could prove immensely beneficial to the entire nuclear industry.
- **Pathway to Pure Fusion.** Since the hybrid represents an earlier application of fusion technology, its early commercialization could provide the utilities with valuable experience in the operation of a fusion facility. It would allow the gradual introduction of fusion technology and actually ease the regulation and licensing issues surrounding its commercial deployment.

Fusion could produce an assured fissile fuel supply for fission

The need

*DOE "minimum scenario" data; 1.5% growth rate assumed after 2010

**DOE data; 3% growth rate assumed after 2000

THE NUCLEAR GROWTH OF BOTH U.S. AND WORLD FROM WHICH THE
FUTURE NEED FOR URANIUM DERIVES

An extrapolation of the "medium nuclear growth" scenario from that of the EPRI strategy document (which was found to be quite consistent with that of DoE) was made from 2020 to 2050 using a conservative (1.5%) growth rate for the nuclear fraction in a baseline case. Sensitivity calculations were done to assess the potential impact of this assumption for both higher and lower growth. These excursions showed but a five year impact on the availability of economical* natural uranium.

* Several life cycle cost estimates of LWR/FFH systems have been made by industry (e.g., Maniscalco, TRW) and utilities (e.g., Fredericks, PA Power and Light) and presented at various meetings to include those of the EPRI Fusion Fission Hybrid Assessment Committee 1981; these showed a consistent breakeven for reasonable support ratios (10) at less than \$90 per lb. (1981 dollars) incentive price. We have, therefore, used \$100 per lb. (in 1982 dollars) throughout this study to define "Economical Natural Uranium."

Fissile fuel supply assurance estimated uranium resources (10^3 st)

Region	Total resource available at a cost of:	Resource categories				Total resource
		US DOE	Reserves	Probable potential	Possible and speculative potential	
		NEA/IAEA	Reasonably assured	Estimated additional	Speculative*	
U.S.	< \$30/lb U_3O_8		205	596	463	1264
	@ 50% CL**		205	298	232	735
	< \$50/lb U_3O_8		594	1080	894	2568
	@ 50% CL**		594	540	447	1581
	< \$30/lb U_3O_8		2005	1798	N/A	3803
	@ 50% CL**		2005	899	N/A	2904
WOCA	< \$50/lb U_3O_8		2788	3189	13681	19658
	@ 50% CL**		2788	1595	6841	11224

*Average of published values for WOCA

**50% confidence level

Sources: "Uranium," the 'Red Book'
OECD-NEA/IAEA, Feb. 1982
DOE News, May 27, 1982
and June 17, 1982

ESTIMATED URANIUM RESOURCES (10^3 ST)

The data in this table is taken from the most recent OECD and DOE sources (see references above table). In order to make these data compatible (in constant 1982 dollars), the WOCA resources should probably be diminished by about 10 percent to account for uranium mining and inflation. (Alternatively, the cost of uranium can be increased by about 10 percent in each category.)

It is interesting to note that for WOCA, speculative resources are considerably greater than reasonably assured resources. In the United States they do not differ significantly. This is a consequence of the fact that the U.S. is much more thoroughly explored than WOCA.

Notice that no data are available for speculative resources in the \$30/lb- U_3O_8 category.

Fissile fuel supply assurance

The dilemma: U.S. has 14% of resource and 33% of demand

U.S.-WOCA SUPPLY/DEMAND COMPARISON

A comparison of U.S. and WOCA supply and demand for uranium is shown here. The demand data are taken from the baseline cases to be discussed later.

This slide shows the dilemma faced by the United States: It has 14 percent of the world uranium resources, but will need 33 percent of the uranium resources consumed by the entire world.

We can examine two scenarios of supply/demand balance to predict the price of uranium versus time. In the first scenario the U.S. will be treated as energy independent (i.e., no foreign imports), and in the second scenario the case of free trade throughout WOCA will be treated.

Approximate generic uranium price factors

Breakdown of the price of U_3O_8

Note: 1.0 = Acquisition factors (cost)

0.8 = Incentive cost factors (price)

1.8 = 100% of uranium "price factor pie"

The problem

Legend*: H — High
R — Reasonable
M — Minimum
D — Declining

Baseline case: RMD
Effect of increasing growth rate
in the first (short-term) period
Uranium is depleted 10 years earlier

*This notation is the same as used by EPRI in the near term time-frame. We have sought to be consistent with the long term projections made by EPRI which use the near term strategic scenarios as a starting point and have carried the corresponding extrapolations out for the succeeding time frames consistently with long term growth rates defined by other EPRI studies.

URANIUM PRICE

The uranium cost is determined by such factors as exploration, mining, milling, and transportation which determine the cost and market, financing and profit factors which determine the incentive price. The incentive price is generally 1.8 times the cost. Resource estimates of DoE for the U.S. and of OECD for the WOGA reflect costs. Thus, for example, $1.8 \times \$50/\text{lb}$ OECD WOGA cost (in CY 81 dollars) = $\$100/\text{lb}$. (in CY 82 dollars), the incentive price which the utility would be required to pay.

THE PROBLEM

If we assume a conservative RMD scenario as the baseline case we see the U.S. supply of economical fuel exhausted by about 2015. Sensitivity calculations show that imports yield but five to ten years extension per 20% import fraction; thus the U.S. dependency in foreign uranium imports builds rapidly. Another sensitivity calculation shows a dramatic acceleration of U.S. and world exhaustion of uranium for new facilities if the traditional forward purchases continue - a situation that will become almost a certainty as resources are depleted.

Conclusions of U.S. Sensitivity Analysis:

- Small resource base renders the depletion date relatively insensitive to all but the most dramatic excursions from the baseline case.
- The noteworthy excursions are:
 - Depletion ten years earlier with initial historic growth rate
 - Depletion ten years later with 40% foreign imports
 - Depletion 5-year earlier/later for each 25% decrease/increase in confidence level