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Volume II

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July 1978

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FOREWORD

On November 1 and 2, 1977, a meeting was convened in Washington, D. C., to review the status of and prospects for fusion-fission energy systems. These volumes present the papers delivered at this meeting and the questions and answers following each paper.

The agenda of the meeting was developed to address, in turn, the following major areas:

- Problem Characteristics - Specific problem areas in nuclear energy systems for application of fusion-fission concepts.
- Current and Planned Fusion-Fission Energy Systems Activities - Current and proposed fusion-fission programs in response to the identified problem areas.
- Economic Considerations - Target costs and projected benefits associated with fusion-fission energy systems.
- Technical Problem Areas - Technical problems associated with the development of fusion-fission concepts.

The greatest emphasis was placed on the characteristics of and problems associated with fuel producing fusion-fission hybrid reactors. Because of the limited scope of the meeting, the broader issues of advanced nuclear reactors and their fuel cycles received little attention.

Since November of 1977, it has been decided to initiate a broadly based formal assessment of the need for and feasibility of fusion-fission energy systems. This decision resulted from the recognition that fusion may have real opportunities to provide solutions to problems of nuclear energy and also result in a nearer term benefit from an admittedly long term and expensive RD&D program. The assessment program is tentatively scheduled for completion in late 1980.

In addition to the assessment program, fusion-fission energy system design studies will continue with somewhat greater emphasis on the requirements imposed by advanced nuclear reactors and their associated fuel cycles. It is expected that these studies will face the chicken-egg dilemma: Will normally evolving fission reactor designs constrain the fusion-fission characteristics or will the flexibility offered by fusion-fission remove constraints on fission reactor design and deployment? Hybrid reactors and LWBR's could represent such a case.

The next major Fusion-Fission Energy Systems Review Meeting will be held at the completion of the assessment and the design studies presently under way. Interim information will be made available periodically at various national and topical meetings. Your continuing interest in the area of fusion-fission energy is appreciated.

Coffman

Franklin E. Coffman
Acting Assistant Director for
Development and Technology
Office of Fusion Energy

AGENDA

SECOND MFE FUSION-FISSION ENERGY SYSTEMS REVIEW MEETING

Wednesday, 2 November 1977

9:00 Opening Remarks - Edwin E. Kintner, Director, Division of Magnetic Fusion Energy

PROBLEM CHARACTERIZATION

J. M. Williams, Session Chairperson

9:10 Uranium Availability - J. Boyd (Materials Assoc.)

9:40 Global Proliferation Concerns - R. Simkins (Dept. of State)

10:10 REFRESHMENTS

10:30 Nuclear Fuel Cycles - S. Strauch (Dept. of Energy)

11:00 Utility Perspectives - P. Bos (Electric Power Research Institute)

11:30 Alternatives to Fusion-Fission Energy - H. Kouts (Brookhaven National Laboratory)

NOON LUNCH

FUSION-FISSION ENERGY SYSTEMS

1:00 Generic Description of Fusion-Fission Energy Systems - S. L. Bogart, Session Chairperson - L. Lidsky (Massachusetts Institute of Technology)

1:30 Present Status of Fusion-Fission Energy Systems Design - K. G. Moses, Session Chairperson

- 1:30 - Mirror Hybrids - D. Bender (Lawrence Livermore Laboratory)
- 2:00 - Tokamak Hybrids - R. Rose (Westinghouse Electric Corporation)
- 2:30 - Inertial Confinement Hybrids - J. Maniscalco (Lawrence Livermore Laboratory)

3:00 REFRESHMENTS

Wednesday, 2 November (Continued)

3:30 New Initiatives in Fusion-Fission Energy System Design - S. L. Bogart, Session Chairperson

- 3:30 - General Atomic Company/ Lawrence Livermore Laboratory - S. Burnett (General Atomic Company)
- 4:00 - Westinghouse Electric Corporation - T. Varljen (Westinghouse Electric Corporation)
- 4:30 - Lawrence Livermore Laboratory (Inertial Confinement) - J. Maniscalco (Lawrence Livermore Laboratory)

5:00 ADJOURN

Thursday, 3 November 1977

9:00 Economic Considerations - C. Head, Session Chairperson

- 9:00 - An Examination of Alternative Nuclear Breeding Methods - B. Augenstein (RAND Corp.)
- 9:30 - Economic Regimes - D. Deonigi (Battelle Pacific Northwest Labs.)

10:00 REFRESHMENTS

10:30 Technical Problem Areas - J. O. Neff, Session Chairperson

- 10:30 - Hybrid Blanket Design - K. Schultz (General Atomic Company)
  J. D. Lee (Lawrence Livermore Laboratory)
- 11:00 - Fusion Physics Requirements - N. Krall (Science Applications, Inc.)
- 11:30 - Environment and Safety - J. Holdren (University of California, Berkeley)

NOON LUNCH

- 1:00 - Tokamak Technology Requirements - D. Steiner (Oak Ridge National Laboratory)
- 1:30 - Mirror and Other Magnetic Confinement Technology Requirements - R. Moir (Lawrence Livermore Laboratory)
- 2:30 - Inertial Confinement Technology Requirements - L. Booth (Los Alamos Scientific Laboratory)

3:00 General Discussion (5-10 minute limit) - GROUP

4:00 ADJOURN

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FUSION-FISSION HYBRID BREEDERS--ECONOMIC AND PERFORMANCE ISSUES, ROLE OF ADVANCED CONVERTERS, INTERDEPENDENCE BETWEEN FISSION AND FUSION PROGRAMS

Bruno Augenstein

December 1977

P-6047

INTRODUCTION

This paper* considers *nuclear breeding systems* (i.e., production of fissile fuel from fertile materials).

The range of breeding technologies considered is deliberately wide. We include systems which breed by using *internal* neutron sources--a reactor-breeder, exemplified by the liquid metal fast breeder reactor (LMFBR)--and systems which breed by using *external* neutron sources--exemplified in this paper primarily by hybrid fusion-fission breeders.

The methodology used is the simple discounted present value technique. Estimated costs for each technology considered are developed to satisfy a specified demand for electricity, time phased, and discounted back to 1980. These costs are then individually compared with a standard Base Case, in which only U-burning light water reactors (LWRs) contribute to power generation.

We also explore and exhibit some of the broad range of critical parameter variations which are possible. *The sensitivity to, or "robustness" against, broad critical parameter ranges ought to be significant factors in deciding on RD&D paths for the many technologies available, and in making RD&D funding allocations.* The hybrid shows a very pronounced "robustness," and so merits consideration as a major RD&D possibility.

We also comment on interrelations among pure fusion, hybrid fusion-fission, and pure fission systems. These are all capital and technology intensive systems which, as a class and *in the public eye,* can arouse intersecting concerns about hard technology, nuclear based methods for energy production. Such publicly perceived commonalities can well make future pursuit of such technologies an all or nothing proposition, in which public resistance to one technology can transfer to the entire class. The pure fusion community should be aware of this possibility.

---

*Delivered at the November 1977 DOE DMFE meeting.

BACKGROUND

We first construct a "check-list" of issues which, ideally, ought to be addressed in evaluating Hybrid Breeders against other breeding system possibilities. This check-list is shown in Figure 1. We should make clear the obvious point, however, that many of these attributes cannot currently be discussed with great precision, although qualitative discussions can be provided. A more comprehensive and exacting discussion would need, in major part, to rely on the *future RD&D work which this paper calls for.*

The general class of nuclear options we propose to discuss in this paper is shown in Figure 2. We want mainly to consider "symbiotic mixes"--mixes in which the makeup fuel required by a *converter* (conversion ratio <1), after the converter discharge has been reprocessed to extract the fissile fuel content contained in the discharge (which provides the bulk of the next fueling), is supplied by a *separate device* which produces fissile fuel. This separate device is an external neutron source breeder--either a hybrid fusion-fission device derived from a "derated" pure fusion machine, or an accelerator breeder.

Figure 2 makes evident the central role of the converter in the symbiotic mix. Later we shall see that improvement of the converter (e.g., by increasing the conversion ratio CR) is generally highly motivated in a symbiotic mix (exceptions can occur if, for example, there are substantial captial cost penalties associated with increases in CR). Converter improvement in turn can come about through two paths: by emphasizing various possible technical enhancements of converters; or, possibly, by emphasizing the development of a class of *"derated" internal neutron source breeders* whose characteristics could be less demanding than the breeder embodiment we start with.

To focus discussion, the three generic breeding systems noted on Figure 3 are addressed. Many detailed technical inputs were kindly provided by LLL for the external neutron source breeder. The hybrid is in active development insofar as one basic part of the machine is concerned--the fusion plasma producing the DT reaction and the required neutron flux. The other basic part of the hybrid is the blanket, or energy multiplying region where also the fertile → fissile

DESIRABLE ASPECTS OF BREEDING SYSTEMS

- FAVORABLE EXPECTED LONG-TERM ECONOMICS
- MAXIMIZE USEFULNESS OF PRESENT UTILITY, INDUSTRY EXPERIENCE AND INVESTMENTS
- MINIMIZE CHANGEOVER PROBLEMS FOR UTILITY, INDUSTRY
- PROVIDE IMMEDIATE UTILIZATION OF MAJOR EXISTING U.S. ENERGY RESOURCE (TAILS STOCKPILE)
- PROVIDE COMPETITION AMONG BREEDING SYSTEMS
- PROVIDE GREAT RANGE OF FLEXIBLE OPTIONS FOR COMMERCIALIZATION, DEPLOYMENT, OWNERSHIP ALTERNATIVES
- MOTIVATE DEVELOPMENT OF IMPROVED CONVERTERS AS WELL AS BREEDERS
- MINIMIZE SENSITIVITY TO UNCERTAINTIES IN CAPITAL COST, PERFORMANCE
- BOUND ISSUES OF START-UP, REQUIRED RATE OF DEPLOYMENT FOR NEW TECHNOLOGIES
- MODERATE, NOT EXACERBATE, PROLIFERATION DANGERS
- BOUND IMPACTS OF SAFETY, ENVIRONMENTAL ISSUES
- PROVIDE FOR FLEXIBILITY OF USE, ACCOMMODATION TO PLANNING VARIATIONS, RESPONSIVENESS TO CHANGE

→ THE LMFBR, AND THE HYBRID OR ACCELERATOR, RESPOND DIFFERENTLY REGARDING SUCH ASPECTS

Figure 1

NUCLEAR OPTIONS

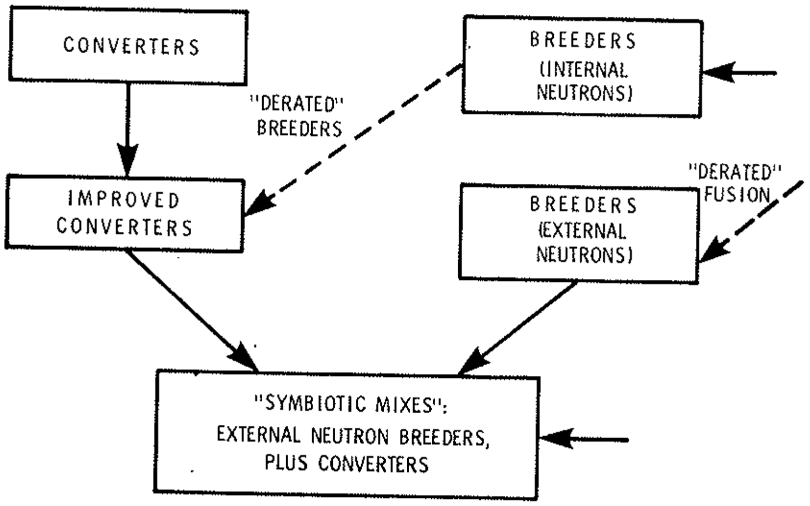


Figure 2

transmutations take place. The blanket is comparable to a "standard" reactor-like region, is decidedly subcritical, and blanket design can draw on the very substantial amount of converter know-how available.

There are differences of both kind and degree between the external and internal neutron source breeders. For example, a hybrid or accelerator breeder is relatively well suited to the concept of a *refresh cycle*. Here fuel elements from a conventional converter, after an economically useful amount of burn-up, are removed from the converter and in a breeder subjected to a neutron flux to breed new fissile material *in situ* in the fuel elements. These fuel elements are then put back into the converter, burned down again, and the cycle repeated. Very preliminary estimates suggest that perhaps, say, five such cycles could be repeated before reprocessing was necessary to separate out residual fissile fuel, actinides, etc. Fuel elements designed to optimize the refresh cycle might look rather different from today's; and the very high total burn-ups demonstrated in the LMFBR development might have materials and design relevance.

THREE BREEDING SYSTEMS

-
    - LMFBR (PROVEN TECHNOLOGY)
    - HYBRID FUSION-FISSION (ACTIVE DEVELOPMENT, NOT YET PROVEN)
    - ACCELERATOR, PROTON, DEUTERON BEAMS (TECHNOLOGY AVAILABLE FOR DEVELOPMENT)
- BREED BY INTERACTION OF NEUTRON FLUX WITH FERTILE MATERIALS (U, Th)
- NEUTRON SOURCE:

LMFBR	HYBRID	ACCELERATOR
- Fission Events	- D-T Reaction	- High Energy Particles
- Requires Initial Fissile Inventory	- Only Initial Fertile Inventory	- Only Initial Fertile Inventory

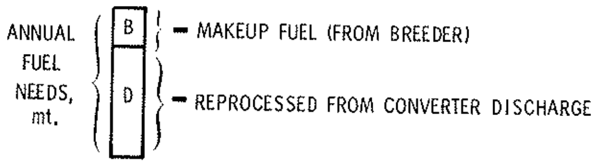
- DIFFERENCES: HYBRID, ACC., VS. LMFBR:
    - EASE OF BREEDING U-233
    - REFRESH CYCLE POSSIBILITIES: DEFER REPROCESSING

Figure 3

In Figure 4 we pursue a little further the notion of "symbiotic mix" which this paper emphasizes. The representative breeder noted is a specific design point hybrid fusion-fission device whose neutron power is 300 MW, whose Q is of the order of unity,* whose duty cycle or capacity factor is 0.7, and which produces 1.7 metric tons per year--in this case, of Pu fissile fuel. This is evidently a *small fusion* device ($\sim \frac{1}{10}$ the neutron power for a 1 gWe pure fusion machine), and is much "derated" from a pure fusion device in terms of acceptable Q, plasma parameters, first wall fluxes, etc.

SYMBIOTIC MIXES

- BREEDER PRODUCES M mt/yr. FISSILE MATERIAL.
  - REPRESENTATIVE DESIGN: $M = 1.7$ mt/yr.
- CONVERTER:



- MIX "FIGURE OF MERIT":

  SYMBIOTIC $N = \frac{M}{B}$
- N DEPENDS ON <u>BOTH</u> BREEDER <u>AND</u> CONVERTER

Figure 4

The mix "Figure of Merit" N should be regarded primarily as an index number by which certain performance aspects of symbiotic mixes can be parameterized. N is also usually *nearly* the number, N', of converters which *one* breeder can support (by providing makeup fuel). The differences N-N' are due to such factors as the rate of demand growth and requirements for new initial fuel loads, transitioning to new fuel types, possible disposition options for the remaining converter fuel loads at the end of useful life (the life is taken as 30 years for all devices--breeders and converters--considered), and so on.

---

*$Q \sim 1$ is a goal of the just-started-construction Princeton TFTR.

Since, in the definition of $N = \frac{M}{B}$, M reflects breeder performance while the denominator (B) reflects the converter performance--as the conversion ratio increases B decreases--N can be increased by improving the converters, by improving the breeders, or by *both* improvements. All other things equal, increases in N improve the symbiotic mix economics. Further, the required *rate of deployment* of the breeders in the symbiotic mix (compared with the number of converters) varies inversely to N.

We need now to be more specific as to what the ranges of B (makeup fuel needs per year per converter) might be. Estimates of B are given in Figure 5.

Clearly these estimates warrant much more attention, by using real reactor designs, improved neutronics calculations, and considering the dynamic changes in converter discharge isotopic composition as the reprocessed fissile content, mixed with the breeder fissile fuel, is recycled through the converter.

The range of B, considering the variety of converter embodiments possible, could be virtually a continuum of values, ranging from perhaps 200-300 kg of Pu for very conservative LWR designs, to a few kg of U-233 or Pu for a "near-breeder" converter design. A U-233 CANDU type of converter, for example, can realistically be considered to achieve conversion ratios near unity (an idealized design with low burn-ups could theoretically attain conversion ratios over 1.0). At such near unity conversion ratios, the makeup fuel needs (B, as defined previously) might be a few tens of kilograms of U-233 annually. We assume that at a CR = 1.0, losses in the reprocessing cycles will require a small amount of makeup fuel to be furnished (hence the non-zero value of makeup fuel at CR = 1.0 in Figure 5).

The specific breeder production rate (M = 1.7 metric tons per year) of Figure 4, combined with B values from Figure 5, provides estimates of the symbiotic mix number N. Values of N thus estimated can range over a very wide spectrum,--from a rather conservative value of N = 5-8 for well investigated Pu burning LWRs, to values of, perhaps $N \geq 40$ for a U-233 burning CANDU design (or for some Pu burning possibilities, which are however rather less certain than is the U-233 CANDU), after an effective steady equilibrium situation is reached.

CONVERTERS — MAKEUP FUEL NEEDS

- 1 GWe UNITS, 0.7 LOAD FACTOR
- SOME EXAMPLES:

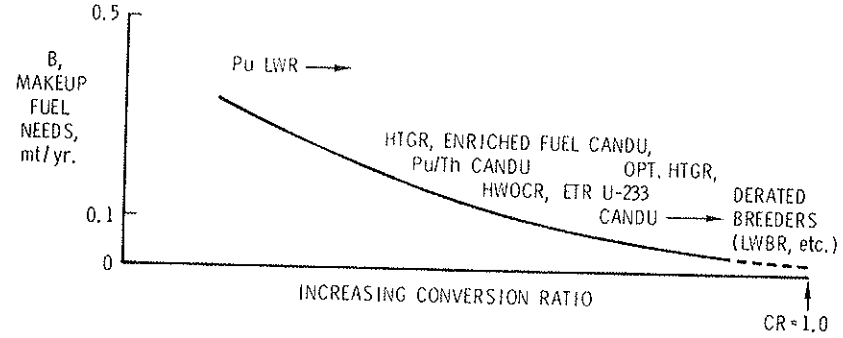


Figure 5

METHODOLOGY AND EVALUATION TOOLS

We come now to some of the quantitative issues involved in comparing the Hybrid (and Accelerator) Breeders with other breeding possibilities--especially the internal neutron source breeders, of which the LMFBR is by far the most adequately researched example.

A choice needs to be made from the range of models which support our main interest--judgment of the possible economic consequences of introducing a Hybrid Breeder into large scale energy systems. We could, on the one hand, use one of the many econometric or optimization models available today--for example the Manne model(1)--to predict at what breeder parameter levels the breeder (in a symbiotic mix) would be an efficient entry into the energy market, and what share of the market it might capture. On the other hand, since we are here mainly interested in *comparative estimates, not absolute estimates,* we could opt

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1. A commercial version of the Manne Energy Technology Assessment (ETA) model is provided by the Control Analysis Corporation on a subscription basis. For a brief list of some relevant models, see Greenberger, EPRI Journal, Oct. 1977.

for a model which captures some important aspects of dynamic cost and benefit streams and investment decisions, opportunity tradeoffs, and issues of time preference in a relatively simple and transparent way. Such a model is provided by Net Present Discounted Value (NPDV) models. We here focus on the NPDV models, as Figure 6 notes. For either class of models a central issue is the choice of parameter values for the Hybrid in the environment of other possible energy sources. The NPDV model allows the effects of various parameter choices to be traced very simply.

ECONOMIC COMPARISONS

- METHODOLOGY:
  - BASE CASE - LWR, WITH INCREASING U_3O_8 PRICE
  - BREEDING SYSTEM - BASE CASE COST DIFFERENCES, 1980 - 2050
  - DISCOUNT TO 1980 at 10%
  - COMPARE NET PRESENT DISCOUNTED VALUES
- TYPES OF COMPARISONS:
  - POINT ESTIMATES OF PARAMETERS
  - PARAMETRIC STUDIES OF UNCERTAINTIES
    - ESTABLISH "ROBUSTNESS" OF OPTION

Figure 6

This paper takes the point of view that use initially of a simple aggregated model (e.g., NPDV analysis) puts the problems of evaluation and comparison in proper perspective. As knowledge of the problem issues evolves, more sophisticated models--sophisticated in conceptual framework, in clarity of causal relations, and in application to interactions--become increasingly appropriate. Without that evolving knowledge, however--which in the end must come from hard RD&D information, and which must recognize that even the most complex current models have important and often only implicit limiting assumptions--our view is that spurious inferences on precision and depth of understanding can easily result from casual use of complex models.

A number of difficult issues occur even in NPDV models, of both a philosophical and practical nature. The role and utility of such models is often misunderstood--because, for example, discounting favors technologies which enter a market early and produce benefits early. Useful background documents for our reasons for selecting NPDV models as the *initial* comparative evaluation tool exist;(2) discussion of what is and what is not included in NPDV analyses can be found therein.

Comparisons via NPDV analysis provide generally stringent bases for assessing potential economic utility of a technology--for example, a viable technology should recover, in a specified time period, discounted benefits in excess of discounted front end RD&D costs, for whatever market share of the total energy market that technology can be predicted or assumed to capture. In our simple analysis that market share is effectively assumed to approach 100 percent for each technology as we compare it *singly* to a standard base case. Models such as the Manne model attempt to predict a market share ≤ 100 percent, for a given technology in the presence of several competing technologies. Such predictions currently contain many uncertainties.

In an NPDV analysis the question of what the discount rate "ought" to be persists, as does the question of whether the *same* discount rate ought to be used for all technologies, when different costs, benefits, risks, time horizons, and probabilities of success are involved. One can make arguments for differentiated discount rates, in some situations. Such arguments have been used on occasion, for example in considerations of actions to be taken to conserve or forego use of resources--actions whose costs are relatively immediate but whose benefits can be much later.

Figure 6 also indicates that two types of comparisons can be made. Of these the second is often the more important. We need to be realistic

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2. See for example: MITRE Technical Report 7611, Proceedings of Engineering Economic Analysis Workshop, "Economic Analysis of Advanced Energy Technologies," August 1977.

and recognize the well documented fact that *early estimates*, especially by enthusiasts, of cost-performance-schedule parameters for a new technology *are generally seriously in error* (overly optimistic). There is merit in assessing how well the kinds of comparisons we make hold up in the face of *uncertainties* in cost-performance-schedule estimates. We will subsequently give examples of such "robustness" assessments for the Hybrid Breeder.

In our comparisons we use a standard base case of an all uranium burning LWR (with achieved conversion ratios) nuclear economy. This LWR system, *by itself*, is to meet the postulated future increment of electricity demand shown in Figure 7. To do so, the cumulative uranium requirements shown in Figure 7 also result. If reprocessing is used, the ore-consumption would be about 25-30 percent less.

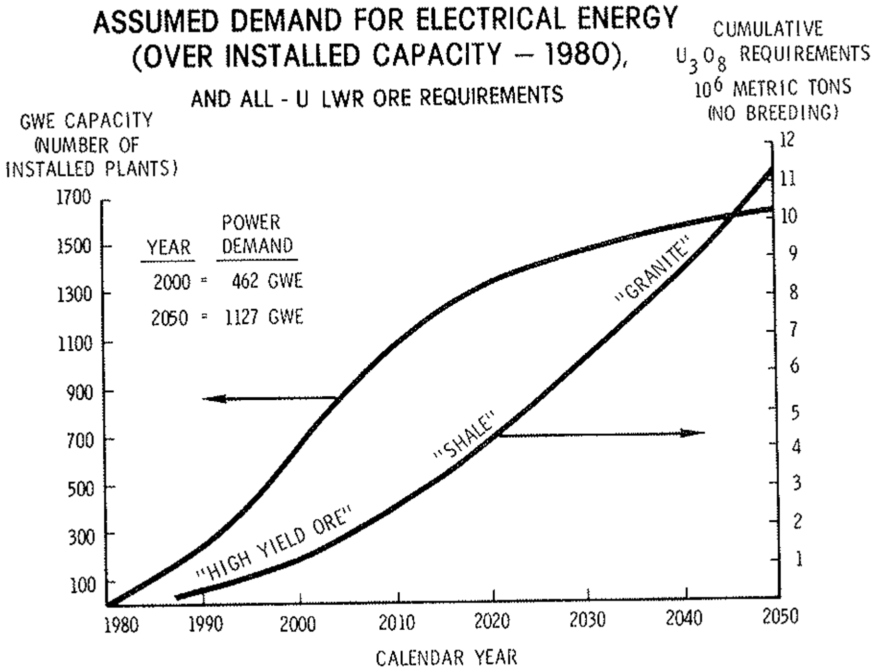

Figure 7

The use of a single technology to satisfy the total future increment of electricity demand is artificial, except as a methodological simplification. However, since our main purpose here is to compare technologies to see *what incentives might exist for RD&D funding* of those technologies, *binary comparisons* are reasonably appropriate, if we are simply trying to see what *group of technologies* warrants RD&D emphasis (i.e., priority assignment). Issues of absolute technology-by-technology RD&D resource allocations, economic mixes of several technologies, and description of a preferred, time phased, composition of the several technologies, is beyond the scope of this paper. These issues in any case depend sensitively on many factors not yet made adequately quantitative by RD&D.

Costs of this all-U LWR system base case are always cited in terms of 1980 dollars. We use a capital cost of $1000 Kwe installed for the LWR, a capital charge rate (itself a complex mixture of relevant economic and investment factors) of 16 percent, and an assumed price schedule for U_3O_8 starting with $50/lb in 1980 and rising $2/year to $190/lb in 2050. The U_3O_8 price rise, when reflected in the LWR fuel cycle costs, produces significant increases in the cost of electricity generation (in terms of mills/kwh) between 1980 and 2050. Our assumptions for LWR costs during the time period 1980-2050 result in year by year costs shown in Figure 8. To generate these values, we have assumed a 30-year plant life and a capacity factor of 0.7.

ECONOMICS OF SEVERAL BREEDING ALTERNATIVES

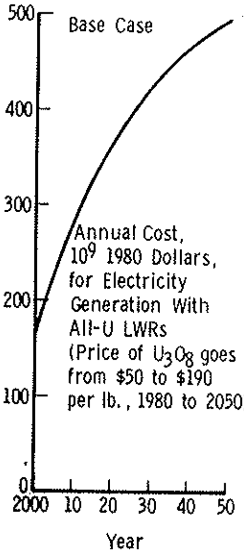

Figure 8

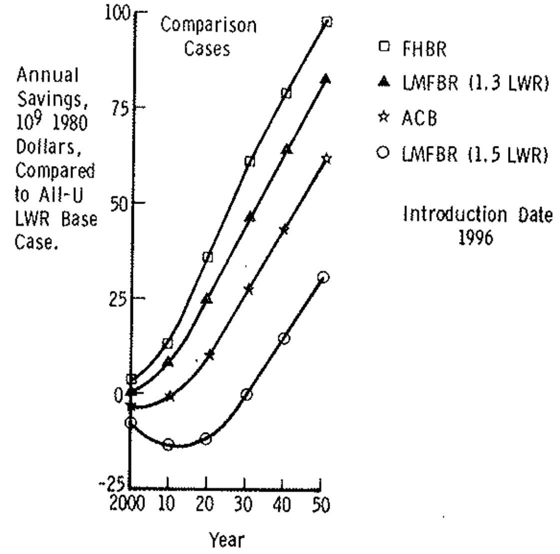

Figure 9

SOME COMPARISONS--HYBRIDS AND OTHER BREEDING TECHNOLOGIES

In all our subsequent comparisons with the previous Base Case we follow the same procedure. We assume that we operate on an accrual basis (vice a cash-flow basis) for the total generating system. In some given year we begin introducing a new technology. In that year we stop adding new all-U LWRs, letting the subsequent numbers of all-U LWRs vary consistent with the 30-year life assumption, and make up with the new technology the difference between the year-by-year electricity required and that provided by the residual inventory of all-U LWRs. Using "best estimates" of the cost-related parameters of that new technology, we estimate *annual cost differences* between the Base Case and the case where the new technology begins to satisfy the electricity demands. With what to us appear to be reasonable point values of the cost-related parameters, Figure 9 shows some typical results for a Pu-oriented nuclear economy, using specific versions of the Fusion Hybrid Breeder (FHBR), Accelerator Breeder (ACB); and two versions of an LMFBR, with capital costs 30 percent and 50 percent more (which may span the probable range) than an LWR of the same electrical output. A Pu burning converter fueled by the FHBR or ACB in the symbiotic mix is assumed to cost \$1000/Kwe installed, and has a capacity factor of 0.7; the converter is a nominal 1 GWe unit. In Figure 9 the LMFBR is also a 1 GWe unit, operated at 0.7 capacity factor; the same capacity factor is used for the FHBR and the ACB. The FHBR delivers a neutron power of 300 MW; the ACB has a beam power of 250 MW.

We then discount these cost differences relative to the all-U LWR Base Case with a *10 percent discount factor* to the standard year 1980, and sum these discounted values between the year of introduction (1996 in the cases shown in Figure 9) and the year 2050, to arrive at a Net Present Discounted Value (NPDV) estimate for these technologies compared to the Base Case. The values shown in Figure 10 result.

We also show some parameter excursions in Figure 10.*

Figure 10 shows our "best estimates" (triangles - Δ) of capital costs (and earlier LLL estimates), and for those estimates the effects of capital costs on NPDV, other aspects remaining the same, for the LMFBR, FHBR, and ACB. The values we use for the symbiotic N are conservative in Figure 10--N = 5 for the FHBR, N = 3 for the ACB. Some further parameter excursions are shown in Figure 11, for the $50 to 190 U_3O_8 price schedule.

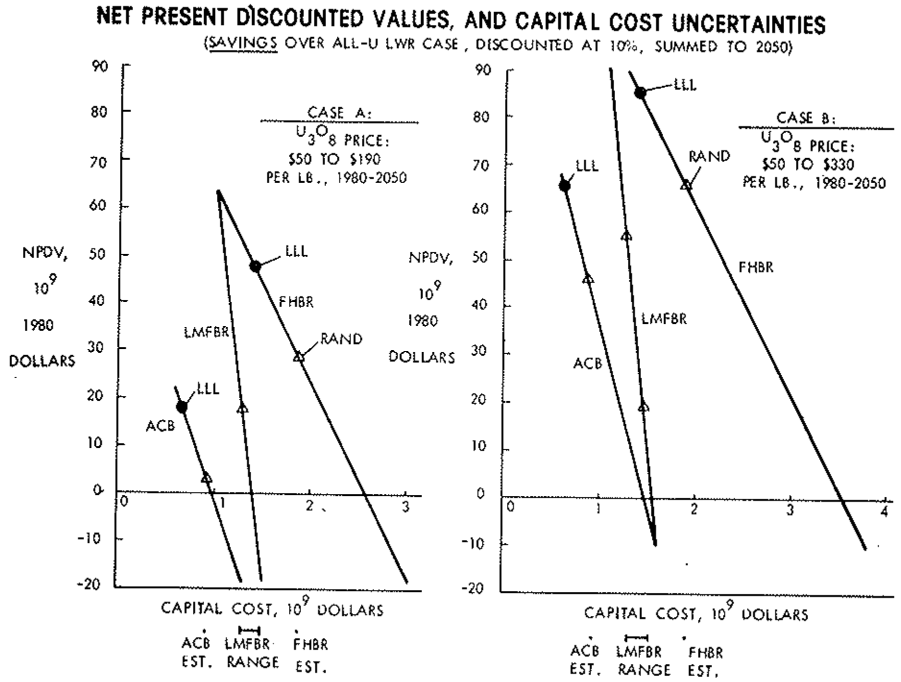

Figure 10

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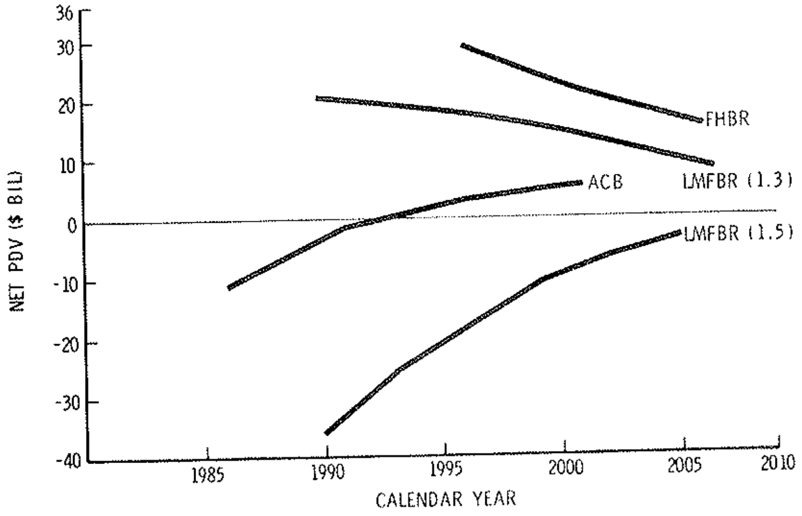
*The significance of *negative* NPDVs can be regarded in several ways. One is that the technology in question should not be introduced at too early a time, when major economic driving parameters are unfavorable. Another is to attribute significance only to *NPDV differences* in technology comparisons, not to absolute NPDVs measured from some essentially arbitrary Base Case. The latter point of view recognizes that the definition of a Base Case cannot be viewed as a prediction of the actual situation, whereas in the first point of view we actually would do our best to make the Base Case itself realistic. In general, the NPDV differences among several technologies being compared would have the most immediate importance. However, there may be cases where a technology *might warrant introduction* before it is economically competitive--e.g., where a time slot is present which is comparable to, or shorter than, the normal transitioning period to adapt to a new technology on a large scale--provided it rapidly becomes competitive.

SENSITIVITY CURVE: INTRODUCTION DATE

Figure 11



Here we have used the "best estimates" of Figure 10, but have now varied the assumed introduction date to account for the possibility that the several technologies may mature at different times. The behavior of these curves is easy to follow. The curves would all have a very small positive value as the introduction date approached the end-year (2050) of the integration period (Introduction date to 2050), would show no changes in ranking, and would have maxima at that year of introduction in which the annual savings first became positive (e.g., from Figure 9, the year ~ 2010 for the ACB shown).

Next we show some typical parametric excursions which permit inferences as to the "robustness" of the technologies against uncertainties in key parameters. Uncertainties exist for *all* the technologies mentioned so far. However, the FHBR, being composed of several as yet not fully demonstrated component technologies, must be regarded at present as having *greater uncertainty bands* for some critical parameters than the other technologies. We consider both Pu-producing and U-233 producing devices, and include effects of two key parameters--symbiotic mix numbers and breeder capital cost.

For fixed breeder capital costs, the symbiotic mix numbers reflect the *joint* effects of breeder performance (e.g., fissile fuel production rates per gigawatt thermal in the breeding device, Kg/GW_t) and converter performance as affected by converter conversion ratio (e.g., Kg of makeup fuel required per gigawatt thermal in the converter). If we consider a given symbiotic mix number N and ask how departures from N can result, such departures can be the consequence of breeder fissile fuel production rate differences from those originally assumed; or converter makeup fuel requirement differences from those assumed; or both. In turn, these differences can arise from many circumstances--in the breeder from blanket neutronics misestimates; departures from the assumed Q; divergence from assumed reprocessing estimates; DT plasma neutron source variations, and so on. In the converter, comparable lists of possibilities can be devised.

Likewise, for fixed joint performance levels (values of symbiotic mix number) the breeder capital cost may be misestimated (as capital costs usually are in an early stage of development of a technology); we want to know the effects of this.

Typical plots of results when we fix the introduction date and parameterize performance (i.e., symbiotic mix number) and capital cost are shown on Figure 12. The introduction date used is 1996 for the hybrids.

The left-hand end-points of the capital cost ranges (i.e., the capital cost of $1.9 billion for a Pu producing hybrid and $2.7 billion for a U-233 producing hybrid) are intended to reflect some "best-estimate) cost and performance designs in which 1.7 metric tons of Pu or U-233, respectively, are produced annually. The realism of such a cost estimate can be gauged by observing that, for the Pu Breeder, we are coupling a small fusion device producing 300 MW of neutron power with a blanket whose thermal power is about 3.5 GW. Because disagreement on such cost estimates is evidently possible, Figure 12 allows for much higher costs. The higher cost of the U-233 producer reflects the additional difficulties encountered in producing that fissile isotope. Those point values then give, for various symbiotic mix numbers N, the NPDV values shown, summing from 1996 to 2050. If the capital costs for the hybrids are higher, one simply follows lines of constant N. From considerations mentioned earlier, the $N = \infty$ asymptote has some physical plausibility in both cases. It is the case in which the converter requires, in effect, infinitesimal amounts of makeup fuel, as would occur for converters having a CR very near unity and with negligible reprocessing losses.

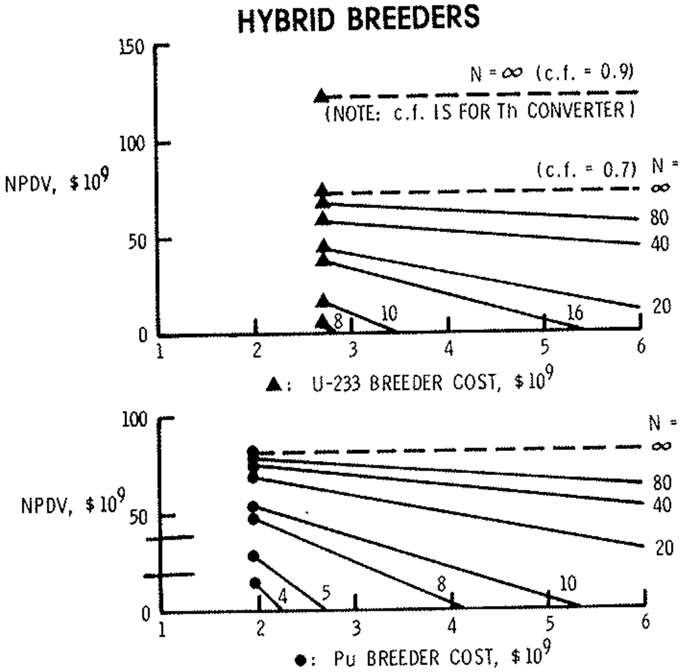


Figure 12

We can comment on several aspects of Figure 12 and the analyses which lead up to the values shown.

a) (1) The accelerator does not have the hybrid charges for the *fusile* materials involved in the hybrid, (2) the hybrid (as we have configured it), and especially the Pu producer, also produces a significant amount of salable electricity (i.e., power which can be put on the power grid, representing the excess of the power produced from the thermal energy *in the blanket* over that required to operate the hybrid device itself--injectors, etc.).

The cost factor (2) is significantly larger than cost factor (1). That is, in our calculation, the offsetting sale of electricity in the hybrid usually far outweighs the additional fusile material charges of the hybrid, and, in the net, generally reduces the "true" production costs for a gram of Pu or U-233 by some 30-50 percent--in instances more--compared with the accelerator.

b) For the U-233 case the lower asymptotic value ($N = \infty$) for a converter capacity factor of 0.7 results from our estimate of somewhat higher converter fuel cycle costs for U-233 converters compared to Pu converters. *If* the U-233 converter can attain the capacity factors of ~ 0.9 achieved in current CANDU converters, the entire sheaf of curves is moved up, as is shown for the $N = \infty$ case in Figure 12.

c) In Figure 12 we have assumed that *all* converters, independent of conversion ratios, values of N, or type of fissile fuel used, have a cost, for 1 GWe units, of $1000/Kwe installed (1980 dollars)--that is, *all* converters are assumed to cost the same as correspondingly sized LWRs. Suppose in fact that a converter cost of $(1+\Delta) \times$ LWR cost is appropriate. Then a *rough* indication of how the NPDV values in Figure 12 are affected can be obtained by using the assumed value of N, but with a "virtual" breeder cost equal to $N\Delta$ plus the actual breeder cost.

From Figure 12 a number of major implications follow. First, the NPDV values show a significant stability against relatively large changes in the capital costs assumed for the breeder in the symbiotic mix. This stability increases as N increases; for $N = \infty$ the capital cost of the breeder would have no effect on the NPDV values. Second, the sensitivity to changes in N (changes which could come about because the breeder fissile fuel production rates may be misestimated; or because the converter requires different amounts of makeup fuel because of converter conversion ratio misestimates; or both effects come into play) also shows a highly nonlinear behavior; at high values of N, $\frac{d(\mathrm{NPDV})}{dN}$ is small, at low values of N it is large.

In summary, the economic performance of the symbiotic mix is *"robust,"* in our sense, *against major uncertainties* in capital cost of the breeders and the performance of the converter-breeder mix (as reflected in N values). The robustness is most evident at high values of N; and it should be remembered that values of N ~10 for the Pu case and ~40 for the U-233 case appear achievable or exceedable by appropriate converter design, for breeders of the scale used here.

This behavior can be contrasted with the relatively much greater sensitivity of NPDVs for the LMFBR, in Figure 10, to changes in capital cost of the LMFBR. This contrast is, in our view, one of the compelling reasons for actively considering external neutron source breeders.

We can show the effects of Base Case variations fairly easily. Figure 13 reflects an example: the impact on NPDV of variations in the assumed annual cost growth for U_3O_8 in the Base Case fuel cycle costs. Naturally, many other such parametric excursions can be simply explored. Figure 13 also gives some rudimentary insight into factors which a simple NPDV analysis usually neglects--in this case, the fact that when we have several competing technologies, the behavior of each is affected by the presence of the others (use of coal, for example, could reduce the reliance on LWRs, and the cost growth for U_3O_8 would be perturbed, in turn impacting on the *relative promise* of the FHBR). It is these kinds of interaction which more complex models could treat more realistically.

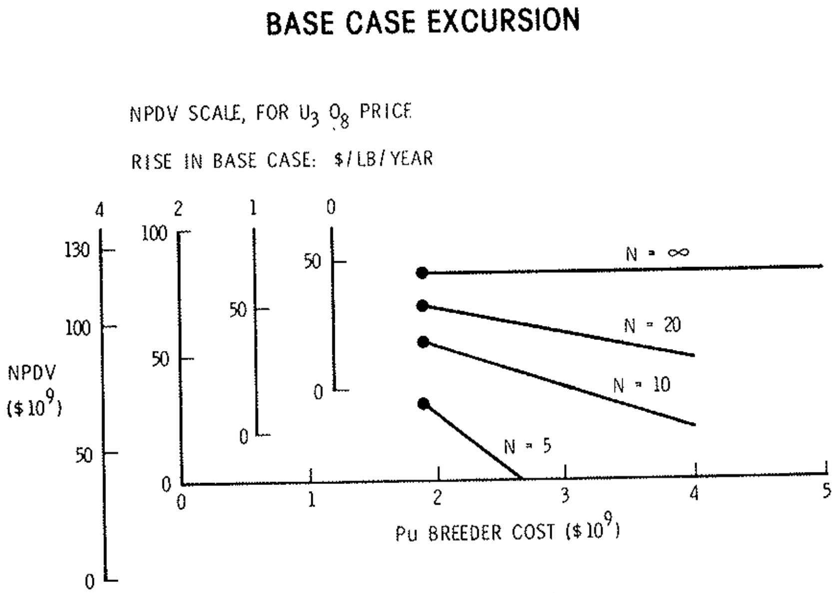


Figure 13

ADDITIONAL REMARKS

We are, of course, not through with the important issues connected with symbiotic mixes by this simple exploration of economic aspects and "robustness."

What we have done so far is to show that the FHBR should be a candidate for active support and development, because it promises to perform commercially at least as well, and probably better, than LMFBRs, if it is an experimental success. Further, admitting that we must currently assume wide uncertainty bands in basic parameters which drive the economic promise inferred, the FHBR's economic promise is robust in the face of such uncertainties--large excursions in key parameters still permit competitive commercial economies and recover probable RD&D costs.

A next issue to explore is how to narrow down the uncertainties in key parameters by analytical and experimental studies, combined with historical studies of how far off initial predictions of key parameters of first-of-a-kind technologies (RD&D and production versions) have been. This exploration, which is underway as part of Rand's studies, can then give us a better sense of where we ought to enter the uncertainty bands to better establish the real multi-dimensional tradeoffs possible.

Then--and probably only then--it can be highly productive to conduct economic promise and possible resource allocation studies via the more complex models of the sort noted in Reference 1., with both RD&D costs and developed commercial article benefits treated with more realism, with a mix of technologies contributing to power generation, and with at least some primitive sense of how to treat supply and demand interactions actually present. Like all complex models, the energy models in question will produce imprecise outputs sensitively correlated with imprecise inputs. The danger is that the model outputs can be, prematurely, used to *infer* the RD&D emphasis which *ought* to be assigned to the several technologies, ignoring the fact that the evidence for any such assignment (e.g., by conclusions as to the predicted market shares which the technologies appear to be able to capture) is itself highly questionable until reasonably precise inputs are available to the model--inputs which *require* RD&D to make reasonably precise in the first place.

Some other important issues are cursorily commented upon in Figure 14.

These issues warrant much deeper investigation. They are all complex issues which must be considered in decisions on whether, and to what degree, intensive RD&D work ought to be pursued to develope, to a commercial level, the sorts of symbiotic mix technologies we have reviewed. Each of the four exemplar issues of Figure 14 already spans broad areas which merit active study--because existing analyses are not yet adequately persuasive to develop a reasonable consensus. For example, in comparing health and safety issues of symbiotic mixes with those of just converters, or LMFBRs, we need to make informed estimates both of the probabilities of complicated and different accident paths and the consequences of such accidents, assuming the inventories of hazardous materials unique to each device and the possible release paths for such materials. The comments in Figure 14 summarize brief subsidiary reviews of the four issues noted.

A cautionary remark is also in order. Even assuming quantitative convergence could be obtained on the final views resulting from in-depth investigations of issues such as are shown in Figure 14, as well as the kinds of economic comparisons we can make, we note that individuals and groups can, and do, *weigh* the *relative* importance of these central issues (for example: economic promise; proliferation risk; environmental hazard) differently. That is, one still has *subjective preferences* in decisions, a fact which in the end introduces all the complications of social preference theory into questions of energy technology choices.(3)

It usually comes as a disquieting shock to many technologists to find that the analytical machinery of social choice theory can illustrate, in a great many cases where multiple possible options can be

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3. See P-5912, "Energy Choices and Preference Relation Paradoxes," B. W. Augenstein, July 1977, and some few references therein.

ordered in preference, how it is essentially impossible to make the clean, wholly deterministic, choices which many technologists still implicitly believe ought necessarily to flow from a thorough, extensive program producing "perfect" information.

OTHER COMPARISONS – SYMBIOTIC MIXES

- HEALTH, SAFETY:
  - DOMINATED BY CONVERTER PART OF MIX
- PROLIFERATION:
  - MORE APPROACHES TO ALLEVIATE RISKS
  - BUT ALSO NEW RISKS - ACCELERATOR BRED FUELS
- COMMERCIALIZATION:
  - BULK OF MIX IS CONVERTERS
  - LOW DEPLOYMENT RATES NEEDED BY BREEDERS
- TRANSITION, TIME PHASING:
  - MIXES MOTIVATE CONVERTER IMPROVEMENT
  - BRIDGE BETWEEN FISSION, PURE FUSION
    (HYBRIDS USEFUL AT DEVELOPMENT LEVEL ALONG THE WAY TO, BUT FAR REMOVED FROM, PURE FUSION NEEDS)

Figure 14

We summarize the views of this paper in Figure 15. The reservation noted comes about because a national decision to pursue *any* breeder development currently remains in question. A personal conclusion is that we should actively preserve the breeding option as protection against unforeseen or dimly perceived contingencies. In this case, the "robustness" consideration provides a strong set of incentives to make external neutron source breeders--of which the Fusion Hybrid can be considered a prime example--an important component of any national program not solely preoccupied by internal neutron source breeders. Part of this robustness comes about because of the role advanced converters can play in symbiotic mixes. The development of advanced converters, ironically, can minimize our *near future* motivation to pursue breeding developments at all. But if the kinds of of symbiotic mixes we have discussed are successfully pursued, we would then have an *assured energy supply for a great many centuries.*

IMPRESSIONS

- IF THERE IS TO BE A NATIONAL PROGRAM FOR BREEDER DEVELOPMENT, EXTERNAL NEUTRON SOURCE BREEDERS MERIT INCLUSION IN THE RDT&E PROGRAM.
- ROBUSTNESS AGAINST CRITICAL PARAMETER UNCERTAINTIES SHOULD BE CONSIDERED IN DECISIONS ON RDT&E PATHS.

Figure 15

INTERDEPENDENCE ISSUES

The concept of a hybrid introduces issues, among others, of fission system programs and developments into a pure fusion program. This has a number of aspects producing mixed feelings in the fusion community; but these are aspects which that community ought to evaluate carefully.

There have been expressed concerns on the possible impact of pursuing fusion hybrid developments on the pure fusion program. In part, these concerns can be considered the normal concerns of an active RD&D community that the momentum and pace of the ongoing pure fusion program might be weakened by introducing additional development paths. Our opinion is that the hybrid, in a sound overall program, can *benefit* pure fusion development by serving as a naturally phased testbed, and at the same time *motivate* continuation of the pure fusion program because it can usefully (i.e., economically) exploit an *early* stage of achievement of the technical and engineering requirements necessary for a successful pure fusion program. The hybrid would then constitute a near future, deliverable product of a pure fusion program. In addition, a hybrid program would serve as part of the necessary effort-in-depth in the pure fusion program to develop, operate, and begin to adapt to prospective commercial use the machines which are to be the outputs of the pure fusion RD&D program. Opportunities to encourage advanced, longer time horizon, programs pressing on with more demanding fusion developments--for example, systems which are completely or nearly neutron free--could be furnished by a hybrid program. The hybrid can serve as a bridge or transition between the fission reactor economy and any pure fusion economy, and can, inter alia, serve to make that transition in a smooth, unforced fashion, independent of the possible time-phasing exigencies of either fission reactors or pure fusion machines.

In these senses, a hybrid can be viewed as complementary to, and not de facto competitive with, the pure fusion program.

Further, the hybrid exemplifies an important aspect of fusion systems which in any case warrants more emphasis. The hybrid uses the neutrons produced in the fusion reaction to first produce an intermediate product which is emphasized--in this instance, fissile fuel--rather than electrical power. Other potentially important uses of the fusion plasma neutrons include economic production of various synthetic fuels--e.g., hydrogen, as one example. The notion of the pure fusion machine producing *neutrons* as a generally useful commodity, applicable to many subsequent intermediate and end uses, seems destined to be one of importance comparable to the production of electricity which is the current prime focus for fusion application. As one important examplar of the general class of intermediate applications of fusion neutrons, the hybrid breeder would constitute a key development.

Finally, it is our view that a number of socio-political factors can link the future of fusion and fission programs. Both programs are examples of hard, large scale, technology. Both use reactions and embodiments which produce radioactive residues. Both will rely on an infrastructure of many comparable industrial suppliers of essential components and systems without which neither program can function. Both can be used, in varying degree and with different kinds of difficulties, to produce nuclear weapons materials. Both can intrude on the environment in ways which are felt to be non-benign by a substantial sector of the public (quantitative differences in the extent of environmental intrusion will not be persuasive to that sector). As much as the fusion community might like its future to be independent of the future of the fission community, these kinds of factors can quite likely work to make the futures interdependent. If the fission program continues to evolve, there will be a substantial public and private incentive to protect and realize returns from that investment. The pace of pure fusion deployment may then not be commensurate with the technical progress in the fusion field in any case. If fission development is stopped (for any reason other than, say, really persuasive economic ones), the sorts of factors listed above could result in a subsequent public transference of non-economic arguments against fission programs to the fusion program, leading to a comparable fate.

All this implies that, conceivably, fusion and fission programs may prosper or erode together. There are therefore incentives for the fusion community to lend support to the fission program. The hybrid could constitute one important means for such support, spanning issues of economics, technology, and public acceptance.

In short, the hybrid could provide an important complement to *both the fission and pure fusion programs*.

DR. RIBE: Fred Ribe, University of Washington. About the third viewgraph from the end, you had a statement about the applicability of fusion-fission to the pure fusion problem. I wanted to question specifically a qualitative statement you made there. "Hybrids are a bridge between fission and pure fusion; hybrids are useful at the development level along the way to but far removed from pure fusion needs." What do you really mean?

DR. AUGENSTEIN: The fuel values, materials, plasma conditions, a great many things.

DR. RIBE: That's what I'd like to question. I think the plasma physics that you have to do for hybrids as being identical to the plasma physics you need to do for pure fusion except, as everyone knows, it's simpler to do Q equal 1 than Q=ignition.

DR. AUGENSTEIN: I would disagree with that statement and one of the ways in which I would disagree with it is that, in this particular case, we're talking here about a fusion machine that generates around 300 megawatts of neutron power instead of 3,000 megawatts of neutron power.

DR. RIBE: Yes.

DR. AUGENSTEIN: And the blanket multiplication gives you the high heat production rate which you can use to generate some net electricity out of these systems, but it's a relatively small amount. There are a number of people that have designed hybrids, at least conceptually here, that I think are more competent to address this question; but the studies I've seen simply say that there are a number of important technical parameters which you can derate substantially in the case of a hybrid design.

DR. RIBE: Well, that's the point. It doesn't say that it's not on the path to pure fusion as far as the plasma physics and the fusion physics are concerned. Quite the contrary.

DR. AUGENSTEIN: Well, that's exactly what that statement says. It's along the way to but far removed from pure fusion needs.

DR. RIBE: Perhaps we're talking at cross purposes. It's far removed from end use but it is right on the way to it scientifically, in the sense that it's something that the pure fusion program is aimed at doing right now.

DR. AUGENSTEIN: I think that's exactly what that statement says.

MR. BOS: Piet Bos, EPRI. In looking at the net present value figures that you use, you discounted everything at ten percent. Are you including the effects of depreciation et cetera, in the financial calculations?

DR. AUGENSTEIN: Yes. There are a number of things which I think I commented on, that net present discounted value calculations have both pros and cons to them. Really, what you'd like to do is include a few more of the things that, for example, a utility planner really takes into account when he makes his financial decisions. This is only one of them and I would have to agree that this is a primitive tool but it is, nevertheless, a primitive tool that captures some of the cost stream aspects instead of just computing values at discreet times.

MR. BOS: However, the main aspect in this whole criteria is capital cost. When you start looking at this type of combination of symbiotic mix, depreciation becomes a very large factor.

DR. AUGENSTEIN: That is the biggest single factor that contributes to these costs and, particularly, if you use a 16 percent capital cost charge that we use.

MR. LOTKER: Do you use a 16 or 15 percent levelized cost of money?

DR. AUGENSTEIN: We use 16 percent.

MR. LOTKER: Well that includes depreciation then?

DR. AUGENSTEIN: That includes some of the depreciation but it doesn't capture all of the things that I think ought to be captured.

DR. ROSE: Pete Rose, Math Sciences. I'd like to follow up on Fred's comment. It seems to me that one of the underlying issues in this whole question of introduction of hybrids into the fusion program has been a general fear of the fusion community that the hybrids will be damaging to the role of pure fusion. Now, you didn't address that directly, and I think your last statement, which is the one that Fred picked up on, is in that same vein. He was arguing from the technological point of view, and I would agree with Fred. Is there anything in your study that has given you any insight from, let's say, an introduction or economic point of view, what the relationship between the hybrid and the pure fusion is?

DR. AUGENSTEIN: I think that's a very difficult question to try to answer reasonably and precisely but let me just say what my own feeling is. Since I'm not a proponent or an opponent of any of these technologies, just a studier of them, my feeling would be that the pure fusion program could benefit by having a hybrid component and it could benefit in two ways. One of them is that it's an opportunity to have a very useful test bed which you're going to need to carry on to the next stage anyway. And, secondly, you have a possibility of getting an early economic payoff from the whole program, rather than a later one. Now, I think you can adduce arguments of that kind which, at least to me, indicate that I think it would be beneficial to have a hybrid component in the fusion program.

Now, it's clear that there is not a unanimous opinion and you're exactly right. There are a lot of pure fusion people that regard this as a competitor rather than a complementary part of the program. I can't answer that.

DR. MANISCALCO: I guess I'll get in on this debate for a second, but I can see the possibility of hybrids competing with pure fusion. For example, one could choose a fusion source for a hybrid for size and geometry reasons even though it doesn't have the Q to allow generation of power with pure fusion. However, I think hybrids will be beneficial to pure fusion in spite of this. People seem to think there's only a fixed amount of money for fusion, and hybrids will compete for some of it. But I also believe that planners are starting to base their funding strategies on how many quads a new technology can produce in a given time frame. If you look at a hybrid that's making fuel for existing power producing systems, its quad impact in the same time frame as fusion is much larger. Therefore, a hybrid could actually justify a substantial increase in the fusion program's budget.

DR. AUGENSTEIN: I think I am inclined to believe all of those arguments. But first, I think, we have to persuade ourselves that introducing the hybrid would not damage the pure fusion program but it would help it in a great many ways.

MR. PALMER: Roger Palmer, G.E. Just a couple of comments. G.E. and Commonwealth Edison have done a number of cost benefit analyses for the LMFBR and some of your results look similar to the ones that we generated at the early stages of what we were doing, and I would just offer a couple of words of caution. First of all, there's been a lot of controversy over cost-benefit analysis and we're all sort of aware that it's good for certain points that you might want to make but it brings up other uncertainties that are always difficult to resolve. I would caution you on a couple of things. With high capital cost systems that breed fissile materials, it's very important how you handle inflation in the calculation. I drew two conclusions from what I saw in your results One is that we wouldn't agree on some of the sensitivities you found. One reason for that is that I believe your 16 percent charge rate has both depreciation and the normal utility rates in it and also implicitly has inflation. Do you actually inflate fuel costs for some of the higher fuel cost systems?

DR. AUGENSTEIN: Yes.

MR. PALMER: You have to be sure you do.

DR. AUGENSTEIN: Of course.

MR. PALMER: Furthermore, in addition to the charge rate, your discount rate implicitly includes an inflation effect too.

DR. AUGENSTEIN: I think we have handled all of those things.

MR. PALMER: Okay.

DR. AUGENSTEIN: Not precisely the way a utility would handle it but I think reasonably well.

MR. PALMER: Okay. Well, in any event, when we've done it, with Commonwealth Edison, our results come out considerably different.

ECONOMIC REGIMES

D. E. Deonigi
Battelle Pacific Northwest Laboratories
Richland, Washington 99352

We at Pacific Northwest Laboratories (PNL) have been carrying out cost-benefit analyses similar to those RAND has conducted, only using more elaborate models. Basically, our models are the same ones used to do the cost-benefit studies for the LMFBR, so there should be strong consistency in the kinds of numbers that the fission community is coming up with for this comparison with hybrids.

This same model, the Alps model, was also mentioned yesterday in regard to the NASAP Project. Only minor equation differences exist between the two systems, so you can expect the results that we see as I go through my discussion to be mirrored in the future results of that study.

It's been mentioned innumerable times here already that the problems and uncertainties of estimating capital costs are very great. To deal with these problems, we decided to aim at defining performance targets or allowable capital costs. In that way, we would give the designer an idea of what's allowed, if he's going to enter the market and be really useful to the utility system in an economic sense.

In our discussion today, we want to look at the effects of entering the market at different points and what it takes to go beyond market entry and produce measurable national benefits. We want to identify reasonable estimates for plutonium value and U_3O_8 costs that can be used in point studies in which designers try to calculate the cost of power and benefits without getting into a large integrated model. And, finally, we want to look at some factors about the introduction date.

To review briefly (because most of you have heard this story before), the model has to cover a long-time period—perhaps 70 years as the RAND does. The prime difference is that the PNL model minimizes costs over that period and derives the mix of plants continuously and does not predetermine it.

The PNL model maintains a very detailed balance on fissile stockpiles. Uranium prices increase only with resource consumption. There's no predetermined U_3O_8 price increase. We consider both fossil and nuclear plants in the system, and I think this alternative generally causes our numbers for allowable costs to come out lower than other people's. For instance, a very high—$300—uranium price could mean that the light-water reactors aren't in the market place.

The PNL model deals only with base-load plants and includes introduction constraints based on the history of new technologies and some phase-out constraints, which have to do with the competition provided by the existing technologies in all cases.

As Table 1 indicates, the reactors in this system are the light-water reactors, plutonium and uranium types; the LMFBR, in this case about a 12-year doubler which is probably an optimistic representation for the LMFBR; the pure CTR, of course, which doesn't involve fission; hybrids, which can have a range of performance that we'll look at parametrically; and fossil-fired plants. The key item in this table, capital costs, as we mentioned before, increases $100 with the LMFBR over the light-water plant. These costs are in 1975 dollars, so they look little smaller than some of the other numbers you've been seeing.

The costs for the CTR are actually target costs, not derived from any individual estimate but necessary for the CTR (this is a pure fission machine) to be competitive with the other systems.

A typical result is shown in Figure 1 for the case where we do not have any hybrids in the system. I think this figure is basically consistent with Dr. Bos' supply projection, with the difference being that our calculations show there is no real problem in terms of the LMFBR's share of the market caused by plutonium availability. I think that only in the area of new technologies are our two figures fundamentally different.

The interesting outcome when we put a high-performance hybrid in the the system was the light-water reactor as the big winner. In fact, one of

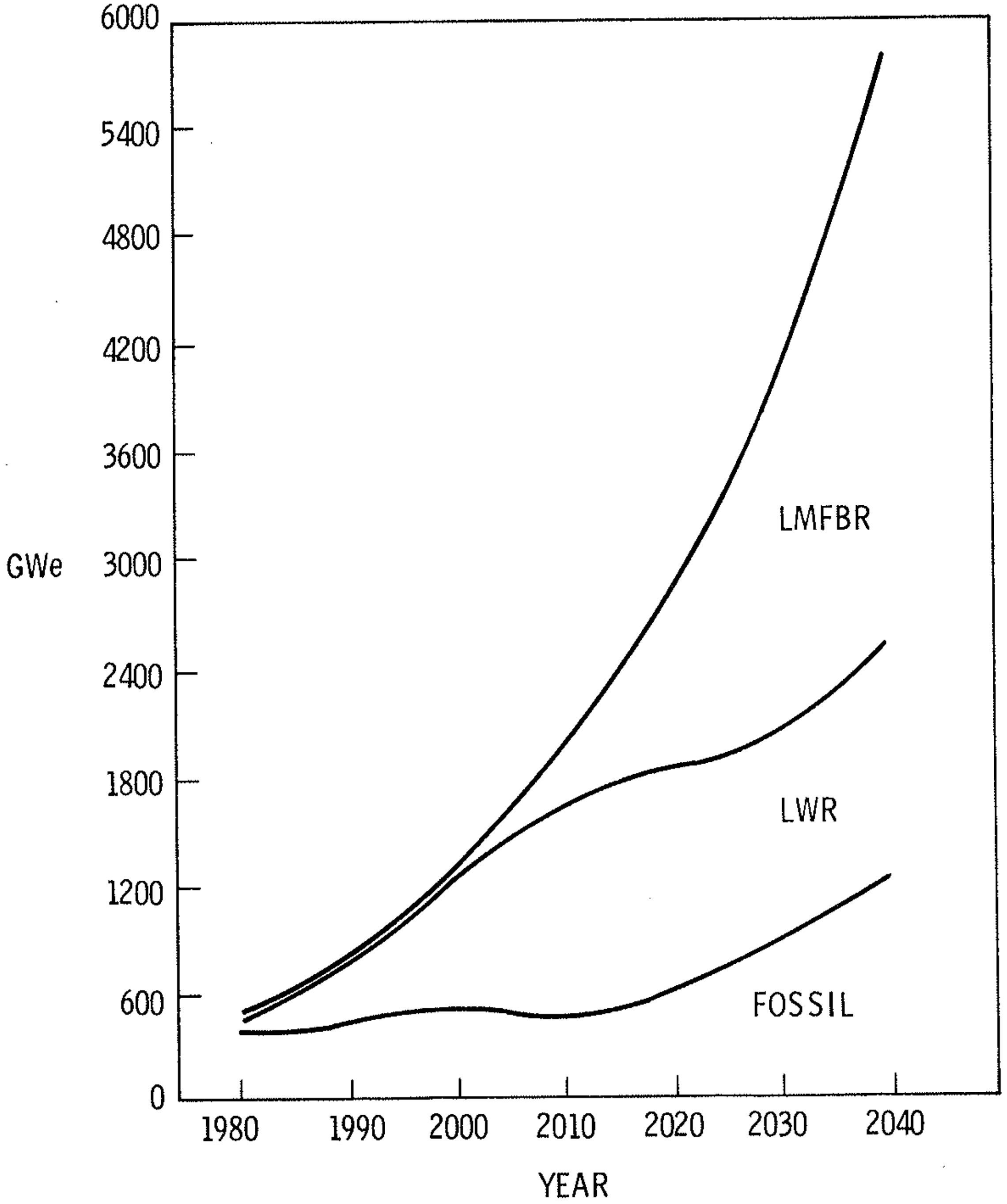
TABLE 1

CHARACTERISTICS OF ALTERNATIVE ENERGY SYSTEMS POTENTIALLY AVAILABLE IN 2000

	LWR URANIUM	LWR PLUTONIUM	LMFBR	CTR	HYBRID	COAL
ANNUAL PLUTONIUM YIELD, kg/MWt	0.069	-0.128	0.142	0	0.5 → 1.5	0
INITIAL PLUTONIUM REQUIREMENTS, kg/MWt	0	0.403	0.684	0		
ANNUAL U_3O_8 REQUIRED, TONS/KWt	0.075	0.012	0.001		0	
ANNUAL SEPARATIVE WORK REQUIRED, kg/MWt	48	2.3	0.080		0	
^{6}Li (ANNUAL), kg	0	0	0	140	~50	0
ANNUAL NUCLEAR FUEL PROCESSED, kg/MWt	12	12	9.5	0	~20	0
TONS COAL (LIFETIME), TONS/MWt						18 THOUSAND
ELECTRICAL-TO-THERMAL EFFICIENCY	0.325	0.325	0.38	0.40	-0.20 → 0.40	0.40
CAPITAL COST, $/KW (1975 DOLLARS)	640	640	740	770	VARIABLE	550 +$5 MILLION/YR OPERATING COST

FIGURE 1

FORECASTED OPERATING ELECTRICAL GENERATING CAPACITY FOR LOW DEMAND GROWTH WITHOUT HYBRID



the major reasons for pursuing the hybrid program is that it allows us to capitalize on existing technology. And you can see from Figure 2 that LWR technology is capitalized on substantially. It's inherent in all of these studies that large numbers of hybrids are never built because typically one is built to support as many as eight light-water reactors in the system.

The LMFBRs did enter the system in this particular case but were phased out after the hybrid became available.

Another result is that the model calculated uranium prices based on consumption. As a result, we ended up with a function shown in Figure 3—the solid line—which indicates the expected price for U_3O_8 as a function of time. The subject of benefits comes up here because the zero-benefit line represents the case that produces no benefits. That is, the technology could be introduced, but it wouldn't actually reduce the cost of energy.

The zero-benefit line in Figure 3 would represent the point of initial market penetration possibly by an aggressive vendor or some combination with the utilities. However, as better systems come along, they will produce net benefits. This is the same kind of present-worth benefit that was talked about before, discounted at 10%, including all the depreciation terms and other financial considerations. Bascially, they hybrid is good enough to displace uranium consumption and hold the uranium price down, in part, ruining its own market. The benefits are realized by displacing uranium use.

Similarly, you can forecast a plutonium price that will rise with time as the uranium price rises. But when we get a satisfactory hybrid in the system, we can expect some drop in that price as the plutonium becomes available, and its price no longer follows the U_3O_8 track. The case here, again, is that if you're going to have a hybrid that's good enough to produce benefits on the order of $10 billion, to repay the R&D program costs, the price of plutonium again has to drop to these levels. That means a mature system operating in these plants—maybe 10 or 20 years after its introduction—should be able to produce a product costing about $40 a gram.

FIGURE 2

FORECASTED OPERATING ELECTRICAL INSTALLED CAPACITY (GWe) FOR LOW DEMAND GROWTH WITH HYBRID ($10 BILLION BENEFIT)

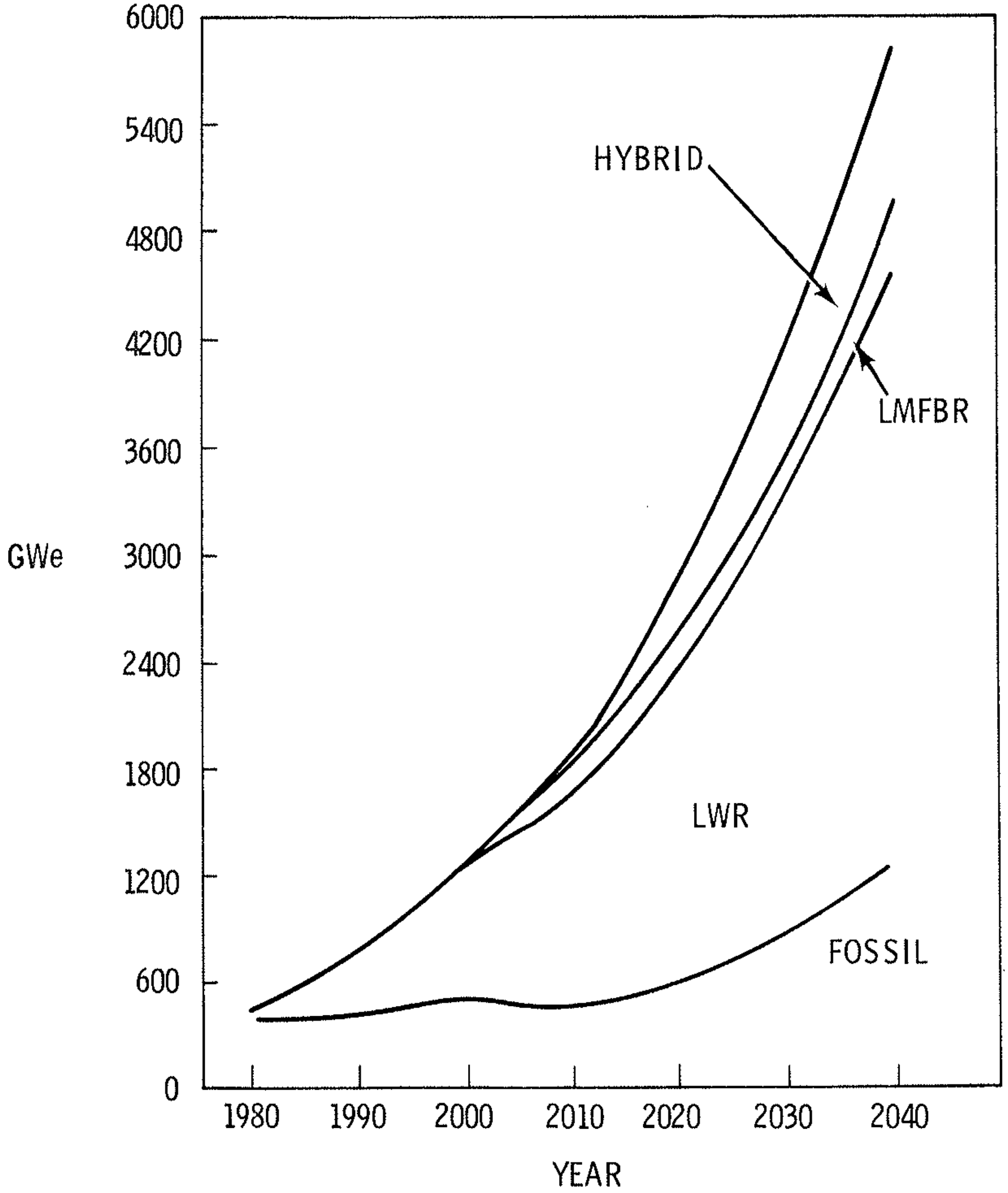
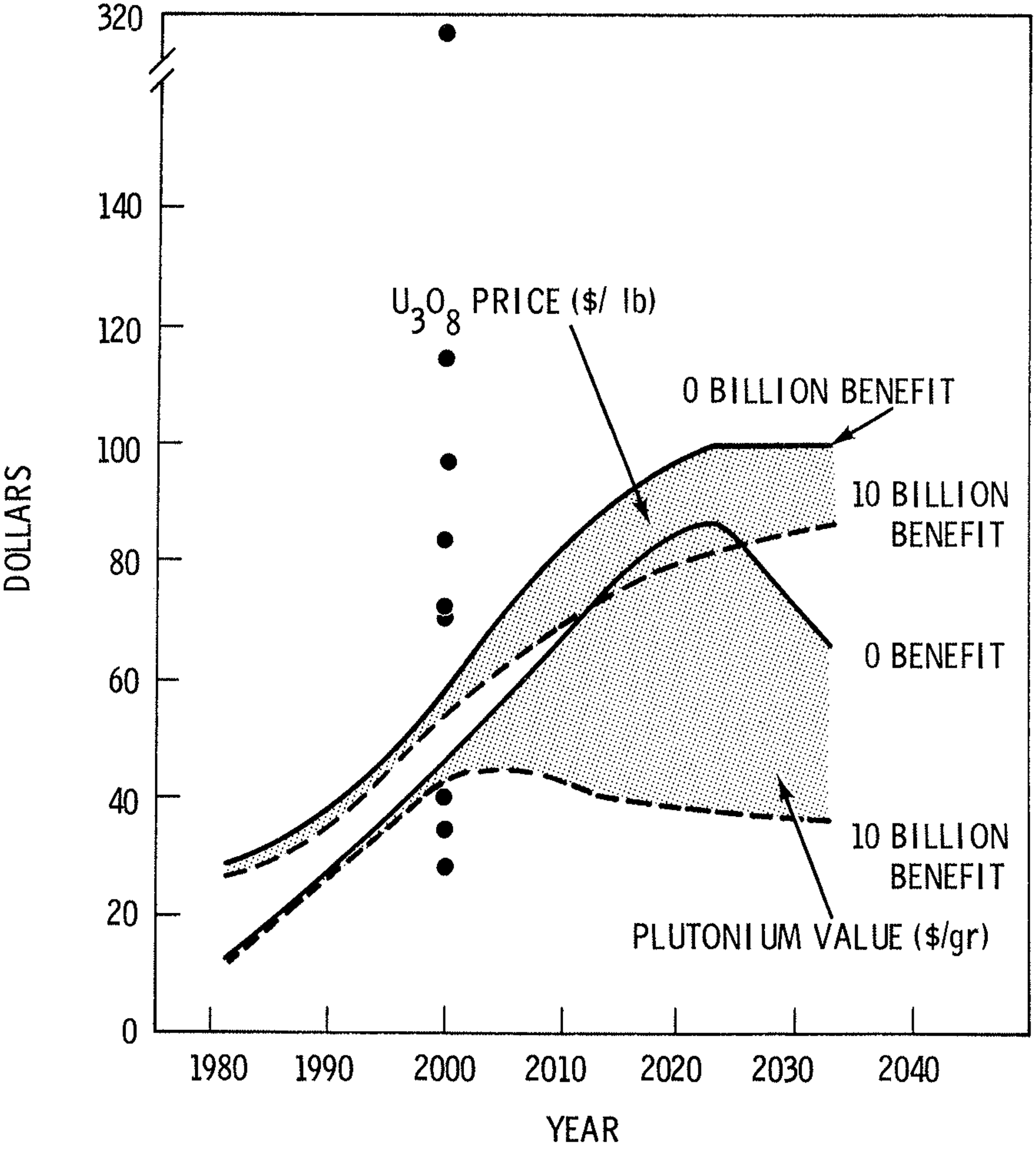


FIGURE 3

FORECASTED PRICES WITH LOW DEMAND GROWTH AND WITH LMFBR



To give you an idea of what current studies are, the dots in Figure 3 represent plutonium costs from various studies published, without naming names. Some of them, obviously, are in the range of acceptability, based on those studies' estimates at this time; a few of them are pretty close; and a few of them seem out of the running.

As an aid to designers in resolving the problem of whether hybrid plants should produce electricity or fissile material, our parametric analysis yields data like that shown in Figure 4, where the annual production of fissile material is compared to capital costs for various net efficiencies. The net efficiencies in the below-zero range represent the electric breeder class where electricity is actually invested in order to produce fuel. This may also be the case for the accelerator breeders in many situations. As you can see, in those cases, unless the production is quite high, the allowable capital costs, in terms of light-water equivalence, are very low and probably impractical.

Typical design parameters for hybrids that we've seen, produce about one kg/MW and give efficiences around three-tenths, which result in allowable costs around 1.75, relative to light-water costs as shown in Figure 4.

Now, for a plant producing a kilogram-for-megawatt thermal year, we looked at some of the possible variations and sensitivities when we do produce a $10 billion benefit, and the result is that the target costs fall in the range around 1.5, as Table 2 shows.

In this case, we commissioned fusion plants 10 years after the hybrid was available, and it was surprising to see that there wasn't much of a change in the LWR equivalence. There was quite a reduction in the number of plants built, however, and not much of a change in the plutonium value because the hybrid, in this case, served the market of light-water plants in operation at that time. That was and is a significant market and is part of the value of the hybrids. It doesn't matter what new system comes in—whether solar or pure fusion—the window to serve that market exists forever.

FIGURE 4

ALLOWABLE CAPITALIZED COST FOR FUSION-FISSION SYSTEMS (2000) THAT YIELD ZERO BENEFIT WITH LMFBR (1992) - WITH CTR (2010)

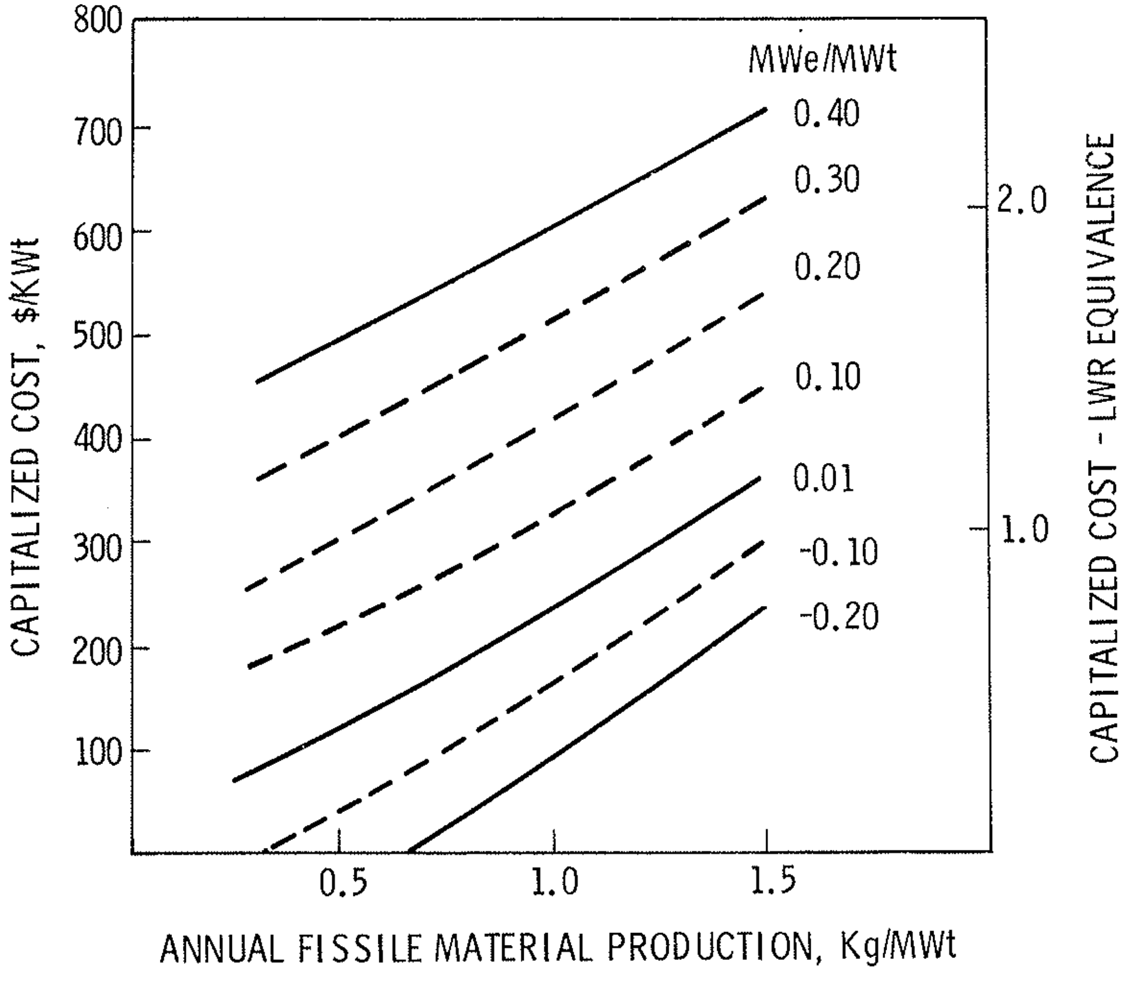


FIGURE 2

EFFECTS OF CTR AVAILABILITY (LMFBR - 1993, CTR - 2010)

	CTR	NO CTR	CHANGE MAGNITUDE
FUSION-FISSION 30-YEAR COST ($/kWt)	500	465	15
LWR EQUIVALENCE	1.45	1.5	0.05
U_3O_8, REQUIRED (MILLION TONS) BY 2040	4.0	3.9	0.1
PLUTONIUM VALUE, 2020 ($/g)	38	38	0
FUSION-FISSION CAPACITY, 2030 (GWe)	190	1036	846

Table 3 shows that by introducing the hybrid 10 years sooner, we've reduced our uranium consumption. But again, allowable cost is not very sensitive. By introducing hybrids sooner, fewer plants have to be built to achieve the same level of benefits. An early introduction, however, doesn't mean that more plants wouldn't be built in a competitive system. It just means that as many wouldn't have to be built to achieve a $10 billion benefit.

Another problem to deal with is growth, because if there isn't growing demand for electricity, the requirements for breeding systems and systems that don't use uranium as much are substantially reduced. Table 4 shows the effect of the existing light-water system. If we look at a lower demand, the allowable cost changes only slightly from 1.5 to 1.4. With lower demand, of course, less uranium is consumed, but actually the number of plants built is virtually the same. So hybrids are demand-insensitive because of the existing light-water market.

Let's look now at the uranium cost schedules shown in Table 5. If we take the uranium costs that we've been using which yield numbers as high as $100 a pound for U_3O_8 by year 2000 and cut those numbers in half, we find out that we consume a lot more uranium than Boyd said yesterday exists because it's cheaper and there's a much larger light-water market, but we build about the same number of hybrids. They simply get built somewhat later because in the case of low uranium cost and low demand, utilities simply wait longer before these plants are economical.

By far the most sensitive parameter that we've found is the removal of the LMFBR, as Table 6 shows. If we assume that it is not available or, equivalently, that its costs are 20% higher than we now have in the system, though both produce the same outcome, the allowable costs go up considerably, up to 2.2 times the cost for light-water reactors.

This is a significant factor as far as allowable costs are concerned. I think, in geneal, these are, of course, closer to what we have seen, but it makes the allowable costs for hybrids sensitive to the allowable costs for LMFBRs, in effect. And then we need to look at the comparison

TABLE 3

EFFECTS OF FUSION-FISSION AVAILABILITY DATE (LMFBR - 1993, NO CTR)

	1990	2000	CHANGE MAGNITUDE
FUSION-FISSION 30-YEAR COST ($/kWt)	480	465	15
LWR EQUIVALENCE	1.55	1.5	0.05
U_3O_8, REQUIRED (MILLION TONS) BY 2040	3.0	3.9	0.9
PLUTONIUM VALUE, 2020 ($/g)	37	38	1
FUSION-FISSION CAPACITY, 2030 (GWe)	374	1036	662

TABLE 4

EFFECTS OF ENERGY DEMAND (LMFBR - 1993, NO CTR)

	MODERATE HIGH	LOW	CHANGE MAGNITUDE
FUSION-FISSION 30-YEAR COST ($/kWt)	465	435	30
LWR EQUIVALENCE	1.5	1.4	0.1
U_3O_8, REQUIRED (MILLION TONS) BY 2040	3.9	2.9	1.0
PLUTONIUM VALUE, 2020 ($/g)	38	36	2
FUSION-FISSION CAPACITY, 2030 (GWe)	1036	830	206

TABLE 5

EFFECTS OF URANIUM COST SCHEDULE (LMFBR - 1993, NO CTR)

	REFERENCE SCHEDULE	LOW-COST SCHEDULE	CHANGE MAGNITUDE
FUSION-FISSION 30-YEAR COST ($/kWt)	465	435	30
LWR EQUIVALENCE	1.5	1.4	0.1
U_3O_8, REQUIRED (MILLION TONS) BY 2040	3.9	5.9	2
PLUTONIUM VALUE, 2020 ($/g)	38	37	1
FUSION-FISSION CAPACITY, 2030 (GWe)	1036	995	41

TABLE 6

EFFECT OF LMFBR AVAILABILITY (LMFBR - 1993, NO CTR)

	NO LMFBR	LMFBR	CHANGE MAGNITUDE
FUSION-FISSION 30-YEAR COST ($/kWt)[a]	680	465	215
LWR EQUIVALENCE	2.2	1.5	0.7
U_3O_8, REQUIRED (MILLION TONS) BY 2040	6	3.9	2.1
PLUTONIUM VALUE, 2020 ($/g)	74	38	36
FUSION-FISSION CAPACITY, 2030 (GWe)	380	1036	656

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[a] INTRODUCED IN YEAR 2000 AND YIELDS 10 BILLION DOLLARS BENEFIT.

between the cost estimates in similar situtions for the two plants in order to draw any real conclusions.

As you can see from Table 6, without the LMFBR, we get higher plutonium prices and fewer plants, but that's fewer plants to produce a $10 billion benefit. It isn't to say there wouldn't be more plants built if, in fact, this situation exists.

We've analyzed just a few situations dealing with producing U-233 instead of plutonium, and some of the non-proliferation and denatured cycles. In some cases we allow the HTGR in the system as a user of the U-233 and, in those cases, the allowable costs move from the 2.2 point up to 2.5 for about a 15% increase in the allowable cost as Table 7 shows. The value of fissile material increases 40%. The 40% change is fairly consistent with most other studies comparing plutonium and U-233 based simply on thermal reactor properties.

Most of the studies I've seen to data that look at producing U-233 in hybrids in place of plutonium tend to show cost increases greater than 15%, although this does give you a little bit of cushion when you're looking at non-proliferating cycles.

That wraps up what I had to say here. We've been trying to establish allowable cost numbers. I think our numbers come out a bit lower than those of other investigators who look at direct comparisons between light-water reactors and hybrids, because we get into scenarios where the light-water reactor may not exist. In many of our cases, the dominant system that comes in when the pessimistic hybrid cost numbers are put in is coal. Without considering coal, you can get numbers that are 50% higher than ours in terms of allowable costs, but I don't know that they're very real, unless there are severe limitations on the availability of coal.

TABLE 7

COMPARISON OF U-233 VS Pu PRODUCING HYBRID

SYSTEM	ALLOWABLE COST, LWR EQ.	FISSILE PRICE (2020), $/g
Pu → LWR	2.2	85
^{233}U → HTGR	2.5	110
CHANGE	15%	39%

MR. HEAD: All right, questions from the audience.

DR. MANISCALCO: Jim Maniscalco from Lawrence Livermore Laboratory. Last year at the Fusion-Fission Hybrid Symposium I asked you a question about at what point your model predicts that an LMFBR will and will not go into the market. At that time, you indicated that market penetration doesn't occur when the LMFBR is about 20 percent more expensive than a light water reactor. Is that correct?

DR. DEONIGI: I can confirm that now, yes.

DR. MANISCALCO: Yes?

DR. DEONIGI: No, I'm sorry. It's 20 percent more than what we have in here now, which is 15 more for a total of 35 percent.

DR. MANISCALCO: How does that stack up with fairly comprehensive studies that show that LMFBRs can penetrate the market with costs up to 50 and 60 percent more than a light water reactor. Can you give me a reason for the discrepancy with your results because I think they also consider coal.

DR. DEONIGI: Yes, some of their studies do and some don't. I think that in the recent cost benefit studies they did, 90 percent of the cases did not consider coal. I think the difference between 35 percent and 50 percent is probably small enough so I wouldn't want to argue. We said in the paper before Bruno's (Augenstein) numbers came out that if you had the 1.5 you ended up with breeders with no benefits but at 1.3 it looked better and so it's certainly in that range, 1.3 to 1.5. Ours is 1.35, as we see as the cross-over point, and Bruno's must be in that range also.

DR. HOLDREN: John Holdren, Berkeley. You talked a lot more about sensitivity of your results to the assumptions used than most people do and I think that's good, but it wasn't entirely clear to me how broad a range of all of the parameters you investigated. The one I'm most interested in is the growth rate.

On one of your early graphs you showed a total capacity of about 5700 electrical gigawatts in 2040. This is on the order of ten times today's capacity. Now, I think nobody knows what things are going to look like 60 years from now, but one real possibility is that the electic capacity then might be only two or three times today's.

Did you go nearly that far in exploring the sensitivity of these results to growth rate?

DR. DEONIGI: No, we didn't go that far.

DR. HOLDREN: How far did you go?

DR. DEONIGI: The growth rates in our base case were about five percent up to the year 2000 and about four percent thereafter. And then in our low demand case, those were both lowered by about a percent in both time regimes.

DR. HOLDREN: How hard would it be to explore a lower rate? A problem with many studies in this area is looking at too narrow a range of future growth. Would it be expensive for you in terms of computer time to investigate what happens at considerably lower growth rates?

DR. DEONIGI: No, that would not be expensive to do. However, I would point out that one of the conclusions we came to on the low growth is the phenomena of the light water reactors that are already there. And so when you lower growth, of course, you affect LWRs. But that market just stays there all the time and needs to be served.

MR. GOODRICH: Bob Goodrich from Northeast Utilities. The last two papers in terms of what our utilities would like to see, are garbage.

Now, if you'll let me dig myself out of a hole, I'll explain. I think what you are doing, in both cases, although I don't know the details of your model, is using a linear program and looking at shadow-type prices. You are also using the levelized annual premiums over the 30-year life of a device rather than the year-by-year cost.

You can show benefits in many cases, over a 30-year life, but when a company has to install a particular plant, they'll go broke in the first four or five years. The effect of cash flow is not included in any of the work that you've done. Is there any -- and I'll ask this of both the previous speakers -- is there any thought of going into more detailed year-by-year costs as opposed to the average costs? The year-by-year costs are more meaningful to a utility who has to provide the capitol, has to get money from his rate payers, and has to provide a return to the stockholder.

DR. DEONIGI: I believe that the results that we've produced, like those for the breeder studies, do sometimes go through the first few years where you may have a net negative flow there; but I believe that that might persist for maybe five years, and then it's expected that the net effect of that technology on the utilities would be positive. I think this is, unquestionably, a real problem;, that you've got to suffer through that introduction period and whether it's the vendor who takes the loss or whether the utility does, or whether the government subsidizes it during that period in some fashion, I think is a tough question still. But I think invariably you do get what we call the learning effect, that you expect those first plants -- the first five or ten plants -- to be substantially more expensive.

And the only reason the utility would get involved is that they would also have to anticipate future plants would be less expensive.

MR. GOODRICH: I'm speaking about the costs -- the cash flow for a particular plant, even if it is cheap in the long run.

DR. DEONIGI: Okay. You're not looking at the integrated utility.

MR. GOODRICH: No, because I have a company which has to build one plant and has to raise the cash to pay for that particular plant.

DR. DEONIGI: In some of the risk sharing techniques though, if you're a utility and you've got that one plant and if you're being subsidized by some larger group.

MR. GOODRICH: It doesn't matter whether it is one utility or a group of utilities. During those first few years, the company may go broke putting in this very high capital cost plant because it can't get the money from the rate payer.

MR. LOTKER: Bob, an option may be for the government to own the plant and sell you enrichment services which is exactly what they're doing today.

MR. PALMER: Just a quick one. Roger Plamer from G. E. again. I guess my conclusion from all of this is that I agree with quite a few of the things you've said here. I think that in some cases, your case can be stronger. I think we need to talk more. We have a lot to share from both the utilities we've worked with in the cost benefit work and the proper treatment of the financial work. I brought one paper along, for instance, that addresses the issue of capital costs and, as you suggest, it treats these in terms of the actual cash flow. We do it on a five, ten, fifteen or twenty year basis and we'd be more than happy to share that with you and I think you can benefit from it as well as we can.

DR. SCHULTZ: Ken Schultz, General Atomic Company. Duane, if I understand it correctly, in your model you have essentially restricted the system to provide no more than a $10 billion net benefit. I think that that gives erroneus impressions, in many cases, by artificially restricting the potential of a given scenario. Can you explain why you've restricted benefits that way?

DR. DEONIGI: Because we're trying to estimate the target costs, the cost level you have to get down to to be interesting. If we allowed the benefits to go higher, then basically, that cost number would come lower.

DR. MOIR: Ralph Moir, Lawrence Livermore Lab. We've been hearing at this meeting quite a lot about non-proliferation and uranium 233. The last slide kind of treats this comparison. Would you comment on the sluggishness of the system to introduction rates and the cost of development of bringing on an industry that has to do with, say, THOREX rather than PUREX and the whole issue of a new fuel cycle and maybe even fission reactors that we don't have now in the system, that would burn the U-233?

DR. DEONIGI: The investment that has to be made, both by the government and the vendors to bring on that kind of technology is very large. That's why, in effect, we steered away from doing that and it was only when the proliferation issue subjects came up that we looked at it at all. Because I think one of the -- the number one thing that's been said here enough times already -- the prime values of the hybrid technology is to allow the utilization of the light water technology in its full, most extensive fashion, something the utilities at least have some comfort and understanding right now.

MECHANICAL AND THERMAL DESIGN OF HYBRID BLANKETS

BY

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December 27, 1977

MECHANICAL AND THERMAL DESIGN OF HYBRID BLANKETS*

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ABSTRACT

In this paper the thermal and mechanical aspects of hybrid reactor blanket design considerations are discussed. This paper is intended as a companion to that of J.D. Lee of Lawrence Livermore Laboratory on the nuclear aspects of hybrid reactor blanket design.[1] The major design characteristics of hybrid reactor blankets are discussed with emphasis on the areas of difference between hybrid reactors and standard fusion or fission reactors. Specific examples are used to illustrate the design tradeoffs and choices that must be made in hybrid reactor design. These examples are drawn from the work on the Mirror Hybrid Reactor.[2]

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* Work done under United States Energy Research and Development Administration contract number EY-76-C-03-0167, project agreement 38.

INTRODUCTION

The fusion-fission hybrid reactor concept has a number of unique features, combining various aspects of both fusion reactors and fission reactors. The principle role emerging for hybrid systems appears to be the breeding of fissile fuel for subsequent use in fission reactors. The hybrid appears to enjoy a number of potential advantages for use in this role. Because the blanket is driven by the fusion source it can be highly subcritical. Because of the large number of neutrons released by fission of ^{238}U by 14 Mev fusion neutrons, the amount of fissile fuel bred per fusion neutron incident upon the blanket can be substantial. System economic considerations appear to require that the blanket thermal energy be recovered and converted to electricity.[3] Thus, a hybrid reactor blanket in general must be designed to produce three products, fissile fuel, tritium to fuel the fusion driver and high grade heat. The design of the hybrid blanket is strongly influenced by the desire to produce these three products, and especially by the desire to maximize the amount of fissile fuel produced.

The nuclear design of hybrid reactor blankets was discussed in the companion paper by J.D. Lee.[1] In this paper the mechanical and thermal aspects of hybrid reactor blanket design will be addressed. Areas specifically to be covered include the selection of the blanket fuel and structural materials, the mechanical design of the blanket itself and the thermal-hydraulic design of the blanket fuel zone. Hybrid blanket design choices will be illustrated with examples from the recent work done by General Atomic Company and the Lawrence Livermore Laboratory on the design of a commercial Mirror Hybrid Reactor.[2]

SELECTION OF BLANKET MATERIALS

The selection of the materials for use in the hybrid blanket is strongly influenced by the characteristics of the hybrid reactor and the desire to maximize the bred fuel that is produced.

Coolant

Helium is favored for the blanket coolant because it does not degrade the neutron spectrum thus allowing a high blanket breeding ratio to be attained. Helium allows operation at high temperature for good pwoer conversion efficiency at modest pressures. Helium is chemically stable and non-corrosive, which is important for reasons of safety and operability. Further, helium is not electrically conductive, which is important for avoiding magnetic effects in magnetically confined fusion systems. CO_2 also enjoys some of these advantages. Its low specific heat may actually be advantageous for hybrid blankets where adequate Reynolds number may be difficult to achieve. Chemical compatibility at elevated temperature, radiolysis and flow induced vibration due to high Mach number flow with CO_2 should be given careful consideration, however, before CO_2 is used.

Fission Fuel Material

In selecting the fission fuel material for the hybrid blanket several reactor characteristics are important. The fuel density should be as high as as possible to maximize the fuel to structure ratio, minimizing spectral softening and parasitic absorption, and thus maximizing fuel breeding. In order to minimize the amount of structural material in the blanket, large diameter fuel rods are desired since with a constant cladding thickness the fuel to cladding volume ratio increases with increasing rod size. The desire for large diameter fuel rods implies the need for high fuel temperature capabilities although at some point the cladding temperature becomes limiting. Fuel irradiation stability is also important, although economic optimization favors frequent removal of the fuel to sell the bred fissile material and thus the peak burnup required of the hybrid fuel appears modest. The properties of a wide range of fuel material candidates are shown on Table 1. Although the metallic uranium alloys have the highest densities, they also have the most restricted temperature and burnup limits. On the basis of neutronic and economic analyses the uranium alloy uranium silicide (U_3Si) was chosen as the fuel material for the Mirror Hybrid Reactor. U_3Si has been developed for the CANDU reactor program[4] and has been irradiated up to 2.5% burnup with very low swelling. U_3Si has a high uranium density, low parasitic absorption and good irradiation stability at temperatures up to 900°C.

Structural Material and Cladding

In order to optimize the hybrid blanket neutronic performance, the amount of structural material in the blanket and the thickness of the first wall must be minimized. This requires a structural material that exhibits high strength at elevated temperature and also has good irradiation life. Inconel-718 was chosen because it enjoys these characteristics. The design strength is in excess of 400 MPa (50,000 psi) to above 600°C, as shown in Figure 1. Radiation-induced swelling is expected to be quite low on the basis of experimental data from irradiations of Inconel-718 and the similar alloy PE-16 in HFIR[5] and EBR-II[6]. The EBR-II data are shown in Figure 2. For irradiation temperatures in the range 320°C to 700°C radiation embrittlement of Inconel-718 is not expected to be a problem based on HFIR irradiation

TABLE 1

PROPERTIES OF FUELS

	U (modified)	U-10 Mo	U-5Fs (EBR-II Fuel)	U_3Si	UC	UO_2	Th	ThC	ThO_2
U-density (g/cm^3)	19.04	17.12	18	15.5	12.97	9.65	11.7	10.96	10.0
Melting point	1133°C	1150°C	1002°C	930°C	2400°C	2800°C	1845°C	2625°C	3300°C
Max. operating temperature	610°C	700°C	660°C	900°C	2000°C	2400°C	1000°C	1100°C	1500°C
Thermal conductivity (w/cm°C)	0.40	0.29	0.33	0.21	0.25	0.29	0.42	0.29	0.021
Irradiation swelling at 1% bu, volume %	3%	6%	4%	1%	1% (< 900°C)	0.4% (< 1500°C)	1 to 2%	1%	< 1%

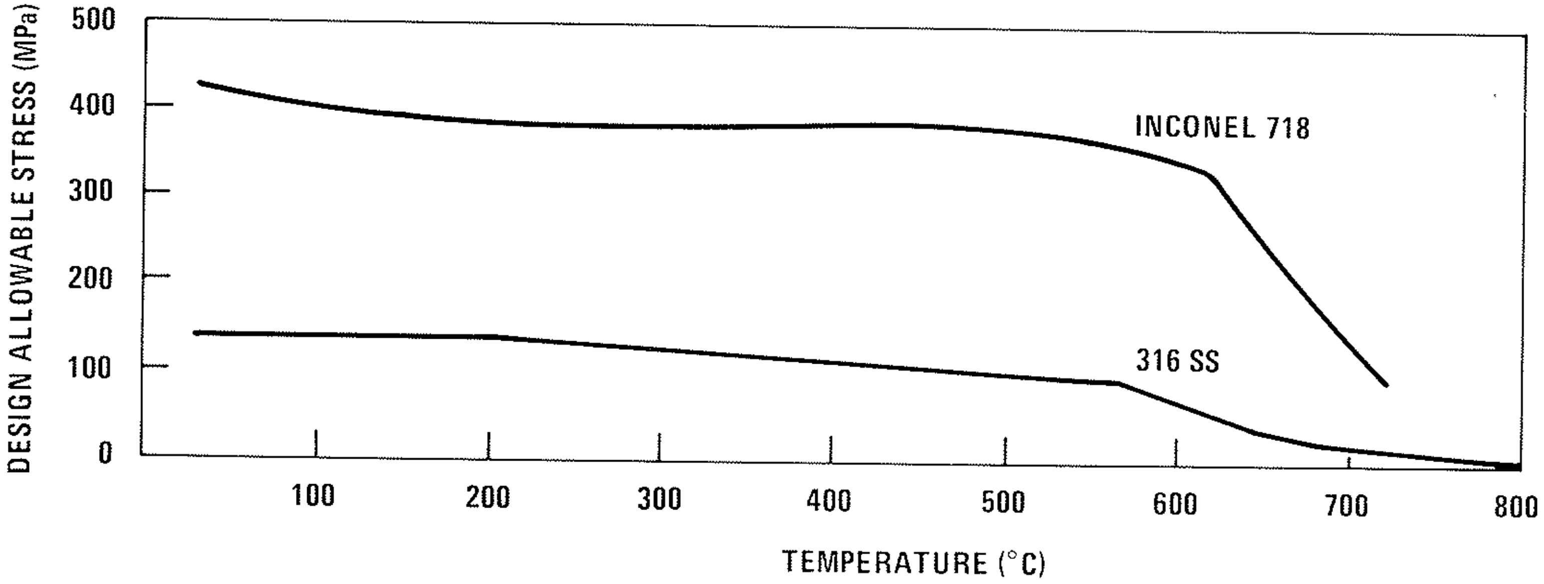

Fig. 1 Design strength of Inconel-718

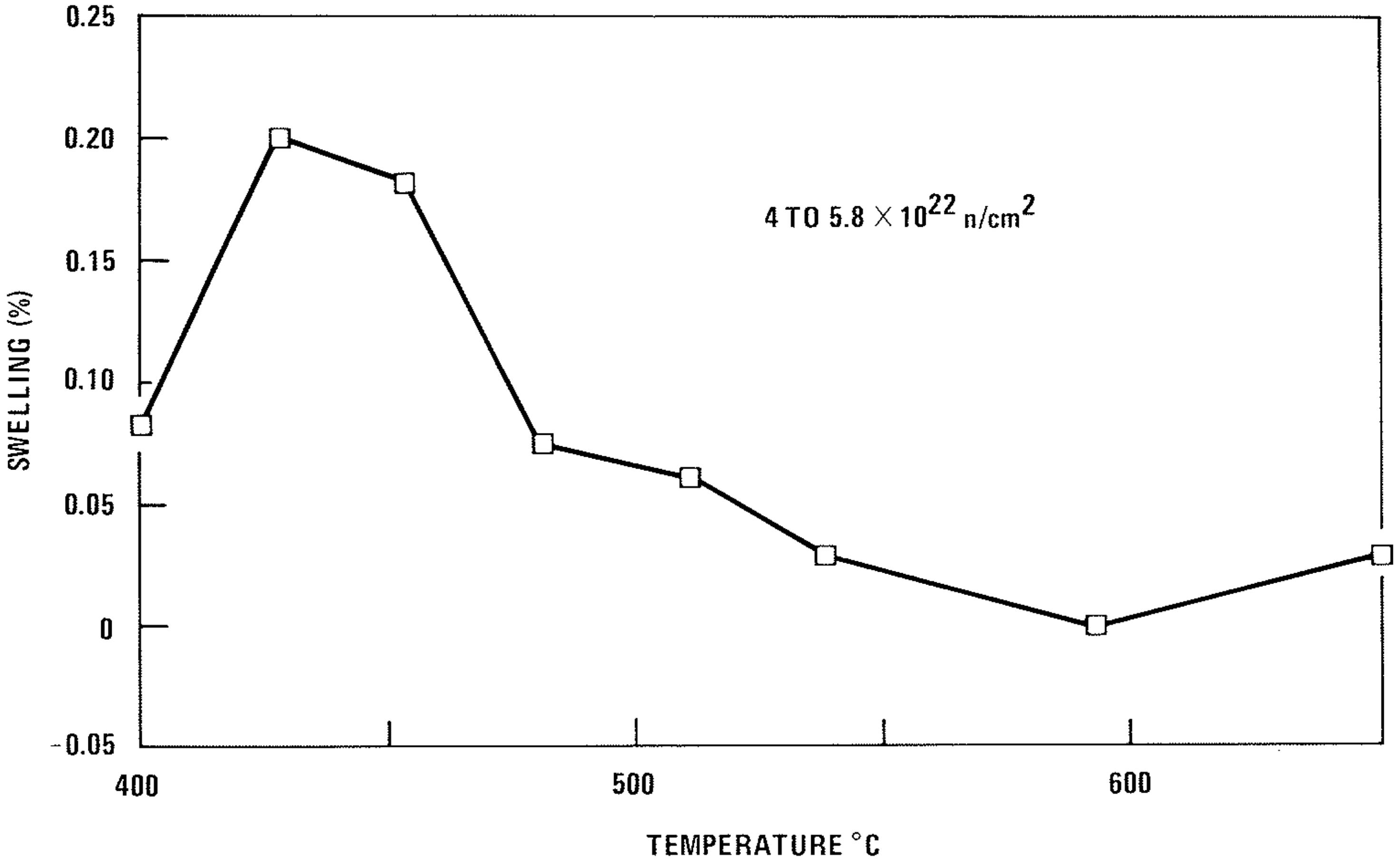

Fig. 2

Swelling of solution treated and aged Inconel 718 as a function of temperature after EBR II neutron irradiation to 4-5.8 x 10^{22} n/cm^2 (E > 0.1 MeV) (Ref. 6).

data for the similar PE-16 alloy shown on Figure 3,[7] which shows at least 1% residual ductility after the radiation equivalent to about 6 MW-yr/m^2 Data from EBR-II irradiation indicate that 630°C may be a safer temperature limit to insure adequate residual ductility.[8]

We have chosen Inconel-718 for both blanket structural material and fission fuel cladding material. This choice definitely appears to be optimum for the structural material. For the fuel cladding material, lower strength capability would be acceptable and higher temperature capability would be desireable. For this reason we are interested in alternate fuel cladding material candidates. Hybrid reactors should be able to draw heavily upon the cladding development programs for the LMFBR and GCFR breeder reactor programs.

Tritium Breeding Material

A unique aspect of hybrid reactors is the desire to breed two products in the blanket. Both fissile fuel and tritium to fuel the fusion reactor are desired. A wide variety of lithium alloys and compounds have been considered for this application[9]. Liquid lithium, molten lithium salts and solid lithium compounds are being considered but no real consensus appears to have emerged. Liquid lithium appears ill-suited to hybrid systems due to the potential hazard from lithium fires. Solid lithium compounds are attractive due to the high lithium density and high temperature capability of some of these compounds. We have chosen lithium hydride (LiH) for the MHR design. LiH has a high lithium density plus hydrogen to moderate the neutrons. It also appears to have excellent irradiation stability as radiation damage anneals out at temperatures above 300°C.[10] A potential

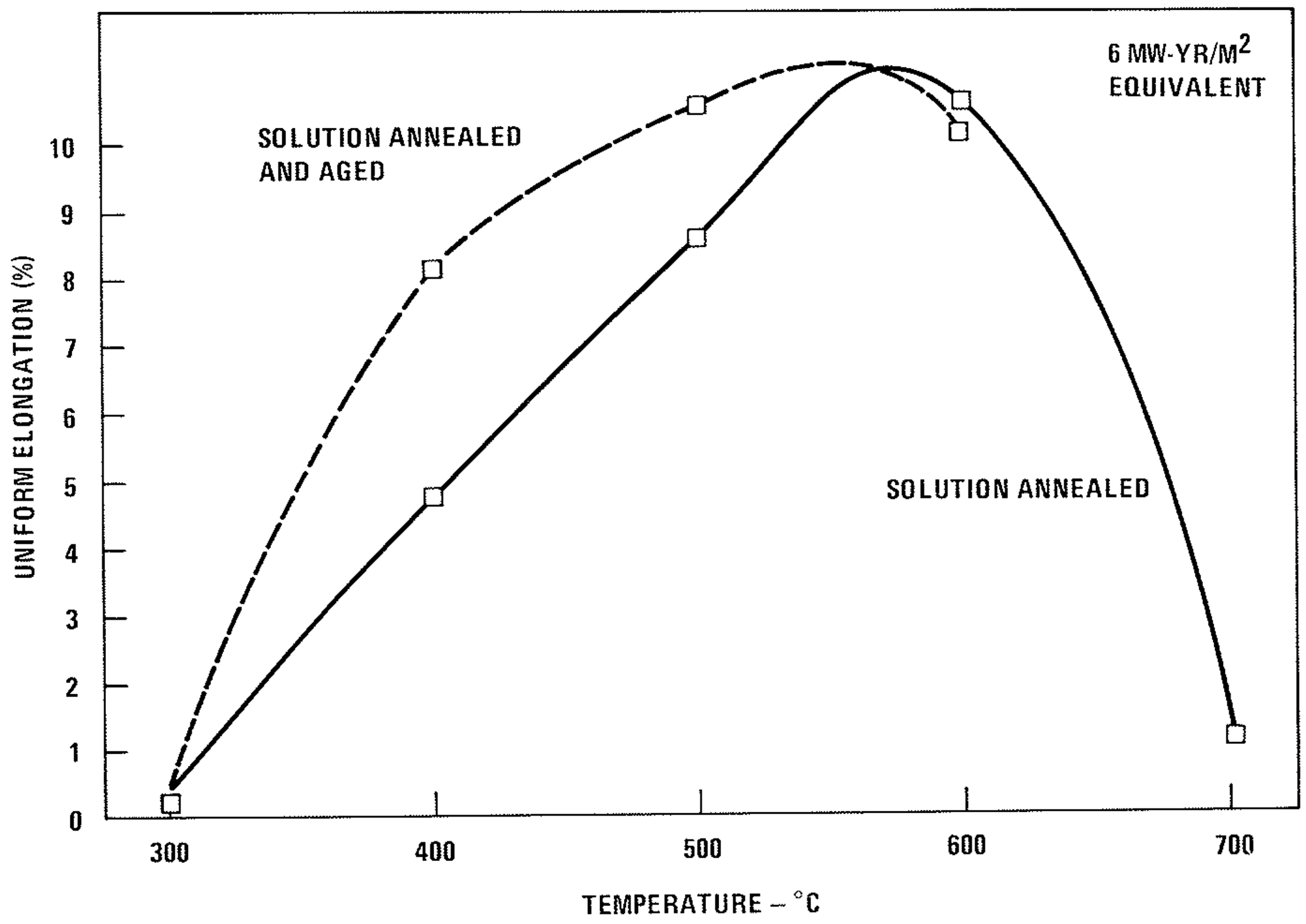

Fig. 3

Tensile uniform elongation of alloy PE 16 as a function of temperature after neutron irradiation in HFIR (tested at the irradiation temperature (Ref. 7).

problem with LiH is its high hydrogen vapor pressure. In a system designed to release the bred tritium by use of vented fuel rods or use of hydrogen permeable cladding, dehydriding of the LiH would be a serious concern. We have opted to contain the tritium in the fuel rods by using hydrogen-retentive aluminum alloy cladding and low lithium zone temperatures. The aluminum-berylium alloy Lockalloy-43 was used for LiH cladding because of the additional strength and temperature capability the berylium adds to aluminum alloys.

The blanket material selections for the Mirror Hybrid Reactor, used as an example, are summarized on Table 2.

TABLE 2

MHR BLANKET MATERIAL CHOICES

Coolant	Helium at 6 MPa
Fission Fuel	U_3Si
Structure	Inconel - 718
Fuel Cladding	Inconel - 718
Tritium Breeder	LiH
LiH Cladding	Lockalloy-43

BLANKET DESIGN

The design of the blanket of a hybrid reactor is strongly influenced by the goals and concerns of the hybrid reactor concept. In a standard fusion reactor the blanket neutronics must be optimized to achieve a tritium breeding ratio of unity. In a hybrid fusion reactor, the main product is bred fuel and thus the blanket neutronics must be optimized to not only breed one triton per fusion but also to maximize the amount of fissile fuel that is bred. To maximize the benefit of the bred fuel it must be removed from the reactor and be used in a fission reactor. This leads to more frequent refueling for hybrid reactors that for a standard fusion reactor. More frequent refueling makes it highly desireable to have a blanket design that minimizes the length of time needed for each refueling. The blanket energy multiplication by fission can result in much higher power densities for hybrid reactors than are expected for standard fusion reactors. These hybrid reactor characteristics and concerns have shaped the blanket module design and blanket fuel design as will be described below.

Blanket Module Design

In order to maximize the breeding performance of the hybrid blanket a thin first wall between the fuel and the plasma is desired. This may be achieved by using high strength materials like Inconel-718 and by using spherical and cylindrical shapes for the first wall pressure boundary.

These shapes allow one to design for pure tension structures. By minimizing bending stresses the required wall thickness can be minimized. To achieve a short refueling time, the number and complexity of remote operations must be minimized. The extent of reactor disassembly required to gain access to the blanket must be kept as small as possible. The blanket module design should be made to minimize the number of pieces that have to be handled during refueling, to minimize the number of operations that must be done with these pieces and to minimize or eliminate remote welding operations, which are particularly time consuming.

The Mirror Hybrid Reactor blanket module illustrating these concepts, is shown on Figure 4. It is composed of only two pieces, the fuel assembly and the Inconel-718 pressure shell. The pressure shell is in the shape of a cylinder capped with a hemisphere and has a first wall thickness of only 2.4 mm. The fuel assembly threads into a socket in the permanent module support structure. The pressure shell is bolted to the support structure with six large bolts in a hexagonal flange at the base of the cylinder. The vacuum seal is a double mechanical Varian-type knife edge seal with secondary vacuum pumping between the two knife edges. The size of the module is such that it can be passed out of the vacuum chamber through the mirror leakage ports without disassembly of the magnets or reactor support structure.

First wall cooling can be a challenging design problem for fusion reactors. In addition to neutron heating and intense radiation, the first wall may also receive up to 20% of the total plasma power as thermal and x-ray radiation and α and impurity leakage from the plasma. This energy

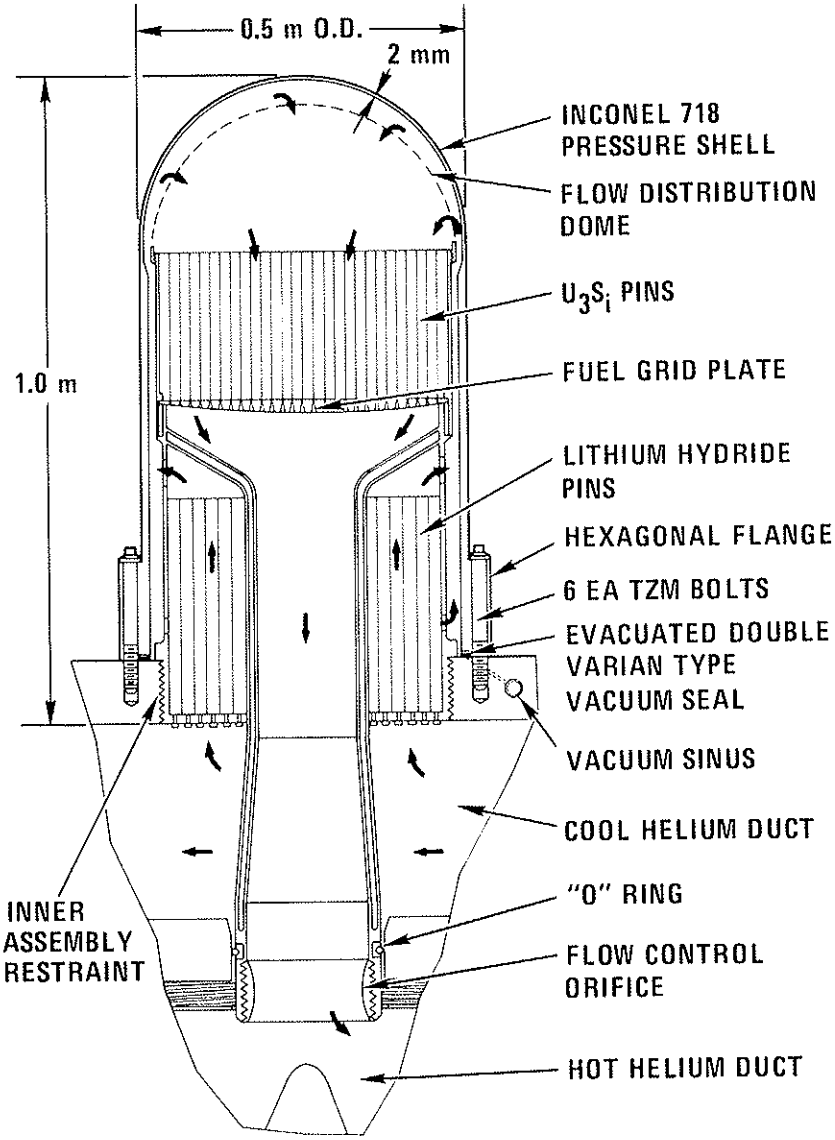

Fig. 4. MHR Blanket Module

must be removed and the wall temperature kept acceptably low while still allowing adequately high coolant temperature for efficient power conversion system operation. Hybrid reactors have an advantage in this respect due to the large amount of fission power produced in the blanket Only a few percent of the total power is deposited on the first wall. It appears that the first wall may successfully cooled by series flow of the main coolant flow.

Cooling of the lithium zone is also required in a hybrid reactor blanket. For simplification of the design the same coolant should be used for both fission zone and lithium zone. Series flow of the coolant through these two zones is preferred for the same reason. The coolant flow path used will depend upon the tritium containment or release scheme. If the tritium is to be released to the coolant or to a purge stream, the lithium zone may be cooled by the coolant after it leaves the fission blanket zone. If retention of the tritium is desired, use of the incoming coolant would be preferred. The design of the Mirror Hybrid Reactor blanket module illustrates the latter idea on Figure 4. Incoming 280°C helium flows first through and cools the LiH zone. It emerges, at only 300°C due to the low power density in the LiH, and flows past the first wall, cooling it. The coolant flow turns and flows radially outward through the U_3Si zone, emerging at 530°C.

Blanket Fuel Design

The fuel design of a hybrid reactor will be very similar to that of fission reactors and should take advantage of the wealth of fuel design and irradiation experience developed for fission reactors. The fuel environment is characterized by high power densities of up to about 500 w/cc on the side of the blanket facing the plasma, a very steep power density gradient in the subcritical blanket, a high fast neutron flux and a thin fission zone thickness, compared to the size of fission reactor cores. The use of a coolant flow path is directed radially outward away from the plasma center is important because of the very steep radial outward power density gradient characteristic of a hybrid reactor blanket. Figure 5 shows the steep radial power density gradient and the hot spot temperature characteristics that are obtained by using radial outward coolant flow along the fuel rods whose axes point in this radial direction relative to the plasma center. As can be seen, the limiting temperatures, the hot spot fuel centerline temperature and the hot spot cladding temperature, are almost constant along the length of the fuel rod.

The fuel configuration for hybrid reactor blankets will be dictated by the need for a large surface area to allow high fuel power density and by fabrication cost considerations due to the large surface that must be covered in a hybrid blanket compared to a fission reactor core. The fuel configuration chosen in the Mirror Hybrid Reactor for both the U_3Si zone and the LiH zone is fuel rods oriented radially with respect to the plasma center. The rods are wire-wrapped to maintain spacing for coolant flow. The fuel rod designs are shown on Figure 6. No fission gas plenum or tritium plenum are necessary due to the highly retentive nature of the U_3Si and LiH fuel material and the modest burnup experienced by both U_2Si and LiH before being reprocessed. The rods are not pressurized and the cladding is allowed to creep down upon the fuel pellet. The high peak power density in the fission zone (500 w/cc) leads to a small diameter fuel

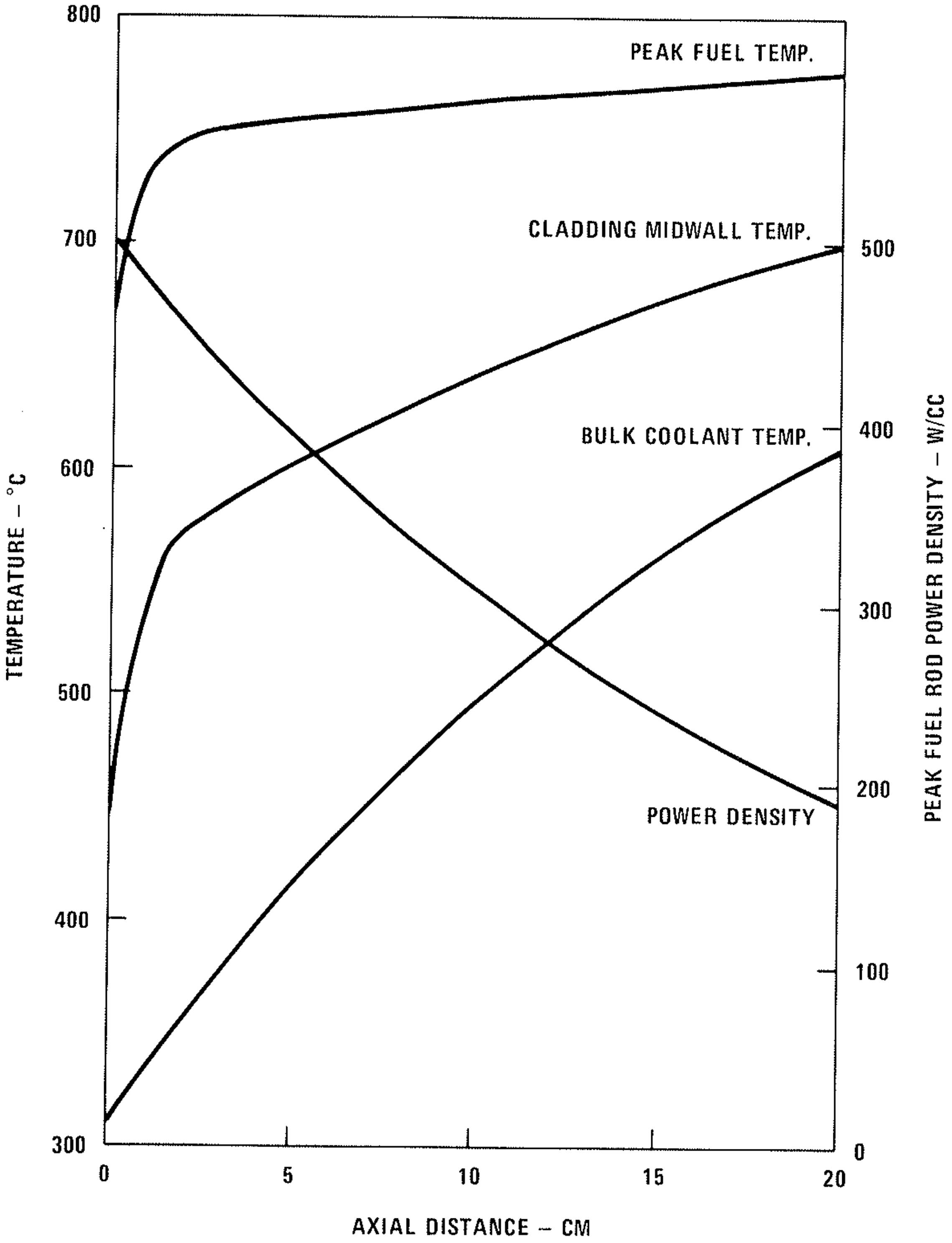

Fig. 5. Typical Hybrid Blanket Power Distribution and Hot Spot Temperatures

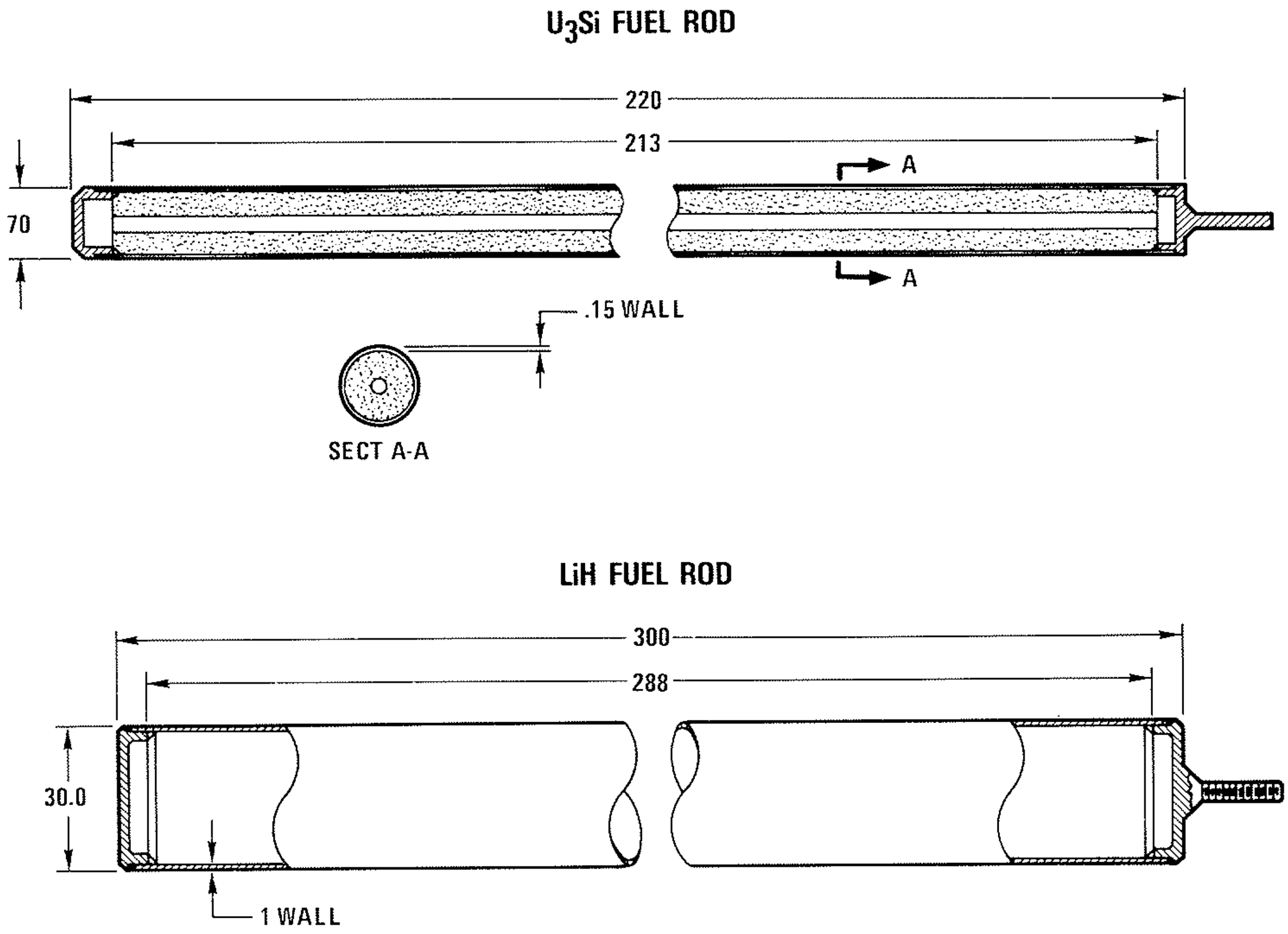

Fig. 6 MHR Fuel Rod Designs

rod (7 mm) while the lower, 30 w/cc peak heating rate in the LiH allows larger rods (30 mm diameter) in the lithium zone. The various parameters of the MHR blanket design are summarized on Table 3.

TABLE 3

MIRROR HYBRID REACTOR PARAMETERS

Fusion power	390 MW	
Plasma radius	2.5 m	
Blanket inner radius	3.75 m	
Plasma Q	0.63	
Blanket thermal power	3590 MW(a)	
Net electrical output	535 MW(a)	
Net ^{239}Pu production	1900 kg/yr(a)	
Power generation cost	31 mills/kw-hr	
Energy multiplication (M)	8.8 - 18.5(b)	
Net fissile breeding ratio (Pu/n)	1.85 - 1.75(b)	
Tritium breeding ratio (T/n)	1.05 - 1.42(b)	
Ratio of ^{239}Pu to ^{238}U	0.0 - 2.3 a/o(b)	
Burnup of uranium	0.0 - 0.75 a/o(b)	
Fuel peak power density	240 - 500 W/cc(b)	
Peak to average power density	1.8	
	U_3Si	LiH
Fuel pin length	230 mm	300 mm
Clad OD	7.0 mm	30 mm
Clad thickness	0.15 mm	1.0 mm
Pitch to diameter ratio	1.05	1.05
He inlet temperature	310°C	280°C
He outlet temperature	530°C	300°C
Peak (hot channel) clad temperature	700°C	392°C
Peak (hot channel) fuel temperature	775°C	560°C

(a) Time average values.

(b) Local blanket values at beginning and end of 5 MW-yr/m^2 exposure.

AREAS OF CONCERN

Although the radial flow configuration described above appears to be ideally suited to hybrid blanket design, it is not without areas of concern. The first of these is adequate heat transfer. Due to the short fuel rod length, the coolant flow per channel is modest and even with very tight rod packing (pitch/diameter = 1.05), good cooling is difficult to achieve. The flow Reynolds number is only about 10^4, which leads to modest heat transfer conductances and thus small fuel rod diameters. In a hybrid reactor the peak fuel power density occurs at the end of the fuel life, due to the buildup of bred fissile material. At the beginning of fuel life the local power density in the MHR at full power, for example, is only 48% of the design power that will occur at the end of fuel life. If the helium temperature rise across the blanket is kept constant by reducing helium flow so as to maintain steam generator temperatures and steam conditions, the helium flow conditions at partial power drop into the transition zone and the fuel cladding temperature exceeds the 700°C hot spot design limit as shown on Figure 7. Because this is a hot spot limit and because the limit is set by time-integrated irradiation embrittlement considerations, we believe that, although this condition is undesireable, the design is acceptable.

A second area of concern is cost. The cost of the blanket fuel is almost directly related to the number of fuel rods. Use of many small diameter, short fuel rods will result in an expensive blanket. These areas are

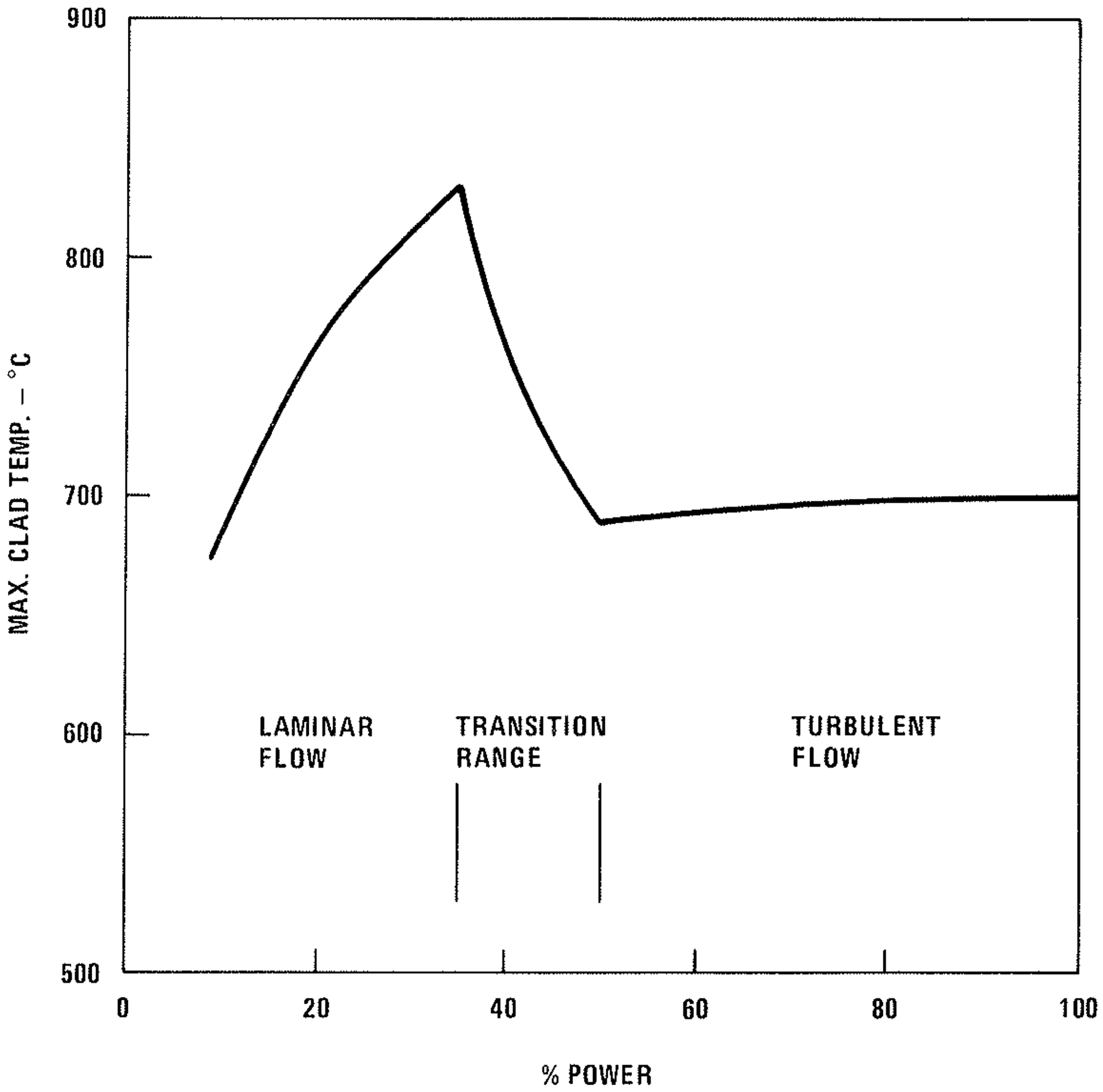

Fig. 7. MHR Hot Spot Cladding Temperature at Partial Power

problem areas that are unique to hybrid reactors. There is a definite need for careful analysis and innovative design ideas to accommodate these problem areas.

CONCLUSIONS

The hybrid fusion-fission reactor concept has the potential to supply copious quantities of bred fissile fuel to support the world nuclear power economy. Because the performance of the fusion driver is essentially independent of the hybrid blanket, the hybrid reactor has a wide degree of flexibility. They can operate on either thorium or uranium fuel cycles or upon a combination of the two. Hybrid systems have nuclear, thermal and mechanical design parameters and goals that are unique; they combine features of both fission and fusion reactors. The blanket mechanical design will be strongly influenced by the geometry, access and first wall cooling requirements of fusion systems. The blanket fuel design will be strongly influenced by the fission aspects of the reactor and will draw heavily upon the fuel design experience of the fission reactor industry. Hybrid blanket design to date indicates that technically viable blankets will be possible using existing fission reactor technology. There are areas of concern, such as accommodation of the very steep radial power density gradient, however, where design improvement through optimization and innovation is needed.

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NUCLEAR DESIGN OF FAST HYBRID BLANKETS

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INTRODUCTION

The objective of this presentation is to:

1. Present the physical motivation for fusion-fission hybrids,
2. outline design considerations for hybrid blankets, and
3. discuss the nuclear performance potential of hybrid blankets.

MOTIVATION

The physical motivation for the hybrid is the fact that fast neutrons will cause the abundant fertile isotopes, uranium 238 and thorium 232, to fission with the resultant release of energy and neutrons.

Figure 1 shows the fission cross section vs neutron energy from 0 to 20 MeV. At 14 MeV, the kenetic energy of a neutron generated by deuterium-tritium fusion, the fission cross section is 1.15 barns for uranium 238 and 0.37 barns for thorium 232. The number of neutrons generated per fission vs incident neutron energy is shown in Figure 2. For 14 MeV neutron induced fission the number of neutrons generated in U^{238} is 4.5 and in thorium 232 is 3.87. This fission cross section and neutron release data only suggests the possibility of significant energy and neutron multiplication. Infinite medium calculations show the actual theorectical potential for energy neutron multiplication of 14 MeV neutrons in uranium and thorium. Table 1 shows results of infinite medium calculations for natural uranium, uranium 238, and thorium. Here breeding reactions refer to (n,γ) reactions in uranium 238 and thorium 232 which result in the fissile isotopes plutonium 239 and uranium 233, respectively.

The energy multiplication and fissile breeding ratios predicted by the infinite medium calculations are exciting, but how good are such calculations? To partially answer this question we have compared calculated and experimental results of a natural uranium pile. Table 2 shows this comparison. The pile was a 106

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centimeter long 99 centimeter diameter cylinder of 85% dense natural uranium with a 14 MeV neutron source at its center. The calculated fission and uranium 238 (n, γ) reactions both are within 7% of the measured experimental values. Based on this comparison we have some confidence in our ability to calculate hybrid blanket performance.

DESIGN CONSIDERATIONS

A thick pile of fertile material is not a hybrid blanket. There are numerous design considerations that must be addressed in order to develop a consistent blanket design. The important design considerations are: nuclear requirements, blanket geometry, refueling and replacement, tritium handling, heat removal, structural integrity, and materials. This list outlines topics that must be considered, all of which interrelate and affect nuclear performance.

There are two major nuclear requirements, tritium breeding and subcriticality. We believe the blanket should breed tritium sufficient to fuel the D-T fusion reaction. We also believe that the blanket should be subcritical under all conditions both normal and abnormal. The blanket geometry must conform to plasma and magnets and allow for penetrations. A uniform current flux of D-T neutrons into the blanket is also very desirable. The blanket geometry must also allow for blanket refueling and replacement. Tritium removal and containment methods are important considerations because choices made effect tritium breeding rate needed as well as type and quantities of permeation barriers used in the blanket. Heat removal and structural integrity both effect the amount of structure needed. Blanket performance is quite sensitive to the ratio of structure to fuel because of competition for the neutrons.

PERFORMANCE

To get an idea of how blanket performance is affected by blanket requirements and design tradeoffs, we compare blanket performance to that of an infinite medium.

In Table 3 we see that requiring a uranium blanket to breed tritium and contains structure results in a plutonium breeding ratio of 2.2 compared to 5.0 for the infinite medium and energy generation of 200 MeV vs 309 MeV. Both total breeding (tritium plus fissile) and energy generation are reduced one-third compared to the infinite uranium medium The term M introduced in Table 3 stands for multiplication of the kenetic energy of the 14 MeV D-T fusion neutron by the blanket.

Uranium metal has swelling problems at burnups and temperatures that are too low to be of much interest for hybrids. As shown in Table 4 the effects of using ceramic forms of uranium fuel are significant. Uranium dioxides performance is half that of uranium metal and uranium monocarbide is two-thirds of uranium metal. Since we are emphasizing fissile breeding we do not need the high burnup and temperature capabilities of ceramic type fuels. We, therefore, are concentrating on metallic types of uranium fuels such as uranium 7 weight percent moly and uranium silicide. Performance with these fuels are approximately 25% below the uranium metal case.

Blankets consist of fuel contained in a pressure vessel of some form. Our conceptual hybrid blankets consist of many individual pressure vessels containing a thorium or uranium fuel followed by tritium breeding lithium fuel. One such blanket module is shown in Figure 3. A major features of this module is a cylindrical pressure vessel capped by a hemispherical dome. To keep the thickness of this pressure vessel as thin as practical the diameter of the modules are relatively small and the pressure vessels are cooled by the inlet coolant, in this case helium, at approximately 300°C. After cooling the hemispherical first wall, the coolant reverses direction and flows through the interior of the module removing the nuclear heat generated in the fuel. Minimizing pressure vessel thickness, especially the first wall, is extremely important because the fusion neutrons must pass through this material before reaching the fertile fuel. A pressure vessel thickness of .5 centimeters (stainless steel) appears to be a reasonable compromise between nuclear performance and mechanical requirements.

Fission zone thickness is dictated by the required neutron leakage into the tritium breeding zone. Fission zone thickness varies between 20 and 30 centimeters for a blanket module of this type. Total blanket thickness is approximately one meter.

Plasma containment dictates blanket geometry. The blanket must not intrude into the plasma volume and must allow for fueling and exhaust penetrations. It is economically advantageous for the blanket to cover as much of the plasma as possible and to have a uniform D-T neutron current over its surface. For mirror confinement of the type portrayed in Figure 4, a majority of the D-T neutrons are generated in a central spherical volume. To meet the objectives of high coverage and uniform current, the blanket is a spherical annulus surrounding the central plasma volume and is inside the coils. The plasma is surrounded by radially aligned cylindrical modules, except for where penetrations are provided for fueling and the plasma leakage fans. As depicited in Figure 5 the blanket forms a spherical annulus that surrounds the plasma and that has penetrations for fueling and leakage. The degree of blanket coverage used is dependent on thickness of the blanket coolant plena and shield, as well as plasma and coil geometries. Blanket performance is strongly affected by coverage. The right-hand graph of Figure 6 shows the dependence of performance on coverage. Dropping coverage from 90 to 80 percent reduces fissile breeding and energy multiplication by approximately 40%. Performance is not linerally proportioned to coverage because tritium breeding must be maintained by increasing local tritium breeding. The left-hand graph of Figure 6 demonstrates how this is done by reducing the thickness of the fission zone.

An extremely important aspect of blanket design is accounting for exposure effects. To illustrate this point Figure 7 shows an example of the effects of exposure on a uranium monocarbide blanket. Exposure is measured in terms of integrated wall loading or energy flux of 14 MeV neutrons across the first wall. M (blanket energy multiplication) is initially 8 and peaks at 32 after an exposure of 20 megawatt years per square meter, a factor of four increase. T, the tritium breeding ratio doubles after 20 megawatt years per square meter. Pu the net plutonium ratio drops to 0 after an exposure of 24 megawatt years per square meter. These effects occur because of fissile plutonium buildup as well as buildup of fission products. After an exposure of 20 megawatt years per squre meter plutonium 239 concentration is 9% and the burnup is 12%. As stated earlier we require the blanket to be subcritical under all conditions. As you can see by what happens to M (blanket energy multiplication) this blanket never goes critical. The fission neutron multiplication factor K achieves a maximum value of 0.7 at 20 MWy/M exposure. K at 0 exposure is 0.3. Criticality by reconfiguration must also be avoided and it is this that is expected to set an upper limit to exposure. Until reconfiguration scenarios are examined, we are setting an arbitrary upper limit on the fissile buildup of 4%. As it turns out, economics dictates the blanket be removed at fissile buildups of less than 3%.

The effects of fractional blanket coverage and exposure must be combined to determine effective blanket performance.

Table 5 gives representative blanket performance for three fuels and various exposures. The last three columns of this table lists effective time average performance for blankets with three fuel types after various exposures. The first five columns list local instantaneous blanket values. Directing your attention to the UC fuel five-year exposure case, we see that as the local T breeding ratio increases from 1.05 to 1.43, the average blanket tritium breeding ratio is 1.05. Local M increases from 8 to 13.6 giving an average M of 9.18. Local net plutonium breeding decreases from 1.38 to 1.18 giving an average net plutonium breeding ratio of 1.09. At five-years exposure, burnup is 1.5% and plutonium 239 buildup is 2.9%. As exposure continues effective T breeding and energy multiplication increase while effective fissile breeding decreases.

The U-moly case is representative of metallic fuels such as uranium silicide. The thorium case gives the lowest blanket performance, but the higher conversion ratio of uranium 233 fuel in thermal fission reactors makes thorium competitive with metallic uranium fuel blankets. Combining the advantages of uranium and thorium in a single blanket should give the best performance.

Fissile accumulation in these three blankets are graphically displayed in Figure 8. After an exposure of five-megawatt years per square meter, one square meter of blanket accumulates 50 kilograms of plutonium for the U-moly case, 35 kilograms of plutonium for the uranium carbide case and 20 kilograms of uranium 233 for the thorium case.

Energy deposition, in fast fission blankets, is nearly exponential. Figure 9 shows the power profile in the fission zone of a U-moly fuel blanket. For this case 54% of the fission zone is fuel, therefore, the peak fuel power density at 0 exposure is 140 W/cc climbing to 280 W/cc at five-megawatts pwer squre meter exposure.

SUMMARY

In summation I wish to emphasize three points:

1. That experiment confirms that 14 MeV neutrons cause fertile isotopes of uranium and thorium to fission resulting in high neutron and energy multiplication
2. That calculations and experiment, at least for the uranium case, agrees within 10%, and
3. Conceptual studies of mirror fusion-fast fission hybrid reactors suggest that blanket design objectives can be met while maintaining attractive fissile breeding and energy multiplication.

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INFINITE MEDIUM RESULTS

(PER 14 MEV NEUTRON)

MATERIAL	ENERGY (MEV)	BREEDING REACTIONS (N,γ)
URANIUM (NAT)	309	5.0
URANIUM -238	233	4.4
THORIUM	64	2.7

TABLE 1

REACTIONS PER 14 MeV SOURCE NEUTRON INTEGRATED OVER THE WEALE PILE

REACTION	CALCULATION	EXPERIMENT
U235 (n,f)	0.266	0.281 ± 0.017
U235 (n,γ)	0.061	-
U238 (n,f)	1.11	1.18 ± 0.06
U238 (n,γ)	4.36	4.08 ± 0.24
U238 (n,2n)	0.388	0.277 ± 0.008
U238 (n,3n)	0.195	0.327 ± 0.052
LEAKAGE	0.504	0.42 ± 0.02

TABLE 2

BLANKET vs INFINITE MEDIUM

	T(ATOMS)	PU(ATOMS)	E(MEV)	M
	(NORMALIZED TO 1, 14 MEV NEUTRON)			
BLANKET	1.1	2.2	200	14
INFINITE URANIUM	0	5.0	309	22

$M \equiv E/14$ MEV

BLANKET

ZONE 1 69% U + 10% SS + 16% LI

ZONE 2 86% LI + 9% SS

TABLE 3

'BLANKET' PERFORMANCE vs FUEL TYPE

(PER 14 MEV NEUTRON)

FUEL TYPE	T(ATOMS)	M	Pu(ATOMS)
U	1.1	14	2.2
UO_2	1.1	7.1	1.1
UC	1.1	9.3	1.4

TABLE 4

REPRESENTATIVE FAST FISSION BLANKET PERFORMANCE

FUEL & EXPOSURE[1]	LOCAL BLANKET VALUES					BLANKET AT EQUILIBRIUM[4]		
	T/N	M	Pu/N	(BURN UP(%)[2]	BUILDUP(%)[3]	T/N	M	Pu/N
UC AT 0 YEARS	1.05	8.01	1.38	0	0	-	-	-
AT 5 YEARS	1.43	13.6	1.18	1.5	2.9	1.05	9.18	1.09
AT 10 YEARS	1.78	21.6	0.88	3.7	5.5	1.20	12.6	0.96
U-MOLY AT 0 YEARS	1.10	10.0	1.80	0	0	-	-	-
AT 5 YEARS	1.60	20.0	1.70	1.3	2.5	1.15	12.7	1.49
TH AT 0 YEARS	1.08	2.5	0.73	0	0	-	-	-
AT 12 YEARS	1.23	5.4	0.61	0.74	2.76	0.98	3.4	0.57

[1] EXPOSURE AT A FIRST WALL DT NEUTRON ENERGY FLUX OF 1.0 MW/M^2

[2] FISSION OF HEAVY METAL

[3] NET ACCUMULATION OF FISSILE MATERIAL IN (%) OF INITIAL HEAVY METAL

[4] TIME AVERAGED PERFORMANCE OF BLANKET WITH 85% COVERAGE

TABLE 5

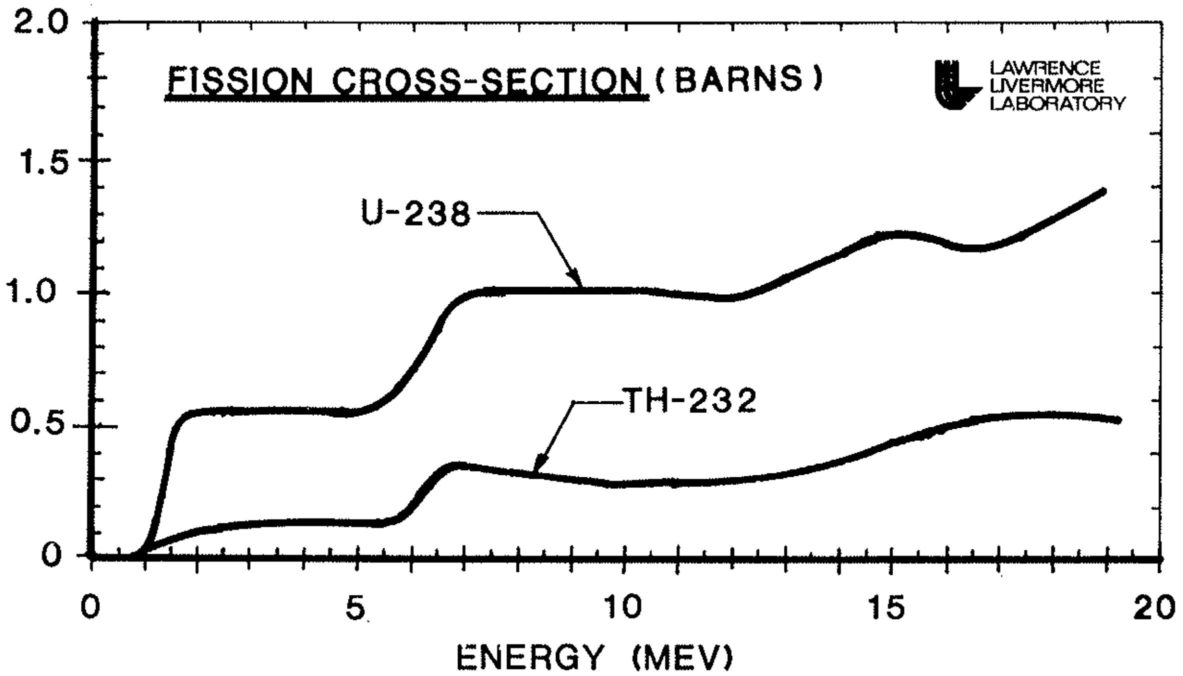


Figure 1

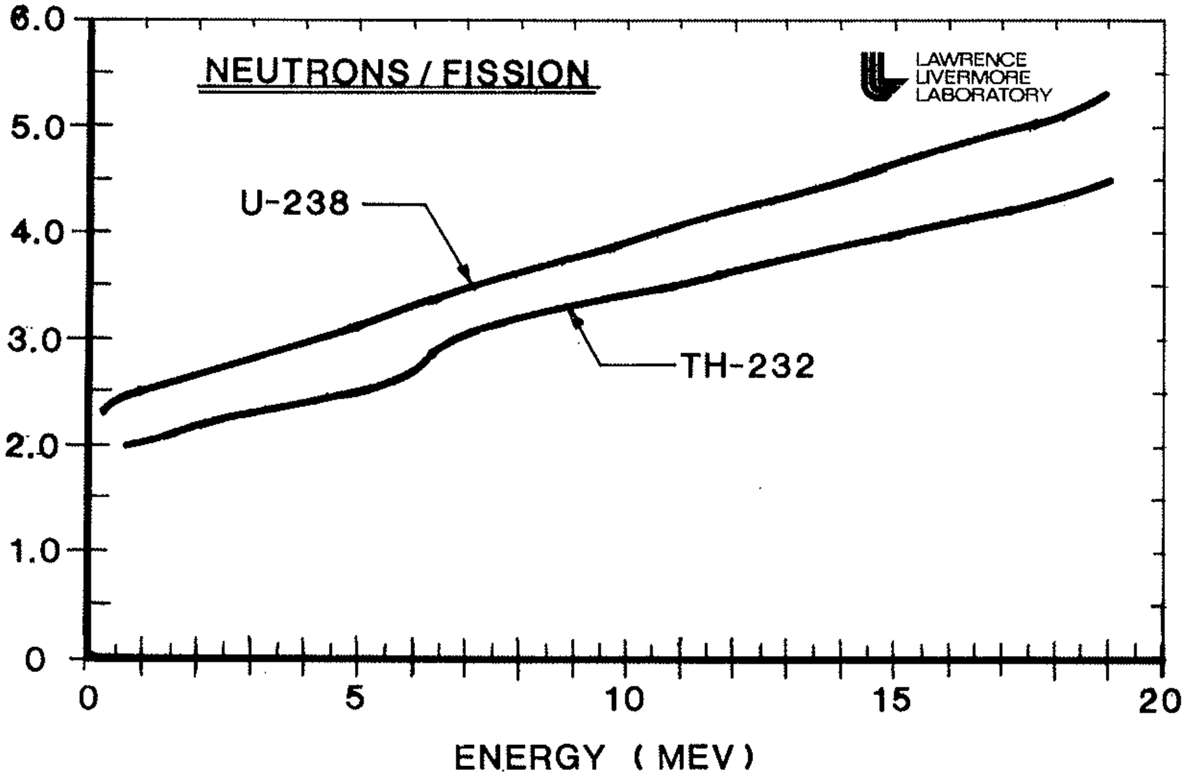


Figure 2

FAST FISSION BLANKET SUBMODULE

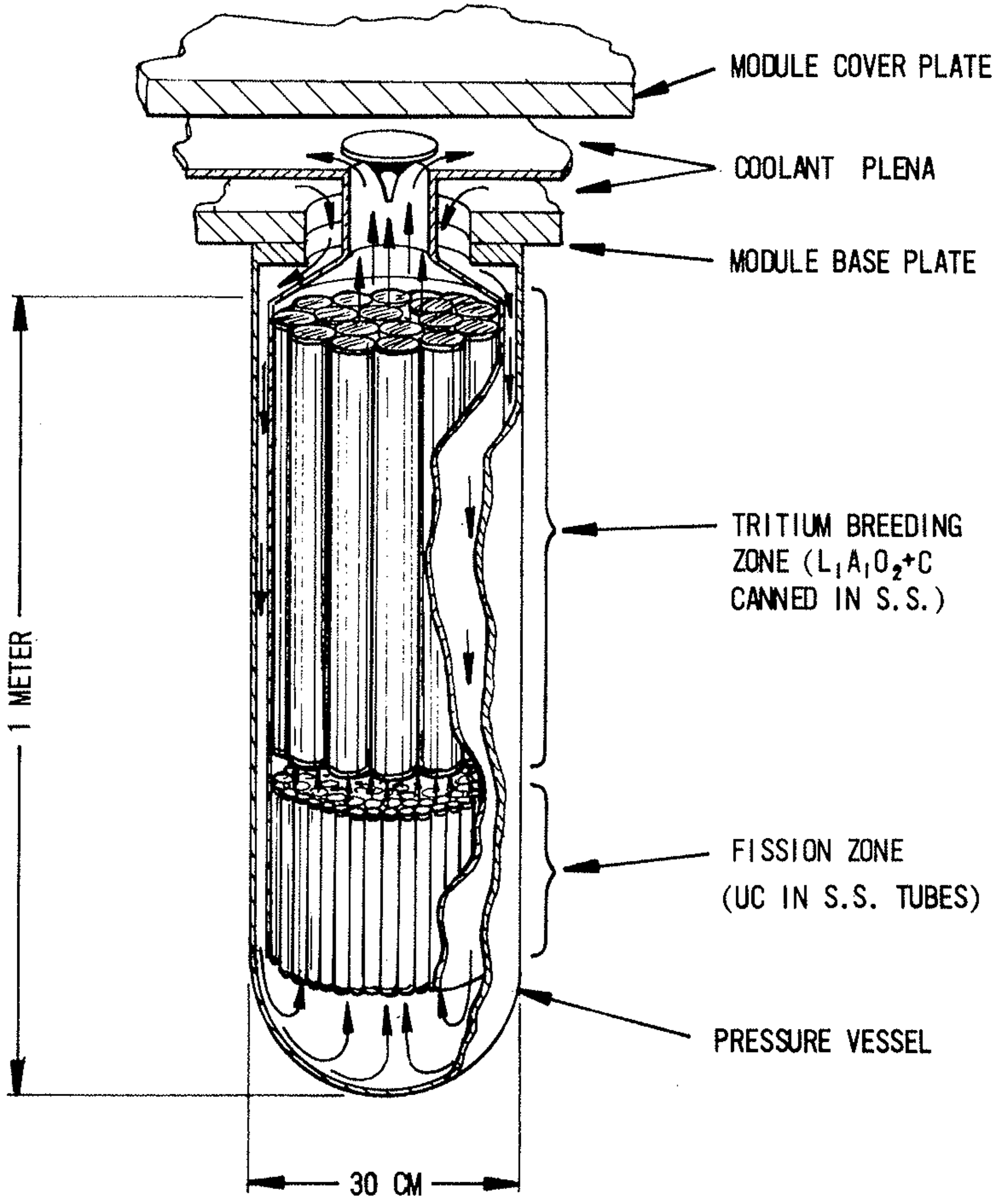


Figure 3

MIRROR GEOMETRY

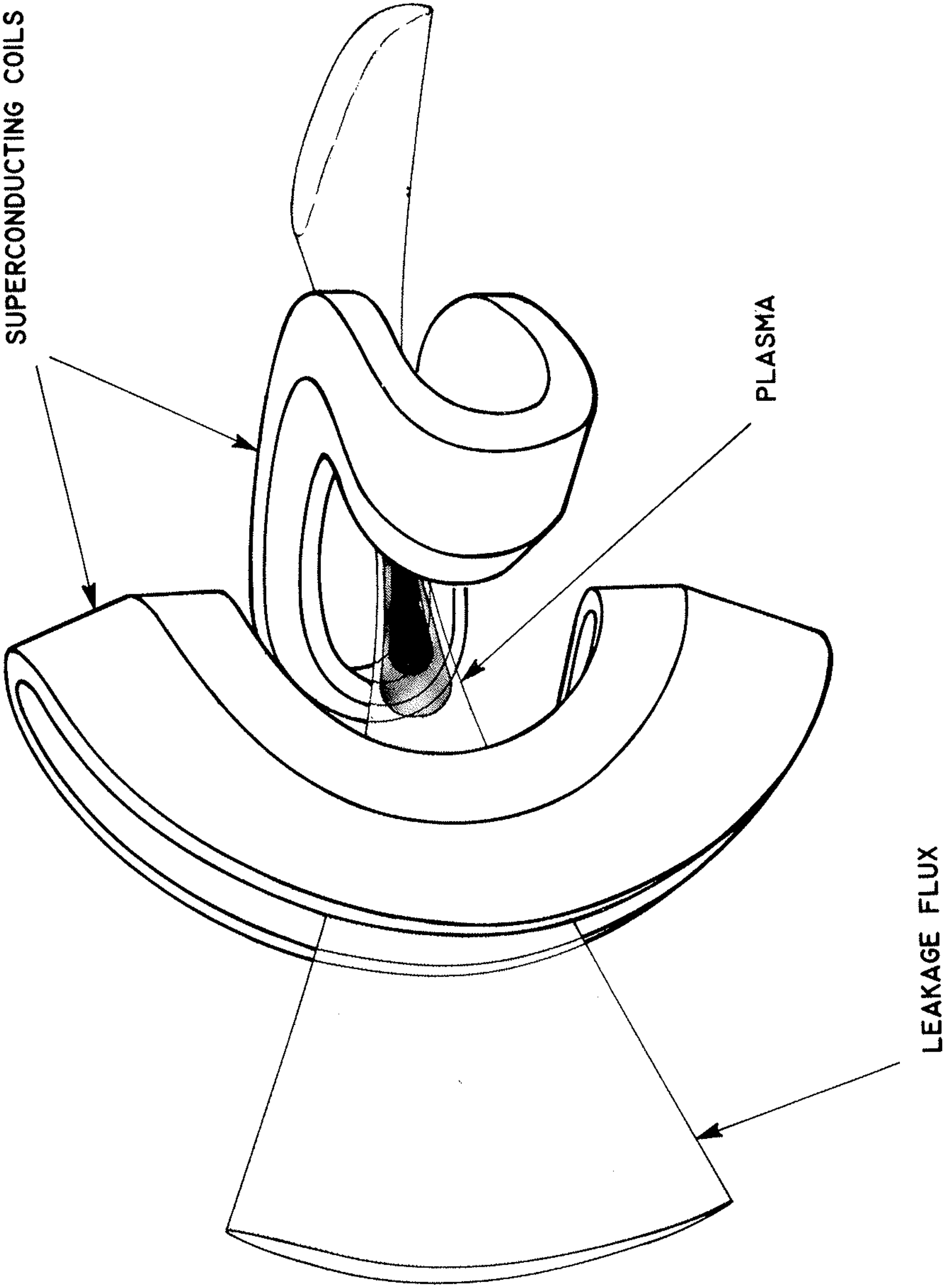


FIGURE 4

BLANKET COVERAGE

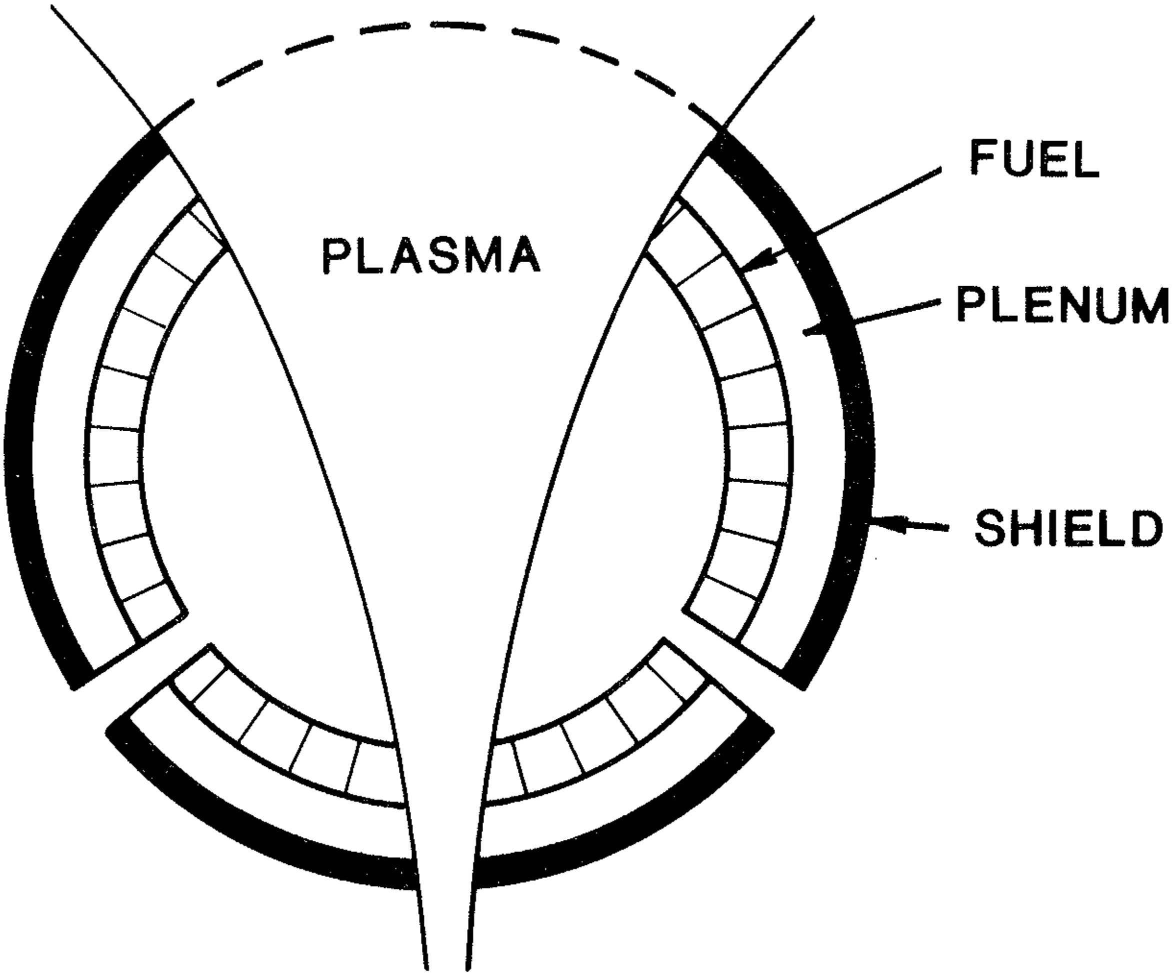
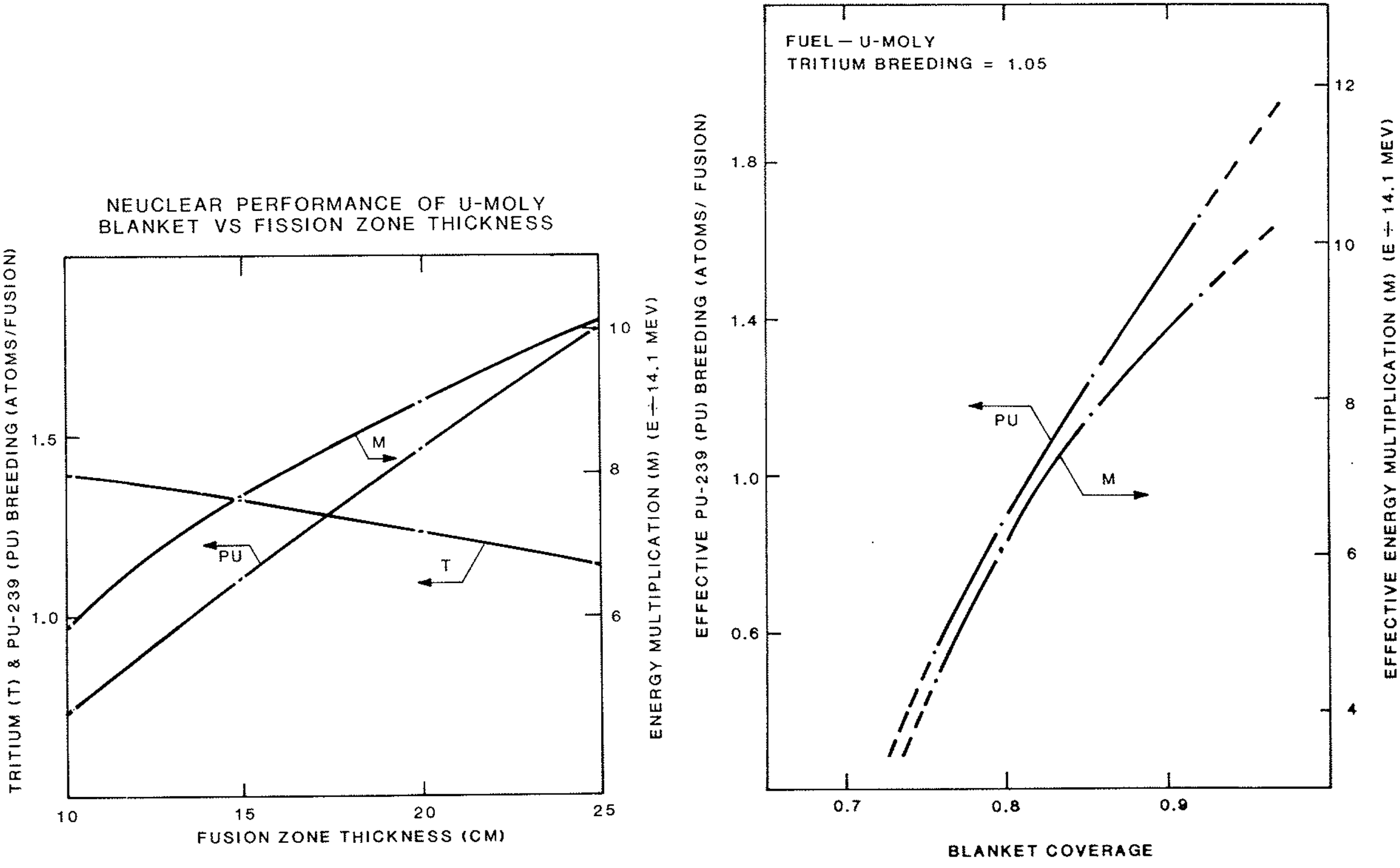


Figure 5



NEUCLEAR PERFORMANCE OF U-MOLY BLANKET VS FISSION ZONE THICKNESS

EFFECTIVE BLANKET PERFORMANCE VS BLANKET COVERAGE

Figure 6

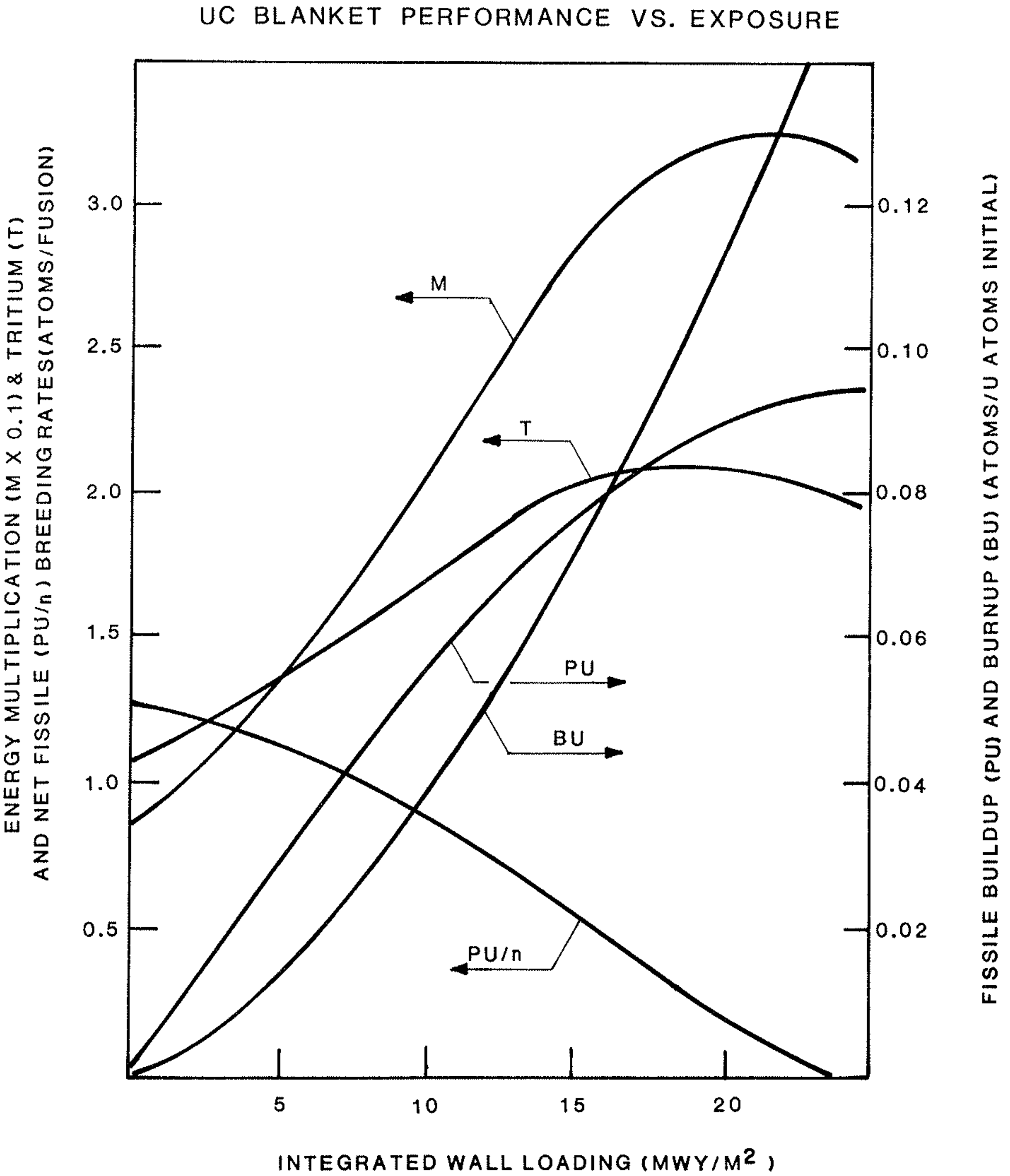

UC BLANKET PERFORMANCE VS. EXPOSURE
ENERGY MULTIPLICATION (M X 0.1) & TRITIUM (T)
AND NET FISSILE (PU/n) BREEDING RATES(ATOMS/FUSION)
FISSILE BUILDUP (PU) AND BURNUP (BU) (ATOMS/U ATOMS INITIAL)
3.0
2.5
2.0
1.5
1.0
0.5
0.12
0.10
0.08
0.06
0.04
0.02
M
T
PU
BU
PU/n
5
10
15
20
INTEGRATED WALL LOADING (MWY/M2)

Figure 7

FISSILE (PU 239 ORU233) ACCUMULATION
VS EXPOSURE

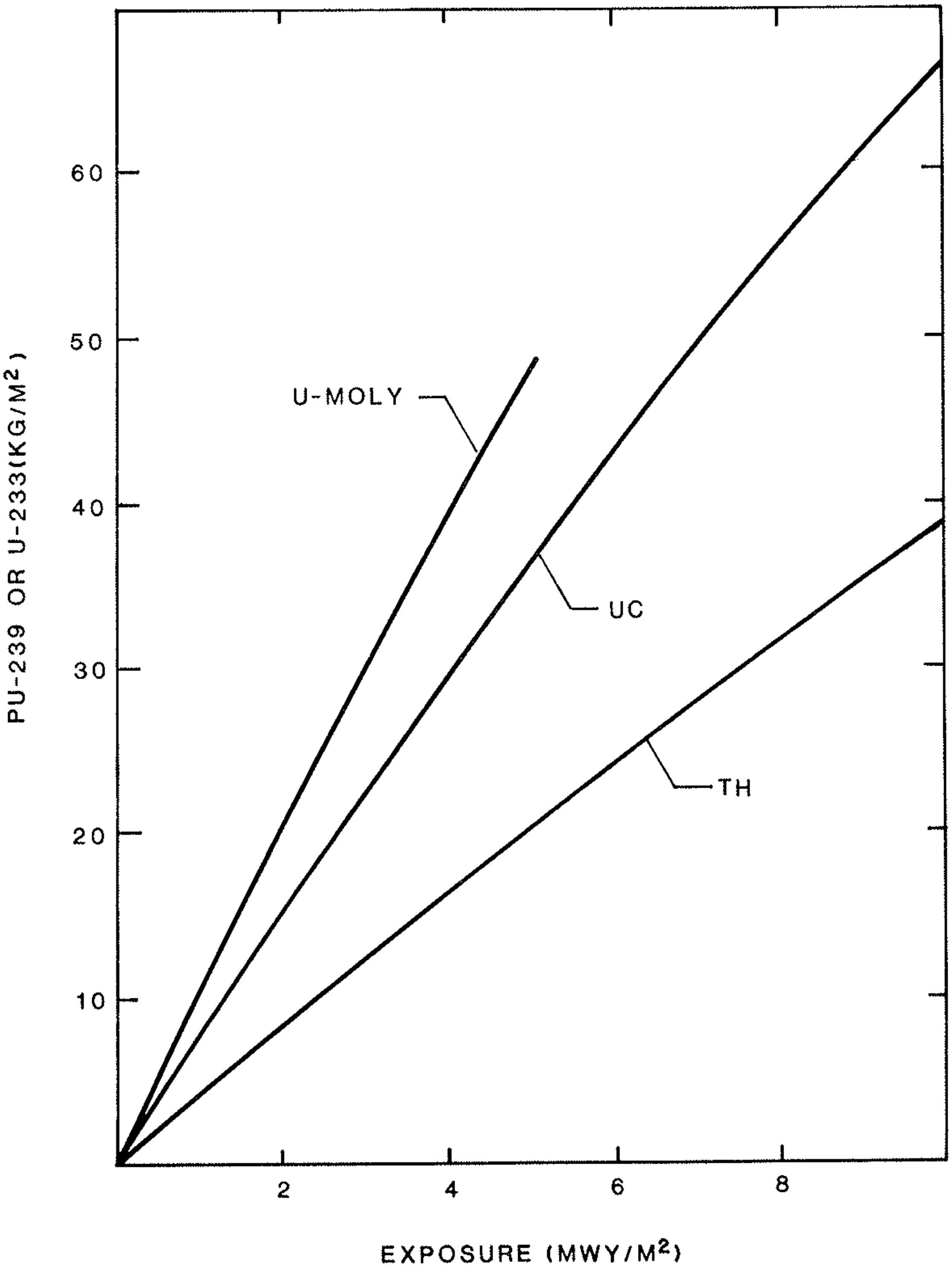


Figure 8

THERMAL POWER DENSITY IN REFERENCE U-MOLY BLANKET

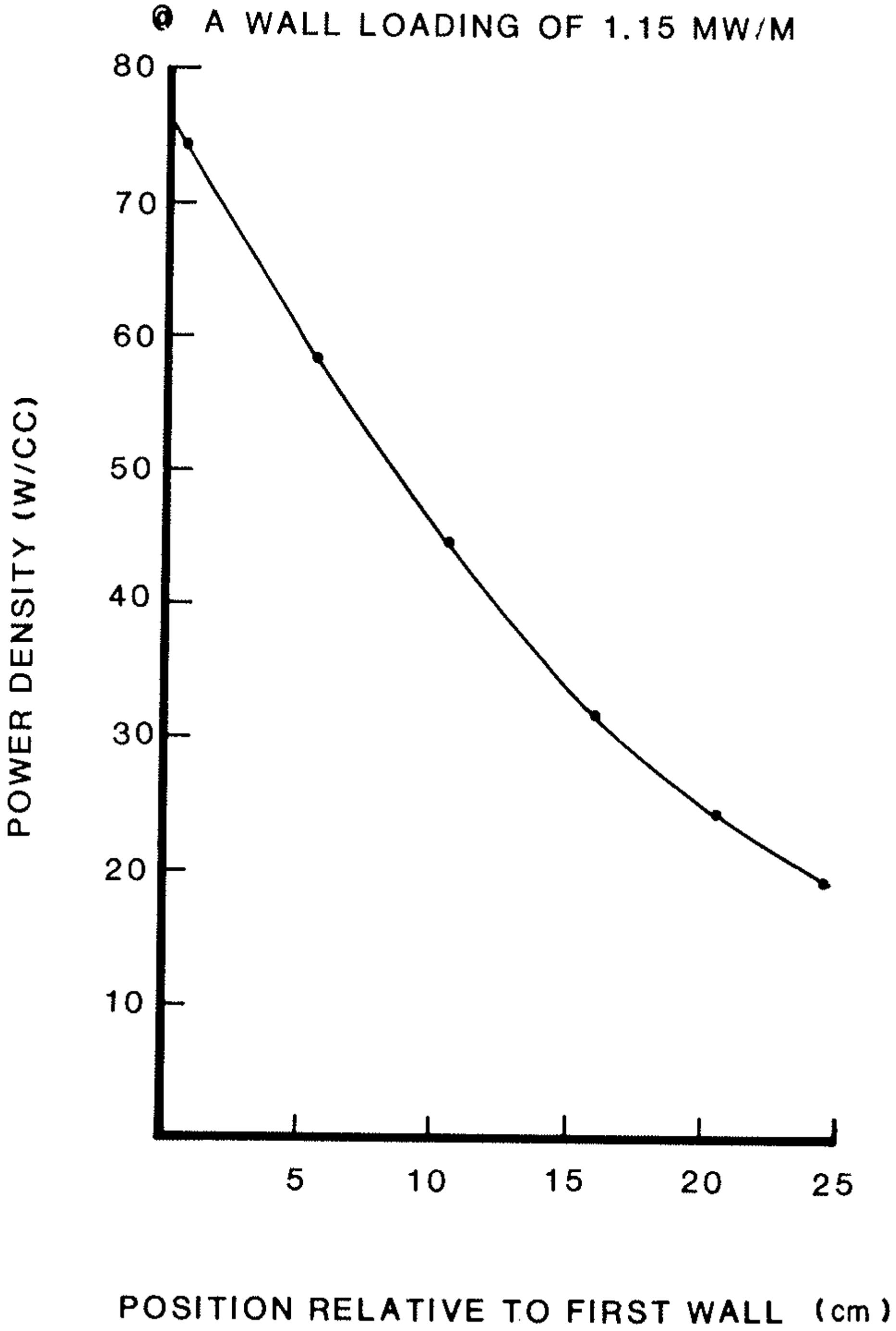


Figure 9

MR. NEFF: Thank you, Ken and J. D. Are there any questions?

DR. TEOFILO: Vince Teofilo, Battelle Northwest. J. D., you showed a slide with the tabulation of parameters of uranium carbide breeding rate, and you came out with the rate for breeding plutonium with uranium carbide of the order of about 1.4 Pu atoms per fusion. Is that a familiar number?

MR. LEE: Yes.

DR. TEOFILO: Does that include the structure and coolant fractions at 1.4?

DR. LEE: Yes, that included the effects of structure and coolant.

DR. TEOFILO: The reason why I ask this is there have been a number of designs this past year using uranium carbide, such as those at Westinghouse and at Livermore, in which rates of the order of 1.7 to 1.8 were obtained. Could you give any reasons or do you have any intuition as to how those extremely high numbers, containing structure and coolant with uranium carbide fuels, could be obtained, even if they were using exotic structural materials such as TZM?

DR. LEE: Well, I think it would be better for those doing the work on the systems you're talking about address that, but my guess is that they haven't got a system that breeds its own tritium.

DR. TEOFILO: I see.

MR. MOSES: I'm Greg Moses from the University of Wisconsin. With your lithium hydride tritium breeding scheme, are you allowing for a four year tritium inventory to run on between the times that you process the breeding material?

MR LEE: Yes.

DR. SCHULTZ: No.

DR. SCHULTZ: Sorry, J. D. The fuel in this particular design is removed as one quarter of the core of the blanket per refueling interval. The refueling interval is roughly one calendar year, about 0.7 full power years. By removing one quarter of it each time, then you have only the requirement to provide inventory for one refueling interval, 0.7 years, roughly.

The initial year of operation is an expensive year, because you have to purchase tritium from someplace. This is a commercial design we've been doing and, as a consequence, we're projecting that there will be an economy available by the time the commercial reactor is built to provide this tritium for the first year. After that first year, the tritium can be stored in the unreprocessed rods in which it was bred, until it is needed.

DR. LEE: We're both half right. After the first year, you still have to buy tritium because the one-quarter of the blanket does not provide enough for the system to run for the next year so you have to ratchet yourself up -- you don't reach equilibrium until the fourth year.

DR SCHULTZ: I stand corrected.

DR. KRAKOWSKI: Bob Krakowski from Los Alamos. I'd like to clarify or at least reinterpret three points Ken brought up. First of all, you mentioned that you thought there was a consensus that helium coolant was useful in fusion blankets and I'd like to say that liquid metal coolants, if you could use them, probably are better and, certainly for pulsed systems including laser fusion, would be a preferred coolant in my opinion.

Secondly, you mentioned that the tritium can be held in the blanket at not much higher activity level because the fission product activity dominates the blanket activity. Even in pure fusion, the activity of tritium is small compared to the structural activity so, in that case, we have a similar activity problem.

DR. SCHULTZ: The tritium, however, is volatile, whereas the structure, for the most part, is not. On the other hand, many of the fission products are volatile.

DR. KRAKOWSKI: And then the third point. You mentioned that there's an easier first wall cooling problem and most of the hybrid reactor designs I'm aware of, operate essentially at the same 14 MeV neutron wall loading and take advantage of energy multiplication by going to more compact systems. So in fact you probably have the same first wall cooling problem as in pure fusion.

DR. SCHULTZ: No, I disagree. First let me address the helium coolant question. I did preface my consensus with magnetic fusion. Being from General Atomic Company, I have concerns about liquid metals in anything, particularly a nuclear reactor.

DR. KRAKOWSKI: The wall loading question.

DR. SCHULTZ: Generally, we are indeed looking at the same sort of wall loadings for hybrids as for pure fusion; that is on the order of a few megawatts per square meter on the time average basis. However, you will find that roughly five to ten percent of that neutron energy is stopped in the first wall. In a pure fusion reactor that means that your blanket cooling system has to then pick up 90 to 95 percent of the energy elsewhere.

In a hybrid blanket where you have a blanket multiplication of ten, the ratio of energy deposited in the first wall to energy deposited in the blanket is on the order of one percent rather than five to ten percent. This means then that the first wall cooling is much more easily accomplished without an auxiliary cooling system.

In fusion systems where the alpha power is also deposited on the first wall, the difference is even more striking; 25 to 30 percent of the system power is deposited in or on the wall for pure fusion, while only 3 to 4 percent would be deposited there for hybrid fusion.

FUSION PHYSICS REQUIREMENTS

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Science Applications, Inc., La Jolla, CA 92037

The people at this meeting clearly represent a broad spectrum of technical specialties. We must be making progress, if we are beginning to interest scientists in fields of nuclear research related to but different than our own. I will try to orient my talk towards the non-plasma specialist in attendance. To those individuals who are already intimately acquainted with the physics of plasma, I apologize.

The plasma considerations on making a fusion/fission hybrid reactor are the same as those underlying a pure fusion reactor. Basically, the same present day problems will have to be solved to do either of these things. However, there are some quantitative relaxations possible on plasma conditions between the two. Ultimately, these relaxations on conditions for the hybrid may turn out to be extremely important insofar as feasibility, particularly economic feasibility, is concerned. That is, relaxing the physics requirements may make viable concepts which are attractive from an engineering standpoint but which don't quite measure up to the needs of a pure fusion energy production reactor.

The idea in magnetically confined fusion is to confine a heated plasma sufficiently long that fusions will more than replace the energy needed to produce the magnetic confining field, heat the plasma to temperatures where the fusion cross section is sufficiently large, and make up plant auxiliary losses. In hybrid schemes, all other things being equal, we can get by with a less than breakeven fusion power providing that the ultimate fission plus fusion energy release substantially exceeds the input energies.

The achievement of magnetically confined fusion in either a pure or a hybrid machine requires satisfaction of a number of strongly coupled plasma conditions. These are listed in Figure 1. I will briefly explain what each of these topics mean and how they interrelate. Then I will survey the present status of each.

First, the plasma must be confined. At the very least, the only magnetic configurations that are acceptable must confine single particles trajectories to lie within at least a subvolume of the field. This condition is usually called "equilibrium" although strict equilibrium is not required. The simplest field configuration is a long straight field that is generated by a solenoid. While cross field radial motion is prevented by the field, the particles can reach and leave the ends with their thermal velocities. In the absence of some clever scheme to plug the ends a linear machine must be kilometers in length to hold the plasma for a sufficiently long time to be exothermic. A sufficiently long system might well satisfy fusion conditions while clearly not being in axial equilibrium.

A seemingly simple way to solve the end-loss problem and so shorten the device is to eliminate the ends by twisting the straight field into a torus. Unfortunately, this doesn't work because charged particles drift vertically in a curved toroidal field, right out of the machine. A variety of ways have been suggested and implemented to some degree or other to modify a simple straight toroidal field in such a way as to eliminate the toroidal drift and this is the basic difference between different toroidal reactor schemes. The approach most favored at present is tokamak, in which a plasma current is driven by a transformer, with the plasma being the secondary. The poloidal magnetic field generated by the plasma current when added vectorially to the toroidal field generated by external coils results in a field structure that twists around the torus. Single particle orbit follow these field lines as they stream around the torus. A particle which is drifting upwards when its on a line that is at the top of the torus is drifting away from the center of the torus. On the other hand, when the same line is at the bottom of the torus, and the particle is still drifting upwards, its drifting towards the center of the torus. These effects cancel out and in a complete circuit around the torus the net drift is zero. Hence, tokamaks confine single particle orbits. Some other toroidal schemes you may recall are the following:

- the stellerator, in which the twist of the magnetic field is provided by external coils rather than solely by plasma currents;
- the bumpy torus, in which the field has bumps instead of twists, the bumps causing the particles to drift both up and sometimes down as they go around the torus and sample the bumps;
- the multipole, in which the magnetic lines do not go around the torus but lie in the plane perpendicular to the toroidal axis, so that their curvature causes drifts around the torus rather than out of it;
- the levitron, in which a solid rod in the middle of the torus provides the magnetic twist.
- the tormac, which combines the multipole idea with a toroidal field to reduce the diffusion's losses.

Single particle confinement only constitutes the initial part of plasma equilibrium considerations. A finite number of confined particles will have an associated plasma pressure, and since the plasma is diamagnetic plasma currents will be induced by the magnetic field. These will change the magnetic configuration and modify the equilibrium. The question is now: how much pressure can be held in the magnetic configuration before equilibrium is destroyed? A figure of merit for this is the maximum plasma beta that still has equilibrium, where beta is the ratio of the particle pressure to the magnetic field pressure. Since fusion energy release is related to beta and is the greater the greater beta, the economics of fusion energy devices improves markedly with the permitted beta. Each device has a specific way in which too high a beta destroys the equilibrium state. For example, in tokamak, one breakdown of equilibrium at large beta manifests itself by opening magnetic field lines, which then intersect the walls of the confining vessel. Any plasma which contacts these field lines is quickly lost to the walls.

A scheme which offers an interesting contrast with the tokamak related toroidal machines and the very long linear solenoid devices is magnetic mirror confinement. The magnetic mirror modifies the straight field by increasing the field near the two ends. This results in reflecting those single particles at the ends, whose velocity vectors are inclined with sufficient angle to the field, hence effectively trapping them within the machine. In essence, the magnetic mirror produces end plugs for a certain class of particles whereas the other particles can still stream out of the magnetic field configuration.

So in practice, there are a variety of magnetic geometries which confine the plasma in quasi-equilibrium. However, in addition to selecting a magnetic configuration that confines single particles, and retains equilibrium up to sufficient beta to permit economic operation, we are concerned that the selected configuration is MHD stable; not all configurations are. Failure of MHD stability results in plasma loss on a time scale determined by the particle thermal speeds. There are a large number of potentially unstable MHD modes: kink, ballooning, tearing modes, and so on. To give a feel for what is involved consider the kink mode shown in Figure 2. The kinking concentrates the field lines within the kink, which increases the pressure there, and makes the kink grow; an unstable situation.

Many equilibrium field configurations are MHD unstable for vanishing beta; these have been discarded for CTR use, and there is substantial experimental evidence supporting this choice. The configurations that are serious contenders for CTR application retain stability up to some limiting value of beta. The maximum beta for stability may be larger or smaller than the maximum beta consistent with equilibrium. The entire picture on MHD stability is not gotten from the parameter beta alone. For example, tokamak configurations are unstable if the plasma current hence the poloidal magnetic field B_p , is too large.

Quantitatively, this limit is that the safety factor

$$q = \frac{B_t}{B_p A}$$

be everywhere greater than unity, where B_t is the externally generated toroidal field and $A = R/a$ is the ratio of the torus major to minor radius. This restricts the current allowed in any particular devices, which in turn restricts the possible equilibria which can be stably attained, as well as restricting the ohmic heating power allowed.

In addition to macroscopic MHD instabilities, the plasma may be unstable to microscopic instability modes which result from details of the particle distribution functions (e.g., particle drifts and currents). While not producing the catastrophic loss of confinement that attends MHD modes, microscopic instabilities result in plasma turbulence which may reduce energy confinement time, as if the collision's frequency were increased anomalously. Such reduction may be capable of compromising the viability of at least some plasma machines. For example, the trapped particle modes predicted for tokamak, if they result in substantially larger plasma transport losses than presently anticipated, could compromise the viability of tokamaks. More on this later.

To continue, a fusion reactor requires a magnetic configuration that confines plasma in equilibrium and is at the same time MHD stable through some operating regime having desirable characteristics (e.g., sufficient beta). Next, we must somehow heat the confined plasma to sufficient temperature, and then retain the thermal energy for a long enough time for fusions to more than replicate the input energy. These considerations are illustrated in Figure 3 where we show the product of plasma density and energy confinement time $n\tau$ as a function of plasma temperature, necessary for breakeven and ignition. Breakeven refers to a pure fusion system. The curve would be lower for a hybrid, of course, as described by previous speakers.

For heating there are a number of possibilities. First, there is ohmic heating. Although the plasma resistance falls off with temperature as $T^{-\frac{3}{2}}$, there is some possibility that ohmic heating alone may ignite a high density-small tokamak of the Alcator-type. Heating by an intense microwave source at a frequency where the radiation penetrates and is absorbed within the plasma is also possible. For pulsed machines such as various pinch configurations shock and adiabatic compressive heating can be used. Laser and e-beam heating has been proposed for linear solenoid devices. However, the present "main-line" heating approach is to use intense beams of neutral D gas, with particle energies exceeding 100 keV. Such beams, because they are neutral, penetrate the confining magnetic field and are ionized by atomic collisions with the plasma; once ionized they are confined by the field. Since each just trapped beam ion has an order-of-magnitude or so more energy than a thermal ion, this is an effective heating mechanism.

Two other strategies are available with energetic neutral beams. In the first the plasma is used as a target, and its temperature is not raised to values where fusions between plasma ions are significant. Instead, fusions between the energetic beam deuterons and the plasma tritons are used. Using this scheme, it is possible to obtain a couple of times more fusion energy release than the beam energy. For this procedure to work the electron temperature must be in the 3-6 keV range, since at lower temperatures the slowing down of the beam by collisions with electrons dominates the fusion rates. This beam-fusion, or two-component-plasma approach is particularly suitable for hybrid schemes since the intrinsically low Q (fusion power/input power) can be supplemented by fissions (either in situ or by recycling U-233 produced through fission reactors).

The second strategy used with beams is to eliminate the thermal plasma and use only the beams. Said in different words, the plasma is built up by trapping the beams in the magnetic bottle; the plasma ions then have essentially the beam injection energy. This is the approach used in mirrors. Simple mirrors have energy multiplications which are at best about unity, making them unsatisfactory as pure fusion reactors, but candidates for hybrid applications.

Once a magnetic configuration has been selected that possesses equilibria which are MHD stable, and the contained plasma is heated to fusion temperatures as shown in Figure 3, or alternately use a two-component beam approach, it is still necessary to ensure that the plasma energy is retained for a sufficient time; τ must be sufficiently large.

The energy confinement time τ is limited by two effects. First, are collisional (called classical) effects. In straight fields each collision between ions and electrons causes the particle guiding centers to jump a larmor radius. When the field is bent, as in the toroidal tokamak, the toroidal drift must also be considered and an even larger jump is experienced. These curvature effects are called neoclassical These random jumps due to collisions lead to particle diffusion. Many collisions are required before a particle leaves the torus, and both convective and conductive energy transport must be considered. In mirror collisions, even between like particles, shift the trapped ions velocity vectors into the loss cone and they escape from the machine. A single collision can result in such a loss, explaining why mirror machines have such difficulty breaking even energetically.

The second effect limiting energy confinement is plasma turbulence due to microinstabilities. These are commonly referred to as collective or non-classical effects. Various modes of such instabilities have been predicted for tokamak and mirror configurations, resulting from anisotropy of the particle distribution functions. In tokamaks this results from trapping particles in the mirror resulting from the higher field at the torus inside than the outside; in mirrors it is the absence of velocity vectors lying in the loss cone. The trapped ion microinstability mode is anticipated to result in transport several order of magnitude larger than that from collisional effects, and hence would limit τ in tokamaks. Except for mirrors, which are observed to operate within a factor of 2-3 of classical, this appears to be a common empirical result for all confinement configurations: confinement is limited by transport due to collective effects and not by classical collisional effects, although in many instances the underlying microinstability mode is unknown.

Two comments are called for at this point. First, it appears possible to have the central regions of a tokamak MHD unstable while the periphery is stable. This condition does not result in catastrophic plasma loss, but does result in increasing energy transport loss rates from the turbulent core region. Second, the plasma turbulence that results in the non-linear limit from microinstabilities typically is manifested as a spectrum of electrostatic drift waves, whose electric fields crossed with the confining B field produce random particle drifts, hence diffusion.

All right; now we have a hot plasma confined for a sufficient time in an MHD stable magnetic configuration. The next consideration is that impurity buildup in this plasma be at a sufficiently slow rate to allow an adequately long burn time to allow fusions to replace the energy required to prepare the plasma. Impurities will be sputtered off the surfaces facing the plasma by leaking ions. They degrade plasma performance in two ways. First, by increasing the radiation loss rate from the plasma, primarily by line radiation. The curves in Figure 3 are for a pure D-T plasma. High-Z impurities are worst, and a high-Z ion can radiate at a rate as much as three orders of magnitude larger than a hydrogen ion. The second degradation produced by impurities is in replacing fuel ions, which produces a drop in the fusion rate, since it is proportional to the product of the D and T densities. For example, one 30 times charged impurity ion replaces 30 singly charged fuel ions. In other words, the available magnetic field can only hold so many particles; if it holds impurities (primarily the electrons that balance impurity charge) then it cannot hold fuel.

Having worked my way to the bottom of the list of Figure 1, I want now to return to the top and give a brief synopsis of what the present status is for each item.

- Equilibrium - There is general agreement that tokamak, EBT, tormac, stellerator, magnetic mirrors, and multipole/levitrons, appear to confine individual particle orbits. To date the highest beta's obtained in toroidal experiments are about 1%, achieved in tokamaks; reactor studies envision that beta must be between 5 and 10% for economic operation. The present values of beta are limited by power balance. When the input power is increased, instability or equilibrium limits on beta may be discovered. Magnetic mirrors and linear solenoids reach values of beta of nearly 1, but with the confinement problem referred to above.

- Stability - MHD stability of tokamaks is confirmed experimentally, providing $q(a) \geqslant 4$. Economic operation of a pure fusion power plant appears to require a smaller q(a) . However, present data is for ohmic heating and there is reason to believe that beam heated machines will have a somewhat less peaked plasma current profile and hence can have smaller q(a) .

In present experiments, when q(a) is reduced, first, a turbulent plasma core is observed. Further reduction of q(a) leads to catastrophic disruption of the plasma ring. The detailed mechanism of this disruption is unknown. The other toroidal devices mentioned above have also demonstrated MHD stability, but they have operated in a much more restricted parameter space than tokamak. Similarly, since the use of the so-called minimum-B configuration, magnetic mirrors have likewise demonstrated MHD stability. Linear solenoids often demonstrate rotation and subsequent MHD activity, possibly associated with end effects.

- Heating - Neutral beam heating sources appear to operate effectively without causing plasma instability. To date such sources have represented only a fractional increase in the ohmic heating. However, beam heating will be dominant in experiments planned for the immediate future, and this is an exciting prospect.

Microwave heating has also been demonstrated in a number of experiments. However, the waves used in these experiments do not scale, for various technical reasons, in a manner suitable for use in larger, hotter machines. The effectiveness of a potentially more desirable mode, lower-hybrid heating, has not been experimentally confirmed, although here also experiments are underway.

At present, peak electron temperatures of 2-3 keV have been obtained in tokamaks. Other toroidal machines typically have operated in the range of a few 100 eV, while linear theta pinches have achieved ion temperatures up to 5 keV. Mirrors, of course, inject hot ions, so the temperature is "built in".

- Energy Confinement - The energy transport rates observed in tokamak are anomalous and cannot be predicted by present theory. The transport rates, due to trapped particle microinstability modes, that are expected to dominate in the thermonuclear plasma regime are based entirely on theory, and order-of-magnitude theory at that.

Nevertheless, at present values of $n\tau$ of a few times 10^{13} have been obtained. See Figure 3, where the dot represents the present status of tokamak experiments. Just as mirrors and pulsed solenoids held record temperatures, tokamak is well ahead of the field in $n\tau$, due mainly to the rapid end loss in both mirrors and solenoids. Other toroidal devices have not been tested on the scale employed by the tokamak program.

- Impurity Control - The behavior of impurities in present experiments is not understood, and there is small confidence that we can predict behavior in the thermonuclear regime. The uncertainties are of two natures. First, the retention time of impurities within the plasma is not known. Classically, the high-Z impurities would concentrate near the plasma center, and would have much longer lifetimes than fuel ions. However, if collective transport dominates the lifetimes would be the same and the impurity profile would be much flatter than for the classical case.

The second area of uncertainty has to do with the sputtering source of impurities. This has to do with such questions as the energy spectrum of ions leaking from the plasma. Present experiments have much lower ion energies than would be encountered in a fusing plasma. The effect of the 3.5 MeV fusion alphas, some of whom will impact the wall, must also be considered.

Two additional comments on impurities: first, the Alcator tokamak was operated with very small impurity buildup. This encouraging result is not typical of other tokamaks. Second, divertors, deliberate insertion of a separatrix near the plasma boundary by external coils, may reduce the impurity problem, and has been tested in part by DITE in Culham, and soon in PDX, in Princeton.

Now, for the comment or two on mirrors. Mirrors appear to be a good candidate for hybrid applications. For one thing they are better understood, in the sense that MHD theory has been more successful vis-a-vis mirrors than tokamaks. In present regimes at least, the energy loss due to instabilities is not very much more than classical. Impurities trapped in mirrors have shorter confinement lifetimes than do fuel ions. The great deficiency of mirrors, breaking even energy-wise in a pure fusion mode, is not necessarily fatal to hybrid operation when fissile production is taken into account.

A similar situation holds with respect to laser fusion. In this case confinement is irrelevant since the idea is to make the fusion time shorter than the time for dissembly of the pellet. Stability remains a consideration, since compression of the pellet core to fusion conditions requires that not too much of the laser pulse be reflected, that the pellet retain its symmetry and that no preheating of the core take place due to classical or collective transport processes. Laser fusion has had considerable success in achieving these conditions, and it may well be that experiments under construction (SHIVA) will produce a neutron output equal to the energy of the incoming laser beam, "break-even". However, when laser efficiency, etc, is considered, these devices remain far from being exothermic. The added equivalent energy output provided by U-233 breeding is a substantial boon to laser fusion and mirrors, in just the area where they most need help.

EQUILIBRIUM

- SINGLE PARTICLE
- FINITE BETA

STABILITY

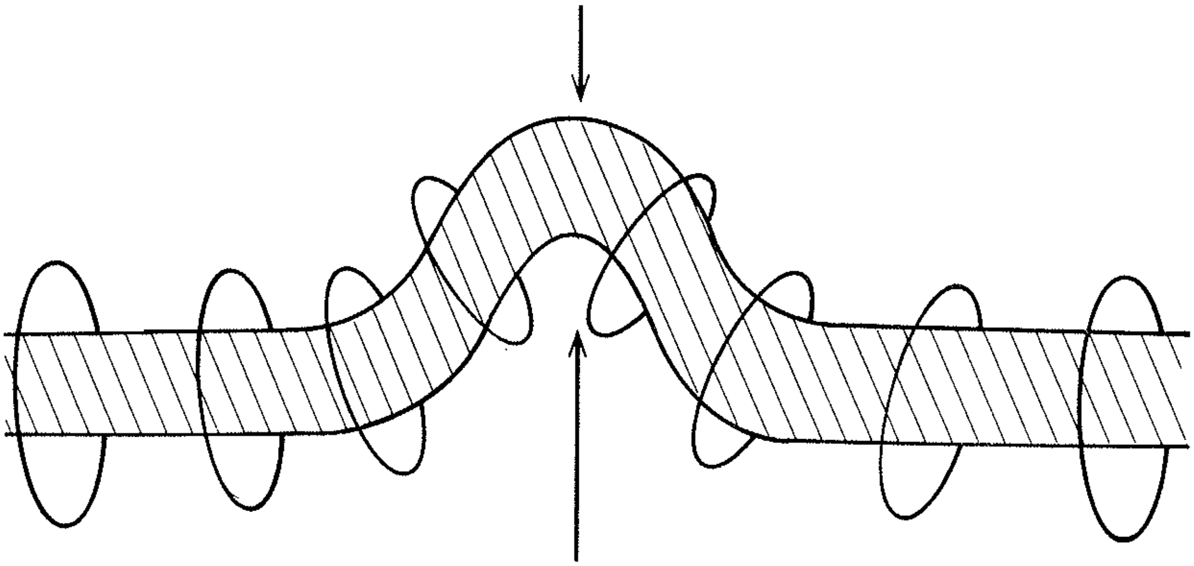
- MHD
- MICRO

HEATING

ENERGY CONFINEMENT

MAINTENANCE OF PLASMA PURITY

FIGURE 1



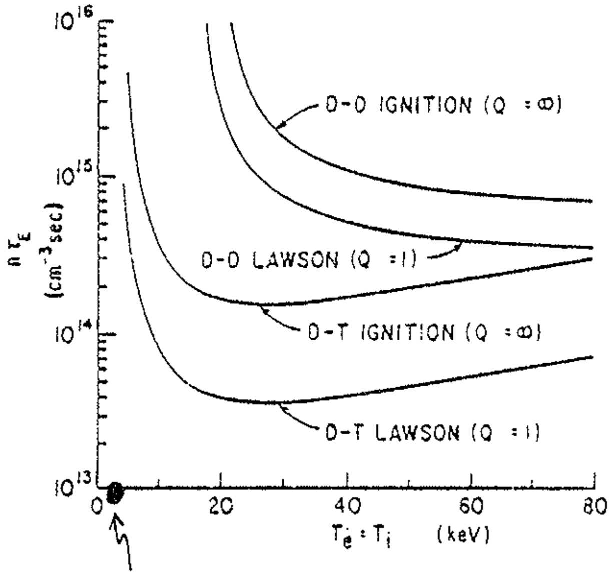
FIELD LINES FURTHER APART

(LOWER PRESSURE)

FIELD LINES CLOSER

(HIGHER PRESSURE)

FIGURE 2



(BEST TOKAMAK EXPERIMENTAL DATA)

FIGURE **3.** Confinement requirements for DT and DD fusion as a function of temperature. Curves for breakeven (power multiplication factor Q = 1) and ignition (Q = ∞) are shown. (Ref. 4).

MR. NEFF: Let's take about five minutes for questions.

DR. RIBE: Fred Ribe, University of Washington. I think it is interesting when Nick, in his masterful presentation, called attention to the heating problem. I would like to make a remark of a general engineering or systems nature, which has to do with heating, and see if people think it is a true statement.

Ninety percent of the magnetic fusion program is the Tokamak and Mirror and these both depend, essentially exclusively, on neutral beam heating. Therefore, the future of fusion, to the extent of 90 or 80 percent, depends on the success of neutral beam heating.

DR. KRALL: Well, anybody else can comment. I would like to comment, first, that I don't agree with what you say, exactly, Fred; one of the rare times I fail to agree with what you say.

If you take a physics point of view, you might say that there are several things you are trying to demonstrate. You are trying to demonstrate whether you can find an equilibrium at a substantial beta, confine it long enough to fuse, and heat it to ignition or breakeven.

You might almost view the use of neutral beams, presently, as a technical device to enable you to study whether hot plasmas are confined, are stable, exhibit finite beta, and have losses that you can tolerate. Historically, it may turn out that is all that neutral beams have done.

Certainly, there are proponents of heating Tokamaks to ignition by ohmic heating; the high-density, high-field concepts. People like Porkolab, and others, and the people in the French community are working very heavily on wave heating with the idea that that is what you are going to need as the neutral beams phase out.

So you might say that so far, ninety percent of the effort in fusion has been devoted at proving you can have an equilibrium at a substantial beta which is stable and a loss rate that you can tolerate. And the tragedy would be if we continued to -- if we actually thought that we actually had the heating scheme and froze out the other heating schemes. That could be a disaster, because we may not.

DR. RIBE: I think that is the point I am addressing. The only seriously advanced magnetic fusion devices in this meeting have been ones -- the Mirror and the Tokamak -- that are neutral beam heated and these are pushed on up into the near gigawatt level of neutral beam heating as conceptual reactors.

And one is left with the impression, and I think it is reflected in sort of the funding of the concepts of the program, that if neutral beam heating doesn't make it, fusion doesn't make it either for fission-fusion or for pure fusion.

ENVIRONMENTAL AND SAFETY ASPECTS OF FUSION-FISSION HYBRIDS

John P. Holdren*

Environment and Safety in Context

Let me begin by trying to put environmental and safety characteristics of hybrids into context as part of the possible overall rationale for developing these systems. I shall do this by making reference to a set of criteria embodying the rationale for any new energy source, namely: fuel supply, energy cost, timing, systems compatibility, environment and safety, and diversity.

Under fuel supply, one wants to ask, how inexhaustable is the fuel, how reliable is it in terms of susceptibility to disruptive interruptions, how satisfactory is its geographic distribution? This criterion really doesn't apply very cleanly to hybrids, however, because their most interesting application appears to be assuring a fuel supply for a complementary energy technology, namely, fission convertor reactors.

The second criterion is energy cost, by which one means, of course, not only the fuel cost, but also the construction costs, the operation and maintenance costs, and the costs of any transmission and distribution systems that are required.

Under timing, there are two main questions. The first one is, how soon can we have it? The second is, how fast can we expand it? Here the hybrid's particular relevance is to the question of how fast one can expand the fission option. That is, in the hybrid's role as a fuel producer, which seems to be the most interesting one, what it permits that alternatives might not permit is a rapid expansion of breeder reactors by supplying fuel for their inventories, or a rapid expansion of converter reactors by providing an ongoing and

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reliable source of fissile fuel for burnup.

Systems compatibility embraces a variety of criteria. One of them is matching sources to end uses. That is, does the technology in question provide energy in the forms in which you need it, at the places where you need it? Another aspect is compatibility of proposed new sources with existing options that you have and with future options that you would like to have. In this respect, the hybrids have another area of strength: they are compatible on the short-term end with fission, being intended, after all, to make fission a more viable option by supplying fissile fuel; and they are compatible with a long-term option we would like to have, being a stepping stone toward pure fusion.

There are still other forms of compatibility; social and regional compatibility are two that, increasingly, are being talked about. Social compatibility means: Does the choice of energy system intrude in any way on other characteristics of the society which you might prefer not to have influenced by energy choices? Regional compatibility means: Do the sources that (for example) the United States chooses have beneficial or negative effects on choices other countries make?

The next criterion on my list is environment and safety, by which I mean to include matters of health and safety, matters of impact on climate and ecosystems, and a category which I will call weapons connections. These matters are the main focus of my remarks here, and I will return to them in detail in a moment.

Listed last among the ingredients of my rationale is diversity. Diversity, I sometimes say, is the last resort of proponents of new energy technologies who can't make a convincing case on the other grounds. At the same time, there is an argument for diversity as an insurance policy against uncertainty. That is, in uncertain times, you should buy lots of different technologies as a hedge against the unexpected or the unpredictable. This argument has a certain amount of merit, but you cannot really use it as a carte blanche to build everything. We know, given finite money, that everything is not going to be built, and some choices are going to have to be made.

Now I want to assert that, among all these criteria, environment and safety take on special importance in part because the attractive characteristics of the hybrid on the other grounds hold only in a rather narrow "window" in terms of what the future might be like. That is, *if* we have a high growth of electricity in the energy future in the United States, and if society chooses to provide a substantial fraction of that high growth with fission, then hybrids look very interesting indeed. If the growth rate of electricity is low, however, or if on economic or public-acceptability grounds the growth rate of the fission option is low, then hybrids look much less attractive. Now, the uncertainty about whether that particular vision of the future in which hybrids are economically very attractive actually will materialize weakens the rationale for spending the money to develop them; this increases the relative importance, in the rationale, of environment and safety characteristics.

There is also a more general argument for special attention to environmental characteristics. It is that the recent evolution of the energy debate is toward ever increasing emphasis on environment and safety charactertistics and that (although this is necessarily a personal judgment) this trend is unlikely to be reversed. That is, I submit that if we look at the short-term trauma over selecting energy choices, we are seeing not a problem due to the absence of choices, that is, the absence of potential resources, but rather an increasingly vigorous (and time consuming) debate over what sorts of choices are environmentally acceptable. I believe that this increasingly intense debate on the social and environmental links between energy choices and well-being, as opposed to the strictly economic links, will continue in the future, however much some technologists might wish simply to be allowed to get on with the task of expanding energy supply.

Environmental Issues Generic to Nuclear Sources

Notwithstanding the breadth of environmental aspects of energy sources, I will confine myself in this presentation to those issues generic to nuclear sources. These can usefully be classified under four headings which are, in increasing order of importance: routine emissions and exposures; management of long-lived radioactive wastes; accidents and sabotage; and weapons connections.

Concerning routine emissions and exposures, I would argue that these are already substantially under control in the fission business and there is no reason to believe that they will not be under control in the fusion business or in the fission-fusion hybrid business, although there are certain interesting aspects of hybrids in this respect that I will mention very briefly.

The second category is management of any long-lived radioactive wastes. This is, I think, higher on the public agenda at the moment than it deserves to be. The radwaste problem is almost certainly manageable, in principle, in terms of impacts on the public. People are troubled, and I am, too, about the notion of rapid expansion of fission power before a solution has actually been chosen, but I think this is more a problem of management than a problem of technical intractability.

The next two categories, in my view, are more fundamentally intractable in principle, largely because of the greater role played by human error and malice. In the case of accidents and sabotage, for example, we cannot count simply on engineering clever systems that are relatively safe against fools. We have to design systems that are relatively safe against malicious people who are not fools in the usual sense of the word.

Finally one comes to the question of weapons connections: the whole proliferation problem on the international level, and the problem of access of bomb-quality materials or radiological toxins to sub-national groups. This complex of issues increasingly is recognized as the Achilles' heel of fission energy.

Relevant Characteristics of Hybrids

What are the characteristics of hybrids, in particular, relevant to an assessment of their relative merits and demerits as concerns these generic environmental issues? These characteristics may usefully be grouped under three headings: radioactive inventories; pathways for their escape or diversion; and systems aspects.

Under the heading of radioactive inventories in hybrid reactors, we are interested in tritium, in activation products, in actinides, and in fission products. We must be concerned, of course, not only with how many curies are in there, but with the hazard lifetimes associated with these (that is, how long the various materials take to decay to relatively innocuous levels), with various kinds of measures of biological hazard potential, and with the form in which the radioactive inventories occur (volatility, solubility, concentration, and so on). One possible disadvantage of fusion and fusion-fission hybrids is that the activation products cannot be reduced very easily to a compact form, if they are dispersed through a large metallic structure of the same elemental composition as the radioactive materials themselves. The fission products from a fission reactor, by contrast, can be reduced to quite compact sizes, although the toxicity is still there. On the other hand, hybrids and pure fusion have the advantage, in principle, of considerable flexibility in choice of materials, which enables one, to some degree, to tailor the amount and the toxicity of radioactive products produced. As everybody knows, in fission, the basic physics tells you approximately what you are going to get in terms both of quantity and toxicity.

Of course, it is not enough to know what is inside the reactors in terms of inventory. One really has to be at least equally concerned about what pathways exist for the possible release of those inventories. Some of the principle issues under the heading of pathways are: criticality behavior, loss of coolant or coolant flow, other stored energy forms, plumbing, and transport and handling.

I begin with criticality. A subject that has been discussed as long as hybrids have been discussed is the possibility of designing hybrid blankets in such a way that they are sub-critical under all conceivable conditions, that is, not only sub-critical under operating conditions, but sub-critical in the event of loss of coolant, in the event of cooling to room temperature, and even in the event of geometric reconfigurations that might be caused by the blanket falling into a void previously occupied by the fusion core.

The matter of criticality, I think, is really not settled in the hybrid business for all of the possible reconfigurations. That is, it is a quite difficult thing to design a blanket that is both economically interesting in terms of fuel production capability and power density and that would remain sub-critical in the most compact configuration that you could imagine. Nevertheless, it appears that hybrids probably can be designed with a very substantial advantage in this respect as opposed to, say, LMFBRs.

On the other hand, it may well be that criticality accidents in LMFBRs have been overrated as a relative source of hazard for those devices. That is, I would personally assess the trend in LMFBR safety analysis as going in the direction of relatively less and less concern with nuclear excursions, and more concern with loss of coolant, sodium fires, and other kinds of events. If it really can be demonstrated that criticality accidents are not a major problem for LMFBRs--and, certainly criticality accidents are not a major concern for LWRs--then the area in which hybrids may have their principal advantage becomes a second-order issue altogether and takes away from hybrids one of their principal selling points.

Another problem, potentially, is loss of coolant or loss of coolant flow. Here, what one would like to have is a system that is passively coolable in the event of loss of coolant or loss of coolant flow, that is, one which by natural convection, conduction and radiation can maintain the blanket below its melting point, or below the point where radioactive compounds contained in it can become volatile. Again, the matter is not entirely resolved. There is a conflict here, as there often is, between economics and safety. That is, one is being pushed, in the designs that have been produced so far, rather steadily in the direction of higher power densities, which means higher after-heat densities, increasing the difficulty of passive cooling.

One does not have--or at least one does not have very easily accessible--the advantage of pot designs in LMFBRs, where, in the event of a loss of coolant flow, the chances are that the core will remain immersed in a pot of the liquid metal coolant. In the case of hybrids, the coolant is invariably in process tubes. It is very difficult to design a reactor in such a way that there is both enough liquid metal in it and a container to catch it, such that leaks in the process tubes would still lead to the blanket being immersed in a pool of effective coolant which could--by convection, as the LMFBR case--take care of the event of loss of coolant flow.

There are other stored energy forms that are of interest in hybrids. One is the energy stored in the magnets. There has been a good deal of attention given over the years in pure fusion systems and, now, in hybrids, to ways in which one could prevent the rapid release of energy in the magnets in a way that could disrupt the system. My own view, from reading the fusion literature, is that this problem is fairly well in hand. At the same time, it was suggested by at least one observer at the joint U.S.-USSR hybrid meeting in the summer of 1976 that there are some interesting questions left to be examined carefully in terms of magnet design for hybrids in such a way that they could not cause a significant reconfiguration of the blanket.

There was a suggestion made at that same meeting that the use of metallic fuel has some significant advantages in the event of a melt-down because the melting point of the metallic fuel would be lower than the melting point of the stainless steel structure surrounding it and, therefore, one could catch the molten fuel and cool the stainless steel from outside. This has an advantage over ceramic fuel whose melting point would be higher than that of the steel and which would eat its way through. There is with liquid metal coolants the possibility, of course, of a lithium fire, or a sodium fire, as is the case for LMFBRs.

In the case of gas coolant, of course, the principal stored energy associated with the coolant is the high pressure. It is my own assessment of the debate in the field that people are less worried about the pressure in the helium than they are about the chemical energy content in the lithium if you choose to use liquid metals. This is the basis for the frequently heard statement that helium is preferable in terms of safety. (Not everyone buys that statement, but some people vigorously assert it.)

By plumbing I mean the whole question of seams, welds, lengths of pipes, and so on, which gives some measure of the vulnerability to leaks, both major and minor. One of the potential problems of hybrids devised so far in this respect is that there tends to be a lot of plumbing and, hence, what appears to be greater than usual complexity in terms of dealing with leaks at seams and welds and valves, and so on. Of course, this is mainly a problem in terms of routine emissions which, I would guess, will remain relatively low on the overall agenda.

Transport and handling refers, of course, to your interest not only in how much material exists in a reactor, but, more seriously (from the point of view both of leaks and of diversion by sub-national groups of fissile material) how often you have to move it around, how far it goes, how many batches there are, and so on.

Finally, there is the question of systems aspects which, in hybrids, belongs near the top of the list. That is, one is not concerned so much about whether a hybrid is as safe or safer than a light water reactor or an LMFBR, but rather, whether a system that contains hybrids is better in terms of environment and safety than a system that does not. It is widely pointed out that, in the fuel-producing mode, you might have only one hybrid for 5 or 10 light water reactors; this suggests to many people that it would not be worthwhile to try to make the hybrid significantly safer than light water reactors.

There are a couple of aspects of this question that I will simply place on the table as issues that people should be thinking about. One is the way in which the whole question of public acceptability is intertwined with safety and environment issues. I suggest that, from the point of view of utilities, who are probably feeling rather badly burned these days in terms of their ability to get things sited in the face of a rather critical public, it would be nice if any new technology had dramatic and transparent safety and environment advantages, even if it were only going to be installed at the rate of one new plant for ten existing ones. This is because the general suspicion of anything new, and the general critical atmosphere with respect to safety and environmental considerations, will somewhat override the effect of "dilution" of the new with the old. I think people are going to look very critically at anything new you want to install and, from the point of view of utilities' interests, this matter will be important.

In terms of fuel cycle and reactor mix, the systems questions, as I see them, are as follows.

First, with respect to fuel cycle, it may be that hybrids based on the thorium cycle could permit you to run a thorium/U-233 fission economy, which would otherwise be very difficult to run. Now, if you conclude that a thorium/U-233 fission economy has significant proliferation or anti-terrorist advantages, and if a hybrid permits you to have such an economy where you otherwise couldn't, then that is a significant systems advantage of hybrids compared to not having them. The trouble is that, at this point, I don't think we know whether the thorium/U-233 cycle really offers significant anti-proliferation or anti-terriorist advantages. Some people vigorously assert that it does; others vigorously assert that it does not; and still others vigorously assert that one cannot even discuss the matter without access to classified literature, which puts us in a bit of a dilemma.

With respect to reactor mix, we are in a similar situation. It might be that the addition of hybrids to the mix permits you to run a system of HTGRs, where otherwise you would need to have a system of LMFBRs. Now, if it is true that HTGRs have fundamental and significant safety advantages compared to LMFBRs, then it is perhaps a big advantage to have hybrids so you can have the HTGRs. On the other hand, not everybody agrees that the HTGR has intrinsic and fundamental safety advantages over LMFBR. The countervailing position is, the NRC is not going to license anything that isn't adequately safe, so why should we spend a lot of money to substitute HTGRs for LMFBRs? One cannot expect a tremendous amount of agreement, even in this audience, on how important the incentive is in that particular area.

Conclusion

We have a great deal of fundamental homework to do in understanding, quantitatively, what hybrids are likely to look like in terms of their environmental and safety characteristics. There is great sensitivity to choice of coolant, to choice of fuel, to choice of structural material, to choice of tritium breeding medium, and to details of the chosen designs. Exploring the ramifications of these many possibilities for environment and safety is a big job, and it is none too soon to start working on it in earnest. This is essential, because the environmental and safety characteristics are so tightly intertwined with the question of whether there is a strong case for hybrids at all.

MR. NEFF: We will take a few minutes to answer questions.

DR. KUREY: Thomas Kurey, General Electric. This comment is not safety related. However, I would like to take this opportunity to comment because the speaker did allude to a scenario, which has been alluded to by most of the speakers previous to this speaker, where fusion-fission hybrids are related to, or put in a picture related to, growth in electical power demand.

Now, I want to mention that there is another potentially significant application of the fusion-fission hybrid and that is for the support of reactors which are used for process heat application. In particular, pebble bed reactors, which operate at very high temperatures, have significant applictions in the process heat market.

A significant amount of work is being done in Germany in this area and we have a group at General Electric Company studying this area of application for gas cooled pebble bed rectors.

I think that in the scenario which we build for fusion-fission hybrids, we ought to keep in mind this alternate application of fission reactors. I think it affects cost benefit analyses, and it affects where fusion-fission hybrids fit into the overall energy picture. I want to reiterate also that the fusion-fission hybrid can also potentially serve the process heat market directly as has been alluded to by some previous speakers.

So, I would remind people that when they are talking about fusion-fission systems to solve fission related problems, which this conference is emphasizing, the support of reactors used for process heat applications should be given attention.

DR. HOLDREN: If I can make just a brief response, I would certainly agree with the first part of your comment, which is, that to the extent that process heat applications of fission expand, the window for usefulness of hybrids expands correspondingly. And, of course, that would enter the cost benefit analysis.

The second part, which is direct use of hybrids themselves for process heat, I find likely to be much less interesting on the same grounds that hybrids, as straight electricity producers, don't look terribly economically interesting in comparison with either pure fission now or pure fusion systems later.

DR. KUREY: Yes, I agree, but I think that even this latter application has to be looked at in a little more detail before we draw our final conclusions.

DR. HOLDREN: Fred Ribe?

DR. RIBE: There is an interesting opportunity to use process heat for the production of storable fuel, just the way your primary product in the fusion-fission plant is storable fissile fuel which, in principle, keeps you off the grid. Production of storable fuel could be a big thing because you are 80 percent off-line anyway, because you are making fissile fuel.

DR. HOLDREN: Yes, this is true. And, in fact, one can get into some very elaborate discussions. I would put this question under the category of compatabiity between sources and end uses, namely to whether process heat is a good use of the very high-quality energy that is produced in nuclear systems at all. It may or may not be. There are some interesting debates around that question of whether, at least at the low temperature end of the process heat spectrum, this is the way one wants to do it. At the high temperature end of the process heat spectrum, it certainly looks like a good idea.

But making chemical fuel -- well, I don't think we want to get into that here. That is really a messy, messy issue.

Ralph?

DR. MOIR: Ralph Moir, Lawrence Livermore Lab.

John, I would like to have you give an opinion about a following assertion I have. You have treated many environment and safety issues, but you have, I think, completely ignored the cost. And what I mean by that is, every time you have an environment and safety advantage that can be gained by technical add-ons, there are generally costs associated with that. And at a very high added cost, you can get tremendous additional safety; at a little bit of extra cost, you can get a little bit of additional safety.

As a technical person in this field, I would like to hear a discussion of how much costs for how much safety. There has been an absence in your discussion of this cost aspect. Would you comment on that?

DR. HOLDREN: Well first of all, I think it is too soon in the case of hybrids to make any quantative statements about how much it would cost you to achieve different levels of safety or different potential proliferation advantages because, in fact, as I have already asserted, we really don't know what those are.

Nobody has looked in quantative detail just at the differences between the various options to know what you are buying in exchange for certain costs. And before you can talk about how much you are getting for what you are paying, you have to know something about both; what you are getting and what you are paying. We don't know enough about either to make any quantative statements there.

Philosophically, of course, one can have a very interesting discussion as to whether it is worth paying anything to be better off than we already are, say, with LWRs and LMFBRs in terms of safety and environment. There is where you get into the problem of, I think, an inseparable intertwining of public perceptions about what is acceptable and technical perceptions about what is achievable.

The fact is, if public perceptions about what is acceptable prevent you from building a large LMFBR economy at all, then the cost of not having something that is perceived as safer can be very high indeed. And there is no way, I think, to put an easy number on that. But what I was asserting in my general statement about the importance of environmental factors is that we are already seeing a lot of evidence that people are becoming as concerned about the environment and social links between energy and well-being as they are about the economic links.

Now, one can't always put dollar values on those environmental and social links; between what one does in the energy sector and how it relates to what people perceive as their total level of wellbeing which includes public health, environmental conditions, and things like fears concerning small probabilities of big disasters.

I don't think we will ever get to the point where the public will regard a one in 10,000 chance of 10,000 deaths, giving an expected value of one per year, in the same way that they will regard a routine insult that is killing one person per year on the average.

Again, this notion of the degree of psychological trauma associated with small chances of big disasters is something that the nuclear community has already had a great deal of trouble with and will have some more.

I don't know how to put a dollar sign on it. I do know that if one can build a system where one can assert to the public with confidence and with a consensus in the technical community that this system is passively safe against certain kinds of events which appear to be threatening, or if one can build a system where you say, if the worse thing happens -- if a Boeing 747 crashes into the top at 600 miles an hour -- you are still not going to have any dead bodies off-site, then one has got a qualitative advantage which would be to the considerable advantage of that technology. What it is worth, I don't think anybody can say.

TOKAMAK TECHNOLOGY REQUIREMENTS:
THE ORNL FUSION POWER DEMONSTRATION STUDY*

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Summary

In this paper, we review the design approach developed in the ORNL Fusion Power Demonstration Study.[1] The major emphasis of this study is in the application of current and near-term technology as the most logical path to near-term demonstration of tokamak fusion power. In addition, we are pursuing a number of concepts to simplify the tokamak reactor to be more acceptable to the utility industry as a future source of energy.

The discussion will focus on the areas having the greatest overall impact on reactor feasibility: 1) overall size and power output, 2) remote maintenance considerations, 3) electrical power supplies, 4) blanket design, and 5) economics.

The tokamak device, by nature of its configuration and pulse operation, is an exceptionally complex engineering design problem. We have concluded that innovative design concepts are essential to cope with this basic complexity. We feel that the feasibility of tokamak fusion power has been significantly improved by these design approaches.

I. INTRODUCTION

The ORNL Fusion Power Demonstration Study was initiated in FY 1976 with the objective of providing a basis for planning a path to tokamak power demonstration. It is recognized that there is no unique set of technological directions, engineering designs or plasma parameters which offers promise for the demonstration reactor. Several such sets, no doubt do exist. In this study, we seek to define one promising set of technologies, design approaches and plasma characteristics. We have stressed the need to simplify the overall design approach since the tokamak is by nature of its configuration and pulsed operation an exceptionally complex design problem.

It is our judgement that the number of new technologies and facilities required for demonstration must be minimized. In carrying out the study we have emphasized the application of current and near-term technologies.

Since the projected cost of fusion power must be evaluated in competition with other advanced energy systems, we have performed systems analysis and costing evaluation as the justification for component sizing and selection. A computer model was developed to scale plasma parameters, design configuration and component cost.

2. PLASMA PHYSICS CONSIDERATIONS

The feasibility of tokamak fusion power is more uncertain in the plasma physics performance than with limitations in technology and engineering. We have taken an optimistic outlook for the plasma physics in selecting operating characteristics which lead to an attractive physical size and power output. These characteristics are consistent with present theoretical understanding of tokamak behavior, but the definitive answers must be verified in tokamak experiments. A representative set of parameters are presented in Table I.

3. SIMPLIFIED DESIGN APPROACH

The following design concepts are representative of the approach taken to simplify the overall reactor design and improve its reliability for commercial application.

A. Size Reduction

Our plasma engineering studies indicate that the reactor size for ignition is essentially in the range of a moderate sized commercial power plant (500 to 1,000 MWe). Assuming that beta values of 5-10% can be obtained, the overall size of the reactor can be quite small in comparison to other recent reactor concepts. Figure 1 illustrates the size comparison between the UWMAK II design of 1975 and the reference design of this study. Also note that a Combustion Engineering pressurized water fission reactor is shown to illustrate current power and utility industry experience in reactor size. This overall size reduction has major implications in enhancing the practicality of tokamak power reactors.

B. Vacuum Topology

We are proposing that the tokamak reactor system be enclosed in a vacuum building. By eliminating the atmospheric pressure on the toroidal plasma vessel, the requirement for leak tightness becomes insignificant since the pressure on both sides is nearly equal. This approach will virtually eliminate the complex remote maintenance and assembly problem associated with welding and inspection of the plasma vacuum vessel.

To establish the engineering feasibility of this concept, we have located an existing vacuum building constructed by NASA near Cleveland, Ohio. In Fig. 2, the DEMO reactor is superimposed in this facility to illustrate that the basic size and containment is within reasonable extrapolation. In addition to the assembly, disassembly and repair advantages, the vacuum building also improves the ability to contain and control tritium.

C. Iron Core Option

Our initial evaluation of an iron core option indicates a reduction in power supply requirements as well as improvements in design. The additional cost of fabrication and construction of the iron core must be carefully evaluated with the reduced cost of power supplies. However, the iron core eliminates the air core windings under the tokamak device which has been a major concern for maintenance and repair (see Fig. 3).

D. Blanket Modular Approach

In order to minimize downtime and facilitate maintenance, the blanket design philosophy has been to seek a modular approach which eases the problems of remote maintenance. Thus, remote maintenance has been identified as a major objective and design consideration in the development of the engineering design for the blanket configuration. In this context, we are stressing small, easily replaced individual blanket modules. Figure 4 is an illustration of one concept under study.

4. APPLICATION OF CURRENT OR NEAR-TERM TECHNOLOGY

The primary technology for the demonstration reactor is listed in Table II. The following concepts were identified in this study.

A. Blanket Structural Material and Coolants

It is our judgement that an alloy similar to type 316 stainless steel will be capable of achieving integral wall loading of 10-20 MW-yr/m^2. This is accomplished primarily by limiting the first wall temperature to 400°C to minimize radiation effects. Moreover, the unique helium production reactions associated with nickel-bearing alloys in thermal neutron fluxes allow an excellent simulation of fusion reactor neutron radiation effects in existing fission reactors. Gaseous helium now appears to be the most attractive blanket coolant for a stainless steel system with lithium as the breeding material.

B. Power Conversion System

The recommended power conversion system would consist of a primary and intermediate heat transfer loop coupled to a conventional steam cycle. Assuming a primary loop exit temperature of about 450°C, a steam cycle thermodynamic effiency of ∿35% can be achieved.

C. Pulsed Electrical System

Our studies indicate that the primary energy storage requirements can be satisfied with conventional motor-generator flywheel sets. Advanced energy storage concepts such as homopolar generators and superconducting energy storage devices may offer some cost savings, but do not appear to be necessary for commercial feasiblity.

5. ECONOMICS

The results of the tokamk plant cost studies[2] indicate the following:

1. Direct captial costs are comparable to other advanced energy systems (1,000-2,000 \$/kWe).
2. Plasma size of 1-2 meters and maximum fields of 6-11 tesla are required.
3. The power output of tokamak reactors can be in the range of 500-1,000 MWe.
4. In contrast to fission reactors, unit captial costs for tokamak reactors do not necessarily favor larger power levels.
5. Multiple reactor units sharing common equipment can significantly reduce unit capital cost relative to the single reactor unit case.
6. Neutron wall loadings in the range of 2-4 MW/m^2 with material lifetimes of 10-20 MW-yr/m^2 will result in near-optimum plant costs.
7. A three-phase program, built around a single-site multiple-unit concept, offers a viable strategy for demonstrating the commercial feasibility of tokamak fusion power.

6. CONCLUSIONS

The concepts evolving from the ORNL Fusion Power Demonstration Study are providing a basis for planning a path to tokamak power demonstration. In particular, this study has provided the following conclusions:

1. Optimistic assumptions on plasma physics performance (β of 5-10%, a of 1-2 meters) result in reactor size and power levels in the range of present power and utility industry experience.
2. The use of a vacuum building improves the reliability and safety of the reactor and significantly improves the problem of remote maintenance and assembly of the blanket vacuum vessel.
3. An iron core ohmic heating system eliminates the troublesome coils under the tokamak device and offers the potential of reduced cost by reduction in power supplies.
4. A modular approach to the blanket design eases the problems of remote maintenance.
5. The technology base for the demonstration reactor can be founded upon current and near-term technologies.
6. The economics of fusion plant design favor multiple tokamak units which share a common electrical plant.

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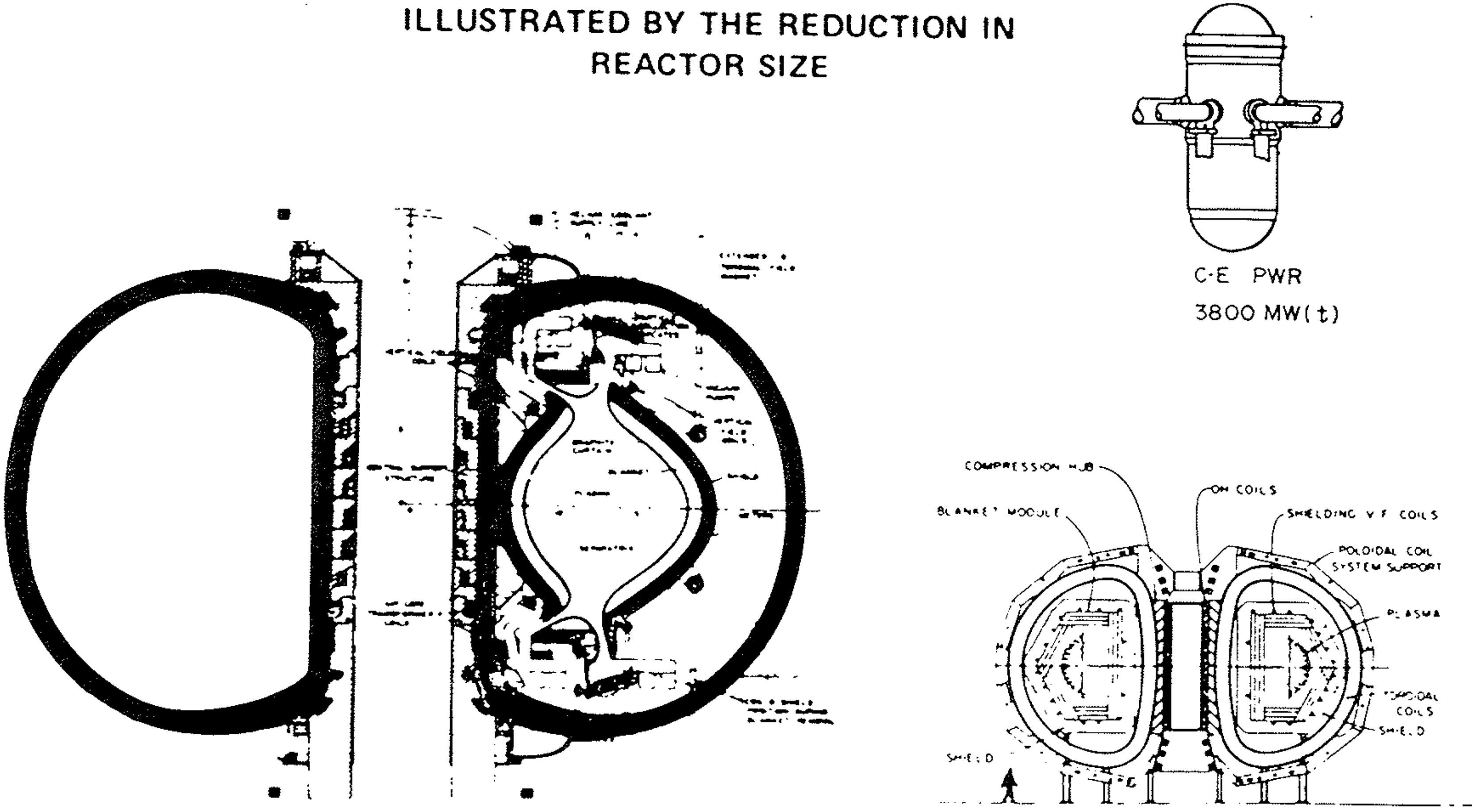
TABLE I. TOKAMAK POWER REACTOR PARAMETERS

Average Beta, β	0.10
Neutron Wall Loading, L	2.75 MW/m^2
Safety Factor, q	3.0
Aspect Ratio, A	4.0
Plasma Radius, a	1.55 m
Plasma Elongation, σ_p	1.6
Field on Axis, B_T	3.4 T
Field at TF Coil, B_{max}	8.0 T
TF Coil Horizontal Bore	7.1 m
TF Coil Vertical Bore	9.6 m
TF Coil Elongation, σ_{TF}	1.35
Ripple (at Plasma Edge)	2%
Burn Time	23 min
Power (Burn), P_B	865 MW(e)
Power (Average), P_A	825 MW(e)
Duty Factor	0.95
Thermal Efficiency, η_T	$\sim$0.35

TABLE II. TECHNOLOGY BASE FOR NEAR-TERM APPLICATIONS

System	Technology	Base
Magnet	NbTi and Nb_3Sn	Large Coil Program
Plasma Heating	Neutral Beam Injection	TFTR
Blanket Structure	Austenitic Stainless Steel	Alloy Development Program
Tritium Handling	Cryopumping and Extraction	Tritium Systems Test Assembly
Pulsed Power Supplies	Motor Generator Flywheel Sets ($\sim$500 MVA and $\sim$35%)	TFTR
Energy Conversion	Steam Cycle ($T_s \sim 750°F$ and $\eta \sim 35\%$)	Industry

THE PROJECTED IMPROVEMENT IN PLASMA PERFORMANCE IS MOST DRAMATICALLY ILLUSTRATED BY THE REDUCTION IN REACTOR SIZE



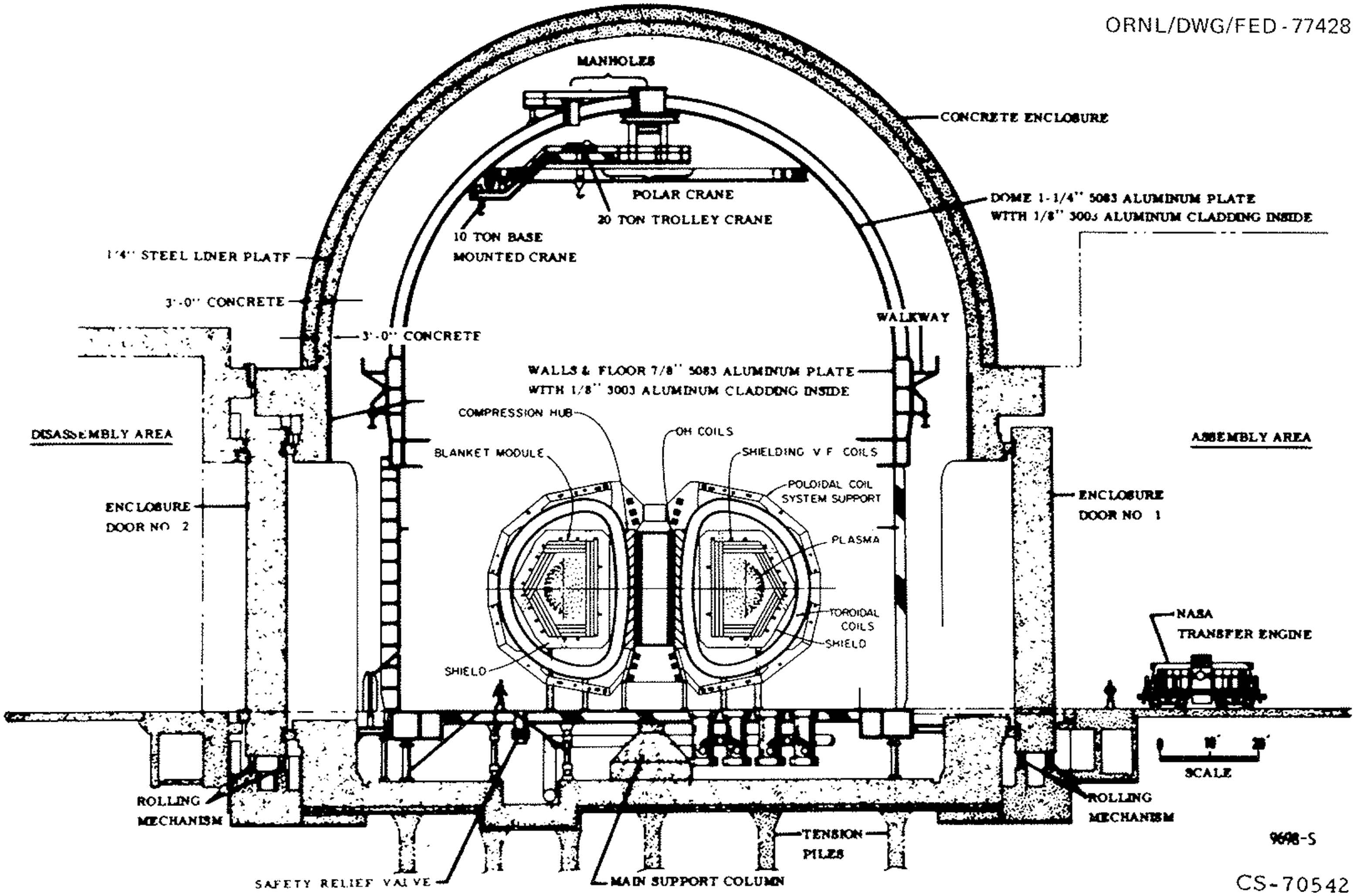
UWMAK II
5000 MW (t)

C-E PWR
3800 MW(t)

ORNL / DEMO
2000 MW(t)

FIGURE 1

ORNL/DWG/FED-77428



CS-70542

TOKAMAK REACTOR SUPERIMPOSED ON EXISTING NASA FACILITY ILLUSTRATES FEASIBILITY OF A VACUUM CONTAINMENT BUILDING

FIGURE 2

THE IRON CORE ELIMINATES THE TROUBLESOME O.H. WINDINGS UNDER THE TOKAMAK

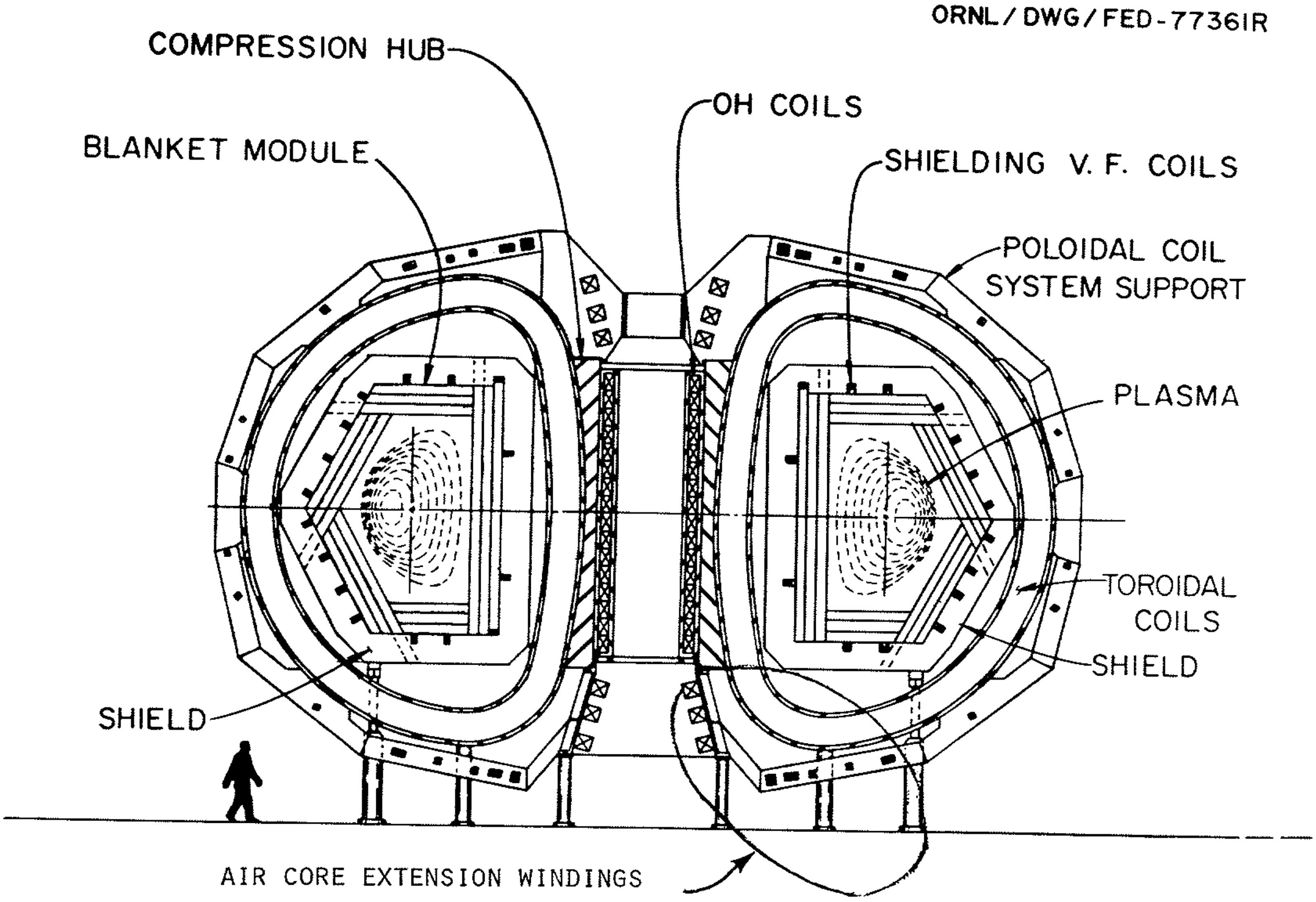
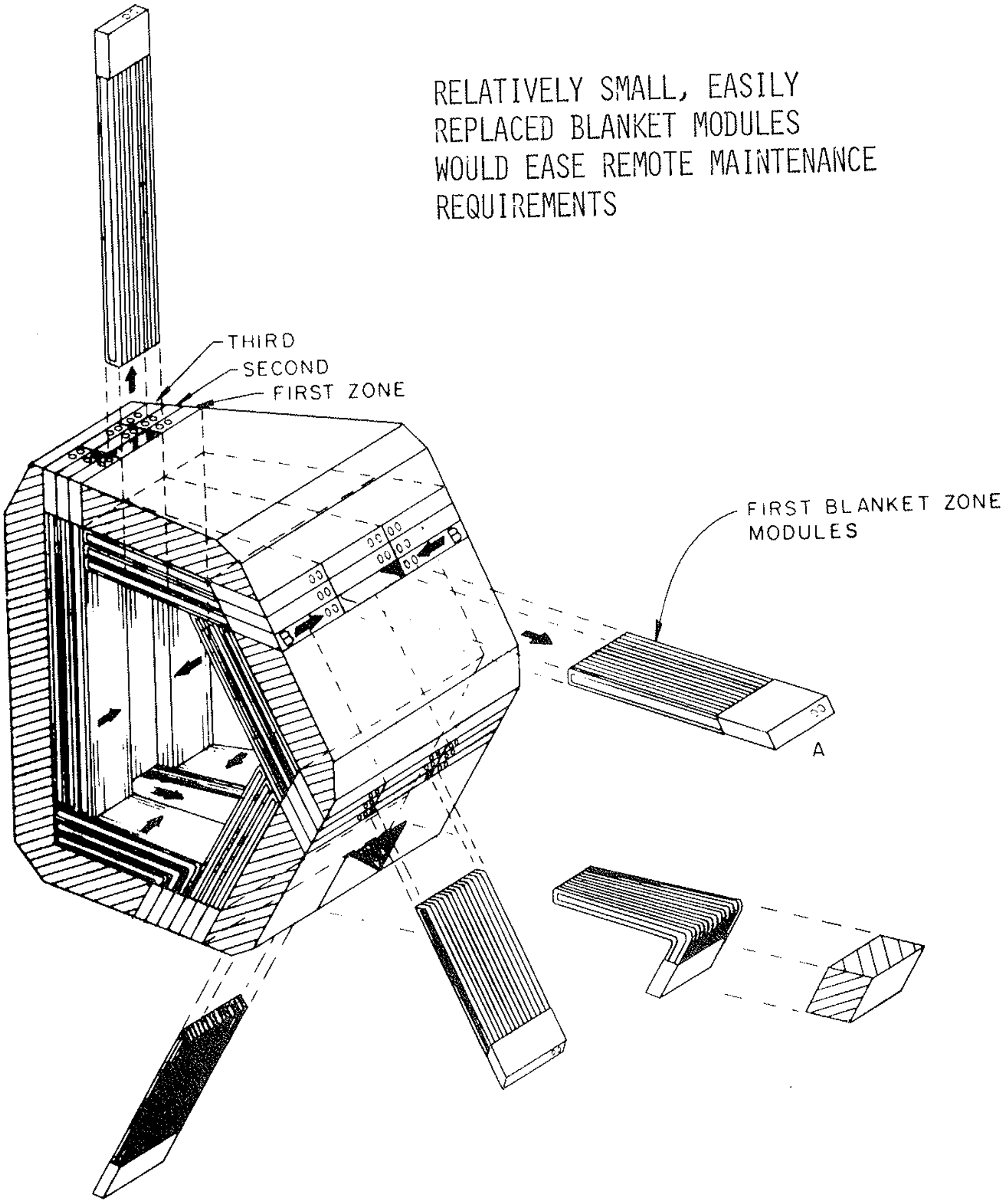


FIGURE 3

ORNL/DWG/FED-77427



RELATIVELY SMALL, EASILY REPLACED BLANKET MODULES WOULD EASE REMOTE MAINTENANCE REQUIREMENTS

FIGURE 4

MR. NEFF: Thank you, Don

Those people who have questions should come to the microphones and Don can recognize them.

DR. KRAKOWSKI: Bob Krakowski from Los Alamos.

Don, could you briefly summarize exactly what the progress was in the last two years that allowed really significant improvements in the Tokamak reactor concept, particularly physics?

DR. STEINER: The progress has been largely in two areas, size scaling and beta. With regard to size scaling, current empirical models indicate that the confinement time improves with the density and the size squared. Based on this model, we would predict ignition in a device with a plasma radius in the range of one to two meters. Reactor designs at Princeton, MIT, Oak Ridge, and GA are projecting radii in the range one to two meters based on this expectation. At the same time, a number of ideas are being pursued for the achievement of high beta. There is the configurational approach, which has been pursued most actively by GA in their Doublet experiments, and also there is the flux-conserving approach relying on rapid heating of the plasma, which has been advocated at Oak Ridge. Accompanying these ideas have been a number of calculations which project an average beta limit in the range of 5 to 10 percent. Several years ago we were talking about limits of 3-5 percent. The projected improvement in achievable beta will be tested in the next two years.

MR. NEFF: Don, I have a question. In your discussion about the materials and the capability of the materials to go perhaps to 20 megawatt years, the implication is that design levels of 2 to 4 percent residual ductility may be acceptable. In the fission reactor industry that is acceptable for fuel pins, however I am not sure it is going to be acceptable for engineered structures.

Could you comment on what you think the criteria really will be?

DR. STEINER: If I understand the question, you are asking if we can really, at this time, define what the design criteria are going to be for a fusion reactor blanket. The answer to that is no. However, relative to wall life projections made several years ago, the situtation is about an order of magnitude better. The question still remains, are those projections adequate in terms of the eventual design criteria. This year, at Oak Ridge, we are going to be conducting what I think will represent the first attempt to get industry involved in a blanket design. This study will look precisely at the issue of design criteria. I think by the end of the year we will be in a better position to answer the question, that is, to cast performance in terms of some specific design criteria.

As a final point, ductility, by itself, is not a very meaningful number. We have to talk about ductility in the operating environment, whether it is a pulsed system or a steady state system. Thus, a half percent ductility may be adequate for some systems, and 4 or 5 percent may not be adequate for other systems. The question is really open right now but I think we will have a better answer in a year's time.

TECHNOLOGY REQUIREMENTS FOR FUSION-FISSION REACTORS BASED ON MAGNETIC-MIRROR CONFINEMENT*

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ABSTRACT

Technology requirements for mirror hybrid reactors are discussed. The required 120-keV neutral beams can use positive ions. The magnetic fields are 8 T or under and can use NbTi superconductors. The value of Q (where Q is the ratio of fusion power to injection power) should be in the range of 1 to 2 for economic reasons relating to the cost of recirculating power. The wall loading of 14-MeV neutrons should be in the range of 1 to 2 MW/m^2 for economic reasons. Five-times higher wall loading will likely be needed if fusion reactors are to be economical. The magnetic mirror experiments 2XIIB, TMX, and MFTF are described.

+Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore Laboratory under contract number W-7405-ENG-48.

Q-REQUIREMENT

In a power plant, recirculation of power tends to diminish the economic competitiveness. A plant that can sell 0.8 units of power for every unit generated will enjoy an overwhelming competitive edge over a plant that can sell only 0.5 units of power under the same conditions. By quantifying in the above example, we can draw several conclusions.

We will consider an injected reactor that amplifies injected power by a factor of 1 + Q, where Q is the fusion power divided by the injected power. We assume the neutrons deposit M-times their kinetic energy in the blanket. The direct converter recovers the injected power plus the alpha-particle power with an efficiency of η_{DC}. The undirect converted power and the blanket power are converted to gross electrical power, P_{gross}, with an efficiency, η_{th}. A fraction of the gross power, $f_{recirculation}$, is fed back to the injector, which converts this electrical power to plasma energy with an efficiency, η_i. The ratio of gross to net electrical power, G, is:

$$G = \frac{P_{gross}}{P_{net}} = \frac{1}{1 - f_{recirculation}} \quad .$$

Based on the expected type of performance, we have chosen the following as typical parameters: $\eta_i = 0.7$, $\eta_{DC} = 0.5$, and $\eta_{th} = 0.4$. Using the above simplifying assumptions, the G versus Q values for three cases are plotted in Fig. 1. Case 1 is for a fusion reactor where M is chosen to be 1.2; case 2 if for a hybrid reactor designed to produce ^{233}U, as well as some ^{239}Pu, where M is 5; case 3 is for a hybrid designed to produce ^{239}Pu, where M is 10.

Each curve has a vertical and horizontal asymptote. The vertical asymptote occurs at breakeven values for Q. The horizontal asymptote shows diminishing returns for further increases in Q. For example, a fusion reactor, under the above reasonable assumptions, must have $Q \geq 2$ to break even; and Q values above 10 result in further small improvements. For a Pu-producing hybrid, the breakeven Q is about 0.25; and a Q above 1.8 results in further small improvements. For ^{233}U, the Q values are about 0.5 and 3.4.

For $G > 2$, the reactor is not economical. For $G < 1.2$, the Q value is high enough so it is not a major issue in economics. The value of 1.2 is, of course, an arbitrary cutoff of a continuous variable.

Based on the Q values for the conceptual designs to date (see Table 1), we conclude:

- The Q of 5 for the mirror fusion reactor seems somewhat low; a Q of 10 is probably needed.
- The Q value of 2 for the hybrid is already high enough.
- The standard mirror hybrid with Q of 0.7 carries an economic penalty.

The hybrid, because its saleable product is fissile fuel (as well as electricity), can perhaps tolerate a slightly lower Q than shown above, but not by much, because of the incipient rise of the curve for falling Q values.

WALL-LOADING REQUIREMENTS

Whereas fusion machines will probably have to go over about 5 MW/m^2 just to become economical, hybrids probably cannot go over about 2 because of safety considerations relating to the power density of the fission plate.

FUSION CONCEPTS AS CANDIDATES FOR HYBRID REACTORS

A number of magnetic fusion concepts are listed in Table 2: Tokamak is considered mainline; Mirrors are considered back-up; and the others are alternate approaches.

To be a candidate for a hybrid, a machine must also be a candidate for a fusion machine, and those programs receiving the most funding are showing the most rapid progress. They are consequently producing the best candidates for hybrids and attracting more programmatic money. This means that, solely because of the funding situation, it may be difficult to move some of the other potentially good hybrid candidates from a not-so-good to a good position (relative to, for example, Tokamak). This funding situation may be unstable.

Tokamak has a large data base, is a good possibility as a hybrid, and is surely going to be an early candidate. Regarding the mirror concept, a great deal is known about the standard mirror, and the mirror work is a medium-sized program at present. Little is known about the two new concepts of field reversal and tandem, but they would be good prospects, however, for hybrids.

Because the other alternate approaches (Fig. 2) are characterized by lower funding priorities, it will be hard for these projects to progress rapidly. However, they have very attractive features. Some of them, particularly the bumpy torus, are steady state and have simple geometry, but little is known about them, particularly their physics, and that is a handicap.

The stellerator is in a class by itself, because there is no U.S. program for this machine, which is a tremendous handicap; and it may not be possible to overcome this handicap for many years. The situation of the molten-salt reactor is analogous. If renewed interest in the molten-salt reacto occurs, it still would be difficult to catch up with the liquid-metal and gas-cooled fast-breeder reactor programs.

The next class of machines, in my mind, do not fit in very well with the hybrids. Their big handicap is that the Q seems too small in reasonably sized devices. An invention is needed along the end-stoppering lines to move these concepts up in the funding picture as well as in the list of prospective candidates for hybrids. The Surmac seems to be completely out of the picture for technological reasons involving the cooling of the floating (isolated) rings.

TECHNOLOGY REQUIREMENTS

Previous comments by Don Steiner, e.g., on tritium, also apply here and won't be further discussed.

Magnets

The magnets for most of the concepts shown in Table 2 (bubble chamber magnets, BBII, and MFTF, a large superconducting magnet under construction) can use niobium-titanium superconductors for which there is considerable experience. Because MFE has a large program to industrialize, i.e., bring in industry on the Large Coil Project, I think the superconducting-magnet technology will be available for hybrids.

Beams

For injection energy up to about 120 keV, there is a large ongoing program based on positive ions. The many users are: 2XIIB (12 MW), PLT (3 MW), DIII (4 MW or more), TFTR (20 MW), and MFTF (40 MW). For energies much greater than 120 keV, a program based on negative ions will probably be needed. There is now a small development program with no working models, no planned users, and no planned experiments. So in the near future, if some hybrids need negative-ion-based neutral beams, we may be in trouble.

I think neutral beam injectors for hybrids are feasible and that the prospects of getting efficiencies over 50% are quite good. The question of the cost of these neutral injectors has been a major one that is probably due to two issues. One is the complexity of remote handling and maintenance resulting from neutron activation. We don't know the costs very well, but our studies indicate something in the neighborhood of 40¢/W. The present sources on, say, TFTR are expected to cost almost five times that much. The 5-fold factor can hopefully be eliminated by a combination of: mass production, use of direct conversion, larger power supplies to handle several sources, elimination of the modulator tube, use of dc power from the plasma direct converters, and more efficient plasma sources.

The second concerns useful lifetime. Under the fusion environment, sources would have to survive six months to a year. At this time, multi-ampere sources will run no more than a few hours of integrated time, and they are all operated with short pulses of around a second.

The problem is that the source elements, i.e., the filaments, the grids, and the arc electrodes, will either sputter away or just simply evaporate away. Neutron damage to the insulators in these sources can, it appears, be kept sufficiently small by proper design.

THE MAGNETIC MIRROR AS A HYBRID

Figure 2 shows the familiar 2XIIB device. We routinely inject about 10 MW. The plasma comes up and stays on as long as the beam and magnet stays on, which is about 10 ms.

The 2XIIB is a deuterium machine. We inject deuterium and get some neutrons. If we injected tritium, the device would work the same. However, D-T is absolutely out of the question, because the device is not designed for D-T; nevertheless, taking the kind of densities measured and calculating the cross sections, we would get about 2 W/cm^3. That is an interesting number, because most reactor designs have power densities of that order. Table 3 shows these parameters.

The next machine, which is about a 3-fold scale-up in linear dimensions of the 2XIIB, is the Mirror Fusion Test Facility (MFTF) shown in Fig. 3. It is superconducting and will be steady state in most respects. We will be injecting about 40 MW of neutral beam. This also is solely a deuterium machine because of the added cost associated with tritium.

Figure 4 shows the MFTF large facility, which should be operational in 1981. If this machine were operated with DT – and I don't propose it to be nor have we any plans for it – it would have 6 W/cm^3 of fusion power in the plasma. That number is based essentially on the machine's design specifications. If it works as well as the 2XIIB ($\beta = 2$), we would have about 90 W/cm^3.

This 6 W/cm^3 of power in the plasma corresponds to about 1 MW/m^2 right at the plasma surface. That is down by only a factor of two from what we need for hybrids. The parameters are given in Table 4. What I am indicating here is that this machine will obtain fusion-like conditions for a hybrid.

The mirror hybrid reactor that is based on steady-state, neutral-beam-fed Ying-Yang magnet is discussed in papers by Ken Schultz and David Bender. Although this device is steady state and very complex, it is much less complex than a Tokamak. The complexity is a drawback, and the Q is about 0.7. We could reduce the cost of the fissile fuel by as much as one-third if Q were increased to almost 2.

TANDEM MIRROR AS A HYBRID

One of the most exciting concepts under investigation at Livermore is the Tandem Mirror concept (Figs. 5 and 6). An experimental facility now under construction, has a plasma that is mirror-confined (about like the presnt 2X machine but having more power in each end) and has plugs or stoppers for a solenoid. The positive potential of the plasma confines the ions in a solenoid.

We have been doing some very preliminary designs on a hybrid based on this concept, and I will describe some of the features shown in Fig. 7. We break the reactor into two regions. The central vault has a solenoidal coil, the magnetic field is straight, the coils are circular and steady state. We see tremendous advantages in being able to pull the coils out, having made them identical, and replacing them with an identical coil blanket system.

The other vault, called the end-plug vault, is composed of two beam systems. One is a small beam that shoots straight down into the plasma. This beam produces a small current, just big enough to maintain the plug density. The other rather large beam feeds deuterium and tritium into the end of the long solenoid at about 125 keV.

The end-plug injector uses only deuterium because the plugs do not need to produce DT fusion; the streaming plasma can be dumped, some of its energy taken out in a direct converter, and the gas pumped away.

We are interested in the Tandem for two reasons: one, the Q apparently can be high, about 1.8; and two, the power density can be more than adequate. The great simplicity is due to the cylindrical geometry without beam penetration. The beams are based on TFTR beam technology and have steady-state versions and direct conversion added. The reactor is modest in size and high in performance.

Several physics questions will be addressed in the Tandem experiment, which should go into operation in early 1979. One question is the alpha-particle build up. If the alpha particles should build up, they would quench the burn, and the device would have to be pulsed. The average Q would be nowhere near 1.8. Cross-field transport may be sufficient for the alphas to be removed. The electric field in this device travels in an outward direction, across the magnetic field, and in a direction that enhances cross-field trans- port of alpha particles. In toroidal machines, the electric field is inward, which should retard alpha-particle transport. Otherwise the problem is similar.

Also there are questions concerning heat conductivity along the field lines. Questions of microinstability of the plugs are being addressed in the 2X and will be addressed in the TMX. If the physics issues are resolved, the Tandem Mirror appears the best candidate for a hybrid.

In conclusion, all concepts mentioned could be candidates for hybrids if they can meet the requirements (e.g., Q $\sim$ 1 to 2) and if incremental funding is received so they can progress in a timely manner.

Table 1. Injector parameters for mirror reactors.

Reactor	Q	$\frac{P_{gross}}{P_{net}}$	η_i	W_{D° INJ (keV)	Power per unit (MW)	Units
Standard mirror	1.1	4.4	0.8	150	270	4
Field reversed	5	1.5	0.7	200	4	12
Tandem	5	1.7	0.7	1200	120	4
Standard mirror hybrid	0.7	3.2	0.7	120	60	4
FRM hybrid	~2	~1.4	0.7	~120	~4	12
TMR hybrid	1.8	1.4	0.7	125	70	2

Table 2. Fusion-concept candidates for hybrid reactors.

Main line:	
Tokamak	Large program and data base, good possibility
Backup:	
Mirrors:	Medium program
Standard	Considerable knowledge
Field-reversed	Little knowledge, good possibilities
Tandem	
Alternate approaches:	
Bumpy Torus	Small program, little is known
Toroidal Z-pinch	
Tormac	Little is known
Fast-slow Liner	Good possibilities
Stellarator	No U.S. program
Linear θ-pinch	Q too small in reasonable size Need end-stopping invention
E-beam Heated Solenoid	
Laser Heated Solenoid	
Multiple Mirror Solenoid	
Surmac	Technology problems

Table 3. Power densities of reactor designs with D-T.

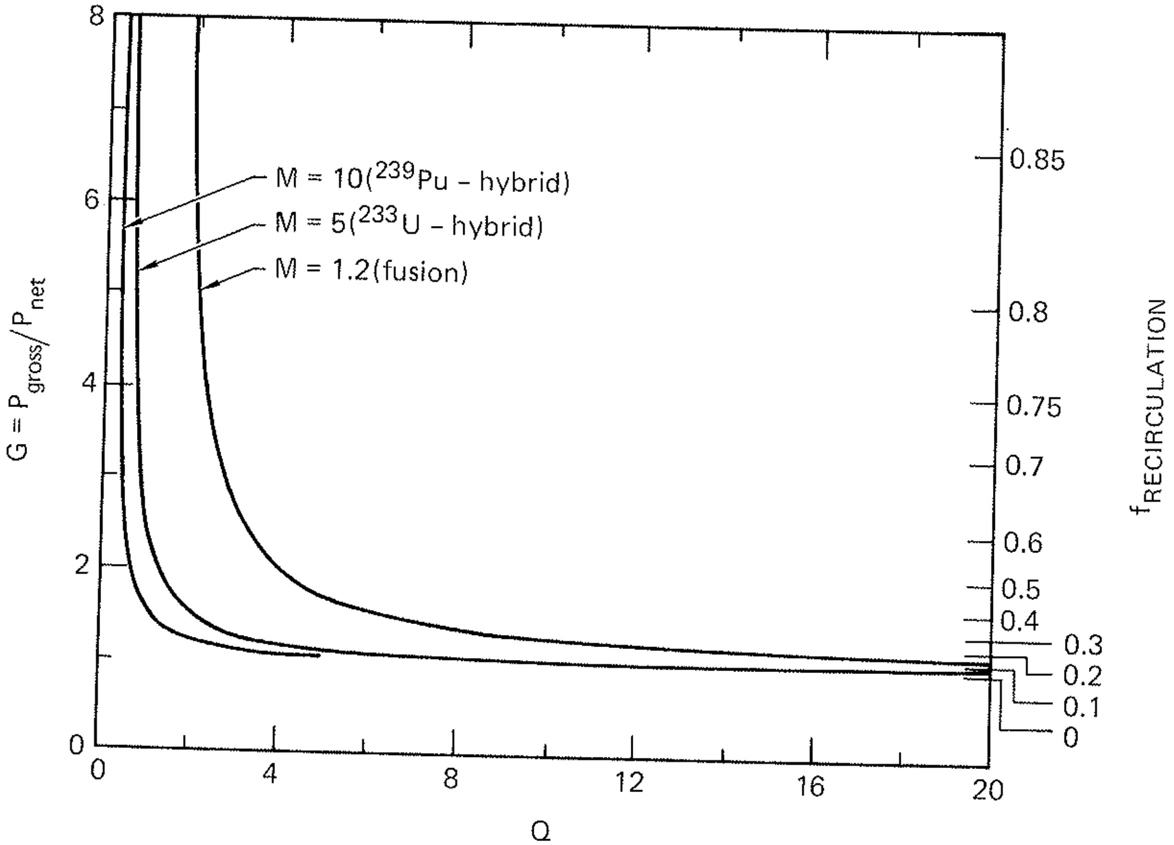
Parameter	2XIIB-like	MFTF-like
$P/V = (n^2\langle\theta v\rangle E_f)/4$	2.3 W/cm^3	6 W/cm^3 (90 W/cm^3 for $\beta = 2$)
$V_{\overline{n^2}}$	1 litre	200 litre
P	2 kW	800 kW
P/A	–	1 MW/m^2
S (14-MeV neutrons·s^{-1})	0.8×10^{15}	0.4×10^{18}

Table 4. Values of parameters for 2XIIB and MFTF devices.

Parameter	2XIIB	MFTF ($\beta = 0.5$)	MFTF ($\beta = 2$)
n	2×10^{14} cm^{-3}	10^{14} cm^{-3}	(4×10^{14} cm^{-3}
B_{vac}	0.7 T	2 T	
$\underline{B}$	2	0.5	(2)
W_{ion}	14 keV	50 keV	
Te	0.18 keV	1 keV	
I	400 A D°	750 A D°	
r_p	7 cm	30 cm	
V	4 litre	200 litre	
τ_E	0.5 ms	10 ms	(2.5 ms)
$n\tau_E$	10^{11} cm^{-3} s	10^{12} cm^{-3} s	
$S_{neutrons}$	3×10^{11} s^{-1} D-D	10^{16} s^{-1} D-D	
$\int s\ dt$	3×10^{9} neutrons/shot D-D	5×10^{15} neutrons/shot D-D	

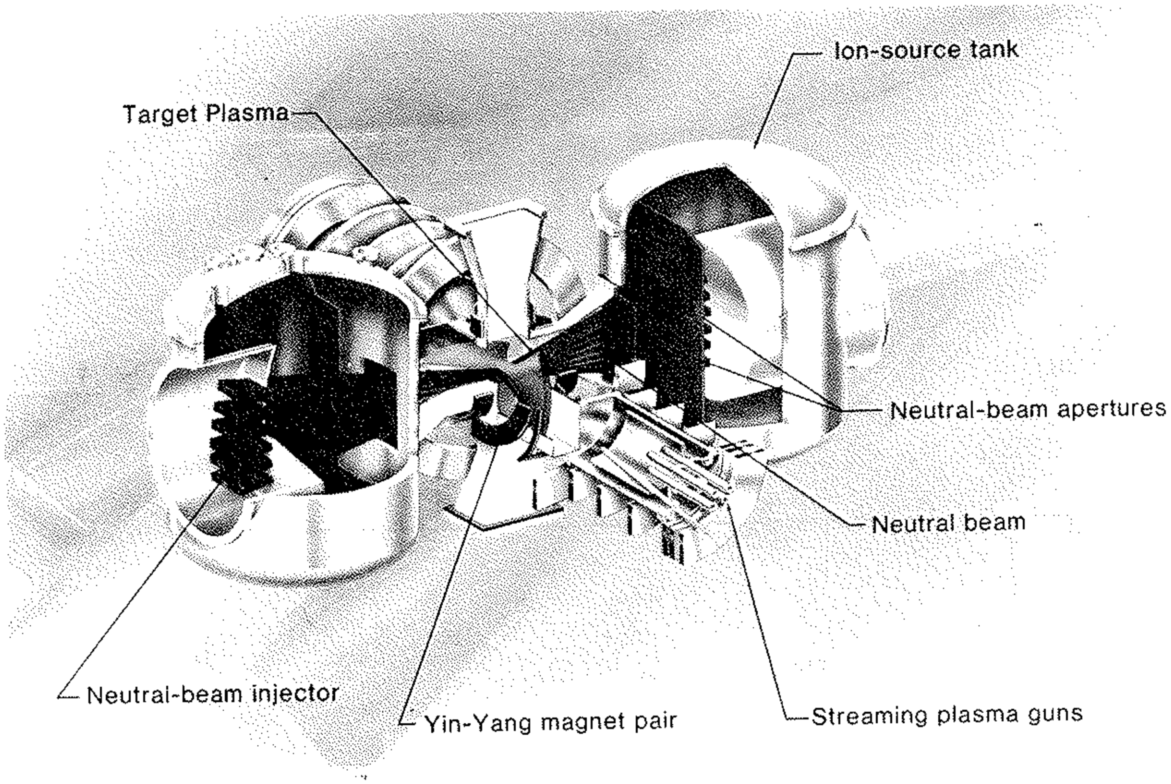
LIST OF FIGURES

DB/mf

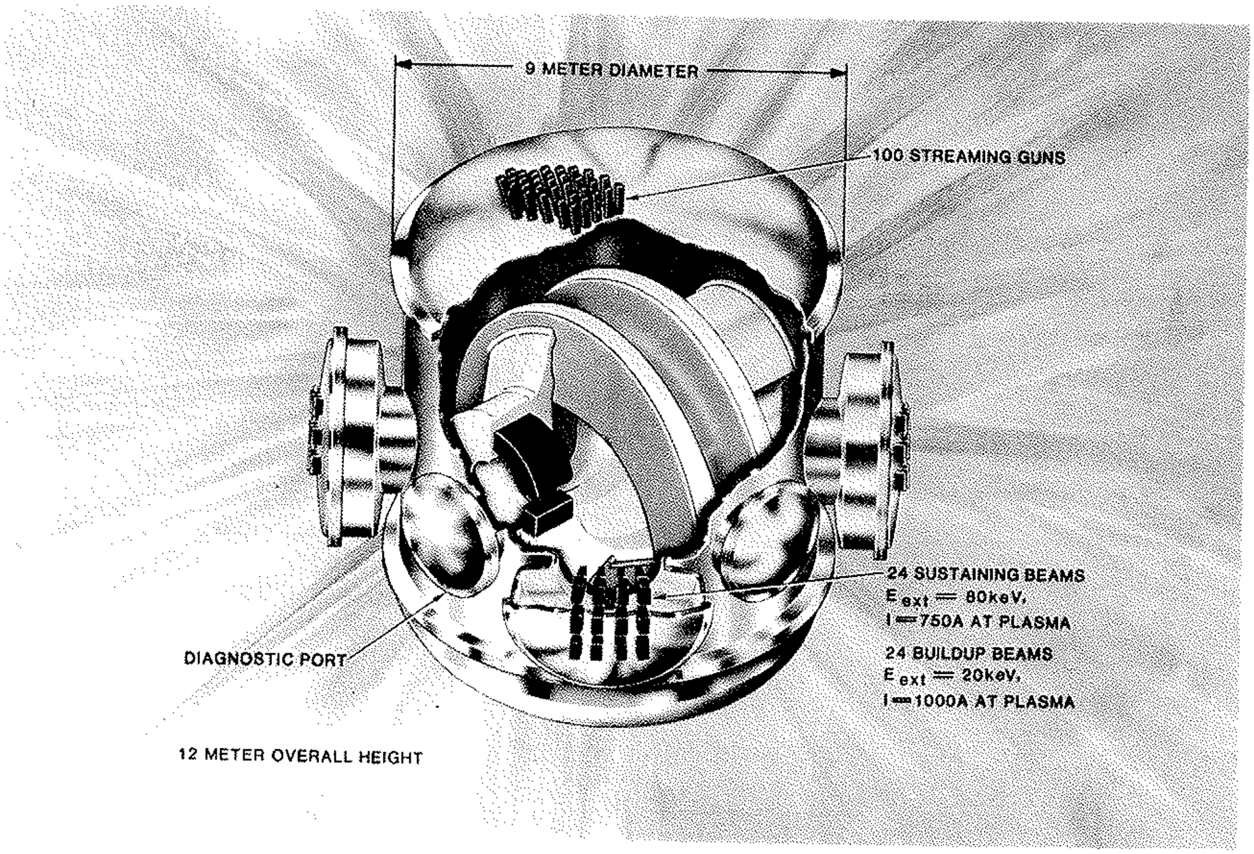


8
6
4
2
0
G = P_{gross}/P_{net}
M = 10(^{239}Pu - hybrid)
M = 5(^{233}U - hybrid)
M = 1.2(fusion)
0.85
0.8
0.75
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$f_{RECIRCULATION}$
0
4
8
12
16
20
Q

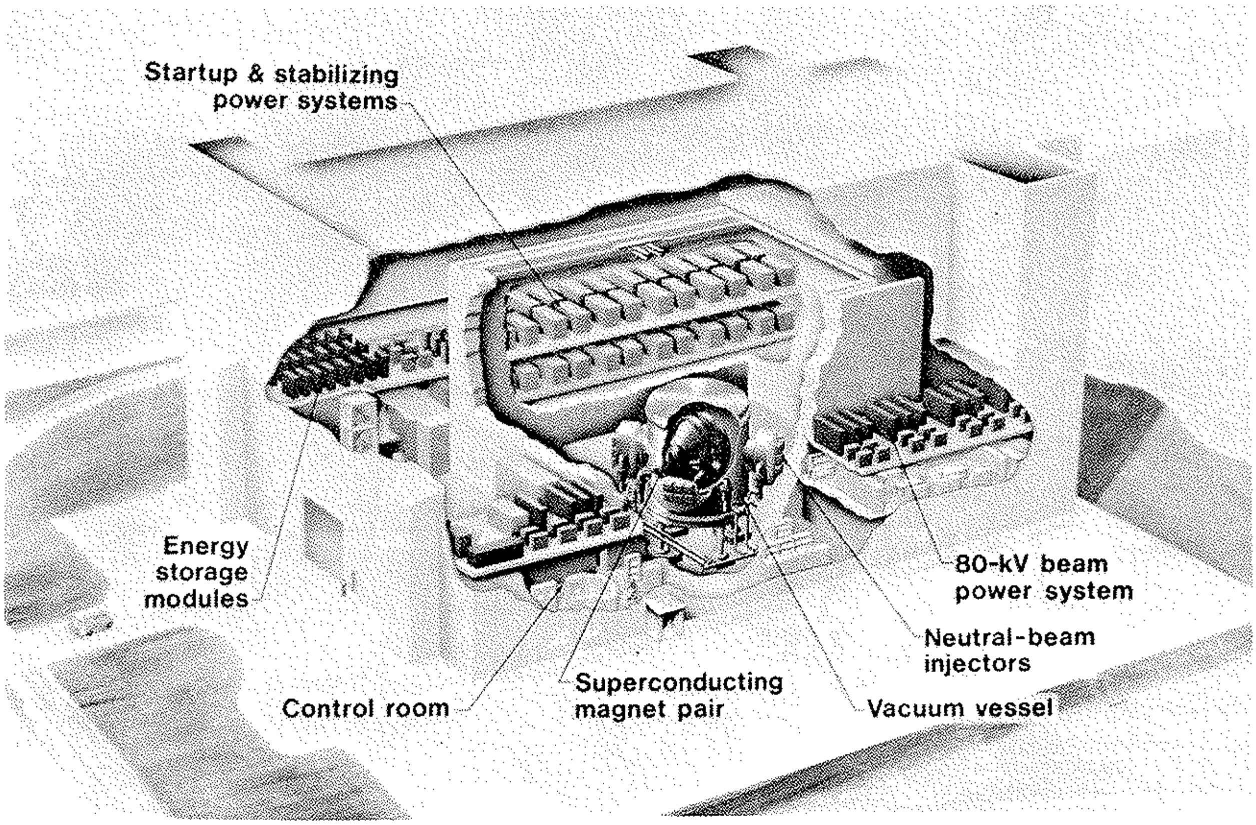
Moir - Fig. 1


Ion-source tank
Target Plasma
Neutral-beam apertures
Neutral beam
Neutral-beam injector
Yin-Yang magnet pair
Streaming plasma guns

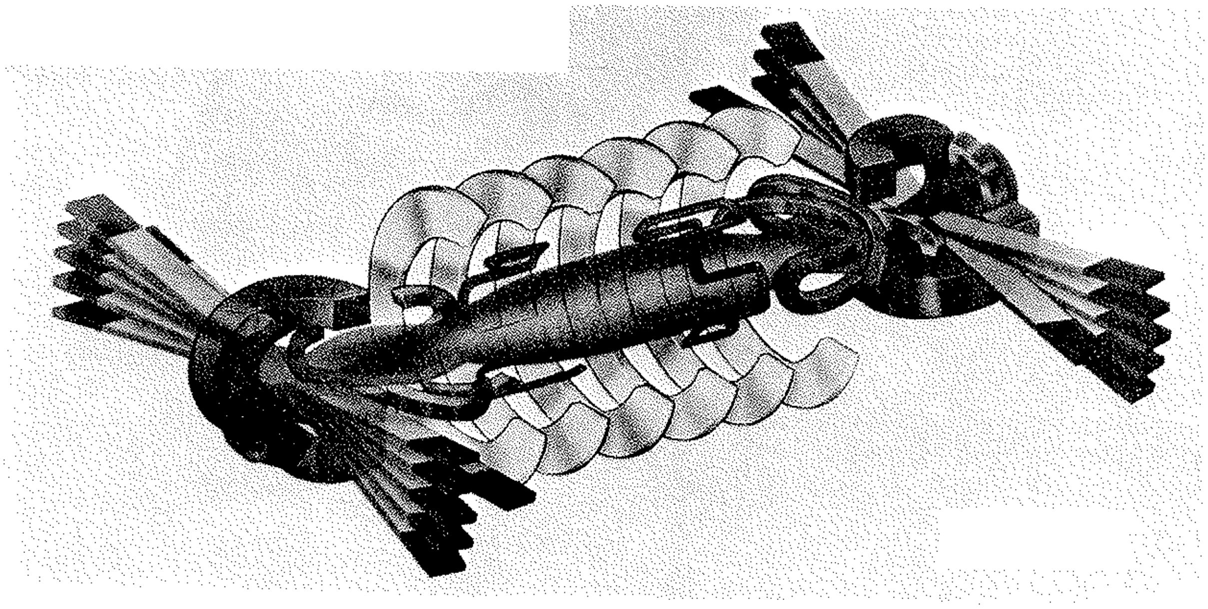
Moir - Fig. 2


9 METER DIAMETER
100 STREAMING GUNS
24 SUSTAINING BEAMS
E_{ext} = 80keV,
I = 750A AT PLASMA
24 BUILDUP BEAMS
E_{ext} = 20keV,
I = 1000A AT PLASMA
DIAGNOSTIC PORT
12 METER OVERALL HEIGHT

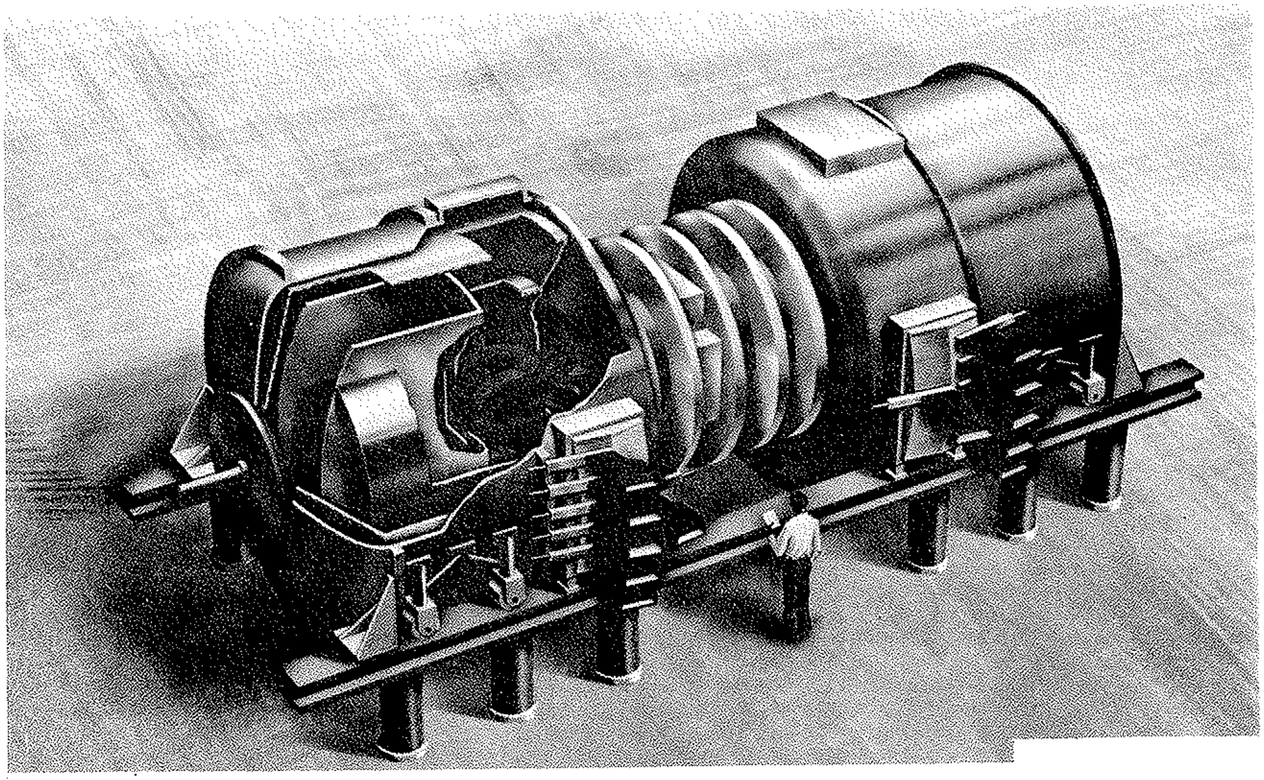
Moir - Fig. 3


Startup & stabilizing power systems
Energy storage modules
Control room
Superconducting magnet pair
Vacuum vessel
Neutral-beam injectors
80-kV beam power system

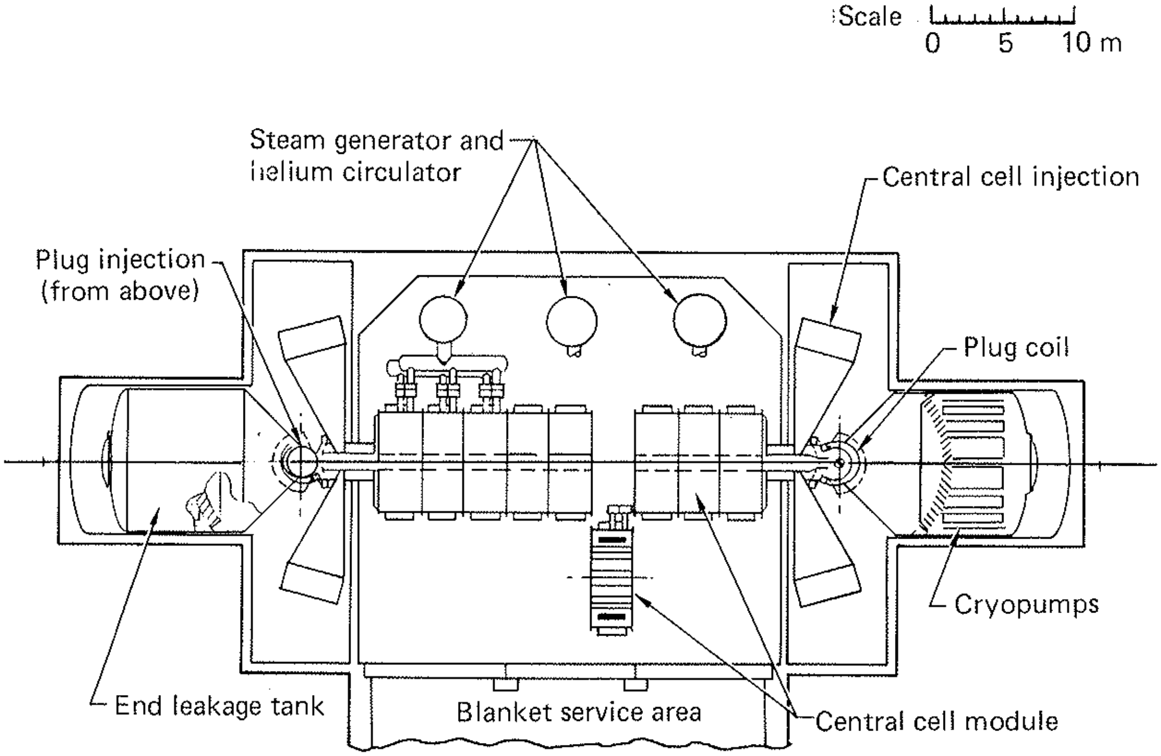
Moir - Fig. 4



Moir - Fig. 5



Moir - Fig. 6


Scale
0 5 10 m
Steam generator and helium circulator
Central cell injection
Plug injection (from above)
Plug coil
Cryopumps
End leakage tank
Blanket service area
Central cell module

Moir - Fig. 7

MR. NEFF: Are there any questions?

DR. NICHOLSON: My name is Paul Nicholson, from Draper Labs.

I think you answered this but I want to be clear. Did you rule out the use of direct converters on either end of the tandem mirror end-stoppers and are you just letting the escaping particles go into a dump of some sort?

DR. MOIR: We intend to use direct converters. We feel like in order to dump particles you have to pump them away and you have to have a vacuum tank. If you do that, we feel we might as well direct convert. And if you direct convert, you have to lower the power density to the order of about a 100 watts per square centimeter. And we think then it should be feasible. We are doing tests beginning this fall, and during the next year, with a 100 kilovolt beam injected into a direct converter that will have about a 100 watts per square centimeter.

So, we've got a very small program mounted to essentially check out the reactor level operation of one of these direct converters. But we are including it.

DR. NICHOLSON: Yes. Let me ask you another question. I think you gave me the information but I couldn't put it together. Going back to Nick Krall's line up of parameters for mirror machines, he was talking of beta on the order of one, temperatures in the neighborhood of 10 to 13 KeV, and densities of 10^{14}. It seemed to me, if you were worried about alpha confinement, that you would possibly want to go for higher densities and trade that off against temperature.

Are you in agreement with those numbers or is there some give and take on the operating point that you are going for?

DR. MOIR: The issue of alpha particles is that they are end stoppered essentially perfectly. And the question is, "how will they transport across the field compared to their production rate?" And it is very easy to see that cross-field transport is very low -- on paper anyway; and low enough to be very worrisome.

DR. NICHOLSON: I was thinking that perhaps you wanted to increase the density in order to get to a more collisional regime and achieve better confinement of alphas that way, and give up some temperature in response to it, but that is basically a physics issue.

DR. MOIR: We are going to be looking at the complete parameter space that we are cognizant of, but we haven't yet.

DR. NICHOLSON: The comparison was densities of 10^{14} in mirrors as against 10^{15} in Tokamak. It wasn't obvious to me why that had to be.

DR. MOIR: Well, when you have that kind of density, and you drive it, you make over two megawatts per square meter. You get all of the neutron power you want, so why should you go to higher density? If you did, you would have to shrink the radius and a number of parameters are coupled there.

DR. NICHOLSON: Okay. Thank you very much.

DR. MOIR: I am surprised that the linear machine advocates are not contesting my contention.

DR. KRAKOWSKI: I will contest that.

Let me just note that linear machines, in reasonable sizes, are very low Q machines and those numbers are based solely on free streaming end loss. I note that there is a fairly wide base of interest and activity in looking at end stoppering techniques that could substantially reduce the size of these machines.

The reason for that interest is the extreme simplicity of a linear machine. One cannot argue with the advantages of a most ideal geometry; purely cylindrical, a few meters in diameter at most, and roughly the size of a typical fission core. For these reasons, there is substantial interest in actively looking at end stoppering methods for linear systems.

DR. MOIR: Some of you may not be aware that at LASL there is an intensive progam on end stoppering addressed at finding an invention.

MR. NEFF: Just a quick calculation in my head here says the revenues of that TMX hybrid looks something on the order of $60 or $80 million dollars a year, which says it would support a capital cost of maybe $600 million or so. Have you done any cost estimates on what the machine would cost?

DR. MOIR: I would like David Bender to respond to that.

DR. BENDER: Dave Bender, Lawrence Livermore Labs.

I walked in on the tail end of this but I think I know what the question is, Jeff. If I head off in the wrong direction, let me know.

I have done a quick analysis on the economics of that reactor, and I estimated the total capital cost of the machine at a billion dollars. Now, if I sold electrical power generated from it at 30 mils a kilowatt hour, that would place then a levelized cost on the fissile material of about $35 or $40 a gram. Now, that was just all capital costs and neglected any fuel cycle charges and any OE&M cost, but just to see whether or not we were headed in the right direction. And it did look like an attractive setup.

COMMERCIALIZATION REQUIREMENTS FOR INERTIAL CONFINEMENT FUSION

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ABSTRACT

Analyzed are the requirements for commercialization of Inertial Confinement Fusion (ICF) and the nature of the ICF Program. The analysis shows that the requirements are of two kinds: scientific advances and technological developments. Detailed examination of each kind reveals that progress in the ICF Program is currently determined by the advances in basic investigations of not yet sufficiently well understood areas of physics. The technology developments, however, are straightforward although challenging and some require long lead times. For successful commercialization of ICF the long lead time technology developments can, and should, be compatibly integrated into the ICF Program in parallel with the research efforts.

INTRODUCTION

The development of Inertial Confinement Fusion (ICF) into a technically and economically attractive energy source faces unique and challenging problems that have not been encountered in previous research and/or technology oriented programs. These problems are caused by the dual nature of the ICF program: It is simultaneously a research and a technology development program and it is expected to succeed soon enough to meet national energy needs.

In general, research programs are established to acquire knowledge and understanding that may be useful in future applications, but economic and/or operational plans are not made to depend on unpredictable outcomes of scientific investigations. Plans and actions crucial to national well-being, therefore, prudently depend on the results of technology development programs for which scientific principles and feasibility are well established and whose success can be assured by the proper organization and implementation of the effort. In such programs a schedule of milestones can be established with reasonable certainty; consequently, a systematic and orderly integration of the results into the economy can be planned and carried out.

The successful commercialization of ICF, however, depends on the accomplishment of both the necessary scientific advances and the required technology developments within a fairly well specified time interval. The interval during which ICF must be made available extends from the time when depletion has increased the price of nonrenewable fossil fuels sufficiently to make fusion economically competitive, to the time when alternative energy sources (e.g., breeders) must be introduced to prevent economic collapse and political chaos. Results of the ERDA Inexhaustible Energy Resources Study (IERS) indicate that the "window" for the commercialization of fusion in general, and of ICF in particular, lies between the last decade of this century and the second or third decade of the next century.

Because 20 to 30 years are needed to bring a major technology through research, development, and demonstration stages, and another 20 to 30 years are necessary to introduce such a technology into the economy, the requirements for commercial availability of ICF must be identified now so that the research and development efforts are properly emphasized and coordinated.

Below, we discuss the requirements that must be satisfied to make ICF commercially available when needed. We begin with a presentation of the current status of the program, continue with a discussion of research requirements, followed by a discussion of the technology development requirements, and conclude with a view of planning strategy requirements imposed on ICF by the dual nature of the program.

CURRENT PROGRAM STATUS

Consistent with the research nature of the current ignition-source development and pellet-design phases of the program, the strategy is based on parallel investigations considering four ignition sources; these are:

- Nd:glass lasers,
- CO_2 gas lasers,
- New advanced gas lasers, and
- Electron beams.

High-energy beams are a fifth possible ignition source, but they are not discussed because of their present relative insignificance. Different ignition sources operate in different regimes of physical parameter space. Different energy-matter interactions are involved, each requiring somewhat different pellet designs. Therefore, pellet design is considered separately with each ignition source.

The Nd:glass laser is the first-generation research photon-beam source used in most target irradiation facilities around the world. Since 1967 Nd:glass laser systems have been developed to power levels of 4.0 TW (ARGUS at Lawrence Livermore Lab). Experiments with this system have resulted in neutron outputs greater than 10^9 from DT fusion targets. Neutron output (of $\sim 10^5$ neutrons) was first reported in 1973 by KMS Fusion Inc., using a split-beam 0.3-TW laser system. Hundreds of experiments with this system and with Livermore's JANUS (up to ~ 1.0 TW) and ARGUS systems have verified results predicted by the simulation code LASNEX within this power range.

Although the Nd:glass laser is capable of providing light pulses of specified high intensity for these initial studies, these laser systems require large investments in optical components and in large glass amplifiers. Glass lasers are inherently limited to a maximum efficiency of a few tenths of a percent and cannot be operated at high repetition rates. These features, along with uneconomical power-scaling constraints, make these systems unsuitable for commercial applications.

The CO_2 gas laser is currently best developed in this class of lasers. Considered a second generation laser for fusion research, its development has proceeded rapidly since 1969 with the invention of the electron-beam-controlled, electric-discharge pumping technique for high efficiency, short pulse energy extraction. Development has produced a 1.25-kJ module as a basis for an eight-beam, 10- to 20-TW target facility for fusion-pellet physics research at LASL. The technology developed in this program has included the following studies:

- short pulse amplification in the 0.5- to 1.0-ns range,
- multiline, multiband energy extraction to increase energy and power,
- saturable absorbers for inter- and intrastage gain suppression to prevent parasitic oscillation, prepulse target damage, and retropulse-system damage, and
- mechanical, high voltage, and optical engineering.

The target physics program has emphasized the understanding of laser-beam target-interaction, and plasma physics with 10.6-μm radiation to address the uncertainties in radiation-coupling and compression efficiency as a function of wavelength. Results from experiments (1976-1977) with a single-beam 0.2-TW laser have indicated essentially no wavelength dependence, originally expected from classical theory based on critical-density/absorption considerations. For example, measurement of hot-electron temperatures at intensities of ~5×10^{13} W/cm^2 for both 10.6-μm and 1.06-μm radiation-matter interactions imply a hot-electron wavelength dependence proportional to the inverse square root rather than the inverse square as predicted by classical theory.[1] This phenomenon is theoretically predicted by inclusion of ponderomotive forces as a result of electric field gradients present at the higher beam intensities. Similar results have been reported from experiments in ICF programs at CEA Limeil (France) and Osaka (Japan).[2]

Results from experiments with a two-beam prototype module for LASL's eight-beam CO_2 laser system (EBS) at powers approaching 1.0 TW have further confined the absence of wavelength dependence with neutron yields within the same range as 1.06-μm results as a function of beam power. Although the range of power levels in these experiments is too limited for an accurate verification of power dependence, the results are encouraging and lend credence to the possiblity that fusion targets might be designed without regard to wavelength.

Should the CO_2 laser prove to be uneconomic for energy production, a new advanced laser must be identified whose laser medium can be circulated to remove waste heat. This laser will necessarily be a gas laser and will probably be pumped electrically (electron-beam-controlled discharge or relativistic electron beam). Requirements for the so-called advanced laser include demonstration of saturated pulse output at the proper width, successful target experiments at 10% of the required intensity for breakeven gain, scalability to power levels of about 100 TW per beam, repetition rates of 1 Hz or faster, and an efficiency of at least a few percent.

Relativistic electron beams (REBs) are an alternative to lasers for initiating fusion-pellet microexplosions. Electron beam accelerators are simple, efficient, and inexpensive compared to high-power laser systems. However, electron beams can be focused adequately for pellet initiation only if either the electrodes or the clouds of plasma or metal vapors are in contact with the pellet. Conceptual approaches to plasma production in electron-beam diodes have been suggested, but further research and design studies will be required to ensure that pellet microexplosions can be isolated to prevent damage to electron-beam pulse-forming lines and cathodes.

The research requirements for the successful development of ICF may be grouped into the following three areas: (1) improved understanding of radiation-matter interactions at very high densities of energy and matter, (2) identification of a fusion ignition source (driver), (3) determination of a fuel pellet design with sufficient gain that, when coupled with driver efficiency, will result in competitive production of energy.

Radiation Matter Interaction

The study of interaction between radiation and matter at high densities is a topic in plasma physics we do not intend to discuss in detail. For the purpose of this presentation it suffices to state the following requirements: (a) firm establishment of the dominant physical processes and interaction mechanisms, (b) their satisfactory analytic and numerical modeling, and (c) experimental verification that in the theoretical investigations all the relevant parameters are included and being considered within appropriate range of their values.

Weak laser wavelength dependence will be further verified in experiments planned for LASL's EBS in late 1978. Most importantly, however, a clearer understanding of radiation-matter interaction physics will be gained at power levels at least ten times higher than previously available. At present, a single beam of the EBS has delivered more than 1.2 kJ in a 0.9-ns pulse at the design intensity into a calorimeter, with no parasitic oscillation and no prepulse. An integrated full-system test is planned for late February 1978, with target experiments to begin in early spring of 1978.

Driver Identification

The ignition source needed to initiate a fusion reaction must transform a conventional form of energy (e.g., electrical or chemical) into a form that can be:

- focused in space to the size of a fuel pellet or smaller,
- concentrated in time into a sufficiently short but intense pulse,
- transferred, i.e., coupled, to the fuel with satisfactory efficiency (~ 10%), and
- made to deposit sufficient amounts of energy to heat and compress the fuel to thermonuclear reaction conditions.

These requirements are met with beam-forming devices: lasers (photon beams), electron beams, and ion beams. Each has inherent advantages and disadvantages.

Laser beams are composed of noninteracting photons and therefore can be propagated over large distances (in vacuum) in short pulses, without beam quality degradation, and can be focused to very small spot sizes. However, they are inefficient energy converters; the efficiency of glass lasers is less than 1%, and that of gas (CO_2) lasers is less than 10%. The efficiency of energy transfer from the laser beam to the fuel pellet is not yet known with satisfactory accuracy, and research efforts are therefore directed at understanding the processes involved. The hope is that with a better understanding of the phenomena it will be possible to improve the efficiency. The efficiency requirements for the beam forming devices will be discussed at the end of this subsection, together with fuel pellet yield requirements.

The most significant development in the CO_2 laser/target physics research program are experiments to be performed in LASL's high-energy gas laser facility using the 100-kJ ANTARES laser system. Construction of this facility began in late 1977, and development of a three-sector prototype of the twelve-sector annular beam, 17-kJ power-amplifier module is under way. Initial measurements of small-signal gain in this prototype assembly have met or exceeded design specifications. The completion of construction is scheduled for 1981 with target experiments planned for 1982. The major goal for this facility is the achievement of scientific breakeven (defined as equality between thermonuclear energy output and laser beam energy incident on target). By extending the investigation of laser fusion to these power levels, a more complete understanding of the physics involved will be gained so that laser and target design parameters can be established with confidence.

Electron beams are composed of (negatively) charged particles, and therefore, at the required intensities, can neither be propagated sufficiently far nor focused to a sufficiently small spot size. These circumstances make the fuel pellet and the ICF reactor design awkward. However, electron beams are significantly more efficient than the laser beams (several times more), and couple to the fuel pellet more efficiently.

Ion-beam applicability to ICF is not yet very well understood; systems and applications studies have just begun. Ion beams have all the characteristics of electron beams, with the additional disadvantages of being more expensive and difficult to produce at the required power levels. However, they can transfer their energy to the fuel pellet very effectively.

Fuel Pellet Design

The considerations summarized above lead to the requirement of determining a generic fuel-pellet design and materials that will not only absorb maximum energy of the beam, but also yield the highest energy per microexplosion, i.e., result in an efficient fuel burn. These goals must be achieved with a design sufficiently simple to make the cost of pellet manufacture acceptable. Clearly, the research on fuel-pellet design must be coordinated with the research on the specific ignition source and guided by the investigations of the radiation-matter interactions in the appropriate regimes of the parameters.

The requirements for efficient beam generation and efficient coupling to the fuel pellet are very simple. To have energy available for sale, the product of beam forming efficiency, efficiency of coupling to the pellet, the balance of plant thermal efficiency, and the pellet yield ratio (defined as the pellet energy yield divided by the beam energy input per microexplosion) must exceed unity. It would be unreasonable to expect a plant thermal efficiency exceeding 35 to 45%; therefore, if a low-efficiency laser (< 1%) is used for pellet ignition and the coupling efficiency is only 10%, the fuel-pellet designer must produce pellets with a yield ratio greater than 3000. If, however, a more efficient gas laser can be used (10%) and the coupling efficiency increased to 20%, then the fuel-pellet yield ratio can be reduced to less than 200.

Research requirements beyond present program plans and goals include the further development, qualification, and optimization of a pellet design at gains appropriate for commercial applications. This development will require a target experimental facility with a driver energy at 1.0 MJ or greater.

TECHNOLOGICAL REQUIREMENTS

Unlike the research, the technology development requirements for the commercialization of ICF can and should be quantified, but should not be linked to specific dates; they should be related to and paced by specific scientific achievements. The quantification is possible because the characteristics and products of a DT fuel-pellet microexplosion - however initiated - can be numerically determined with sufficient confidence and accuracy to conduct systems and applications studies. The results of these studies lead to the formulation of technology requirements which will be summarized in this section. Because the date at which the basic physics of fuel-pellet ignition and combustion will become firmly established is uncertain, it is unrealistic to specify the dates at which the given performance of materials or subsystems must be attained; unnecessary constraints should therefore be avoided in the program that requires both scientific and technological advances.

In general, the technology developments are needed to provide reliable, long-life, high-repetition rate, pulsed operation of the following reactor elements: (1) reactor vessel, (2) fuel system (pellet manufacture, injection, and tracking), (3) driver, (4) beam transport system (including the last optical surface), (5) power supply, (6) tritium handling, and (7) balance of plant auxiliary systems. The requirements on each of these elements is discussed in more detail below.

The Reactor Vessel

The presently envisaged commercial applications of ICF will be in the areas of: (a) electric power generation, (b) neutron and/or heat generation for nonelectrical applications (e.g., synthetic fuel production), (c) fissile fuel breeding, and (d) combinations of the last three functions, i.e., hybrids. For all applications, however, the reactor will be designed around the energy source; that is, the fuel-pellet microexplosion. Thus, it is necessary to consider the characteristics of the fuel-pellet energy release and their effect on the reactor vessel.

Following ignition and explosive burn of the DT fuel pellet, the energy is released in the form of (a) fast (14-MeV) neutrons, (b) x rays, and (c) energetic ions comprising pellet debris. The neutrons pass through the first wall of the vessel relatively unimpeded and interact with the blanket material; the x rays and pellet debris must be stopped by the first wall of the reactor vessel. Thus, the first technological requirement for commercialization of ICF is the development of materials for the construction of reactor vessels that will: (a) resist erosion by energetic ions (sputtering), (b) minimize evaporation caused by x-ray and debris impact heating, (c) tolerate cyclic thermal and mechanical stresses, (d) resist neutron damage and activation, and (e) be chemically compatible with lithium or its compounds at elevated temperatures.

In the case of particle-beam drivers, the much higher gas pressure in the vessel (> 100 torr) is sufficient to prevent target debris and x rays from impinging on the vessel wall. The overpressure in the gas produced by absorbing this energy is not a severe problem in reactor-size vessels. The neutron damage to the vessel walls and blanket structures is not appreciably different between that of particle-beam and laser-driven systems.

The several approaches that have been proposed to mitigate the loading pulses and extend the lifetime of the first wall have been discussed in detail elsewhere[3] and will not be repeated here. Note, however, that the exact specification of the first wall design requirements will be determined to a large extent by the details of the fuel pellet structure, which will be determined by the outcome of current investigations in the areas of driver development and driver-pellet energy coupling.

The Fuel System

Although the configuration of a working fuel pellet has not yet been determined, the requirements it must satisfy to make ICF commercially successful are well understood. The pellets are likely to be of a simple one- or two-shell design that can be manufactured at essentially the cost of materials, which should not exceed a few mil/kWh. Such pellets could be produced for tens of mil/kWh by combining the current pellet manufacturing methods with mass-production techniques. Therefore, a mass-production technology for such pellets must be developed to reduce the projected cost by a factor of ten and to increase the production rate to 10^5 to 10^6 pellets per day.

Techniques must also be developed to inject the fuel pellets into the reactor cavity at a rate from 1 to 10 per second with the velocity of about 100 m/s, and to track or illuminate the pellets accurately so that the driver beam can be aimed to deliver its energy at the moment the pellet reaches the center of the cavity with spatial accuracies within a few micrometers. Either pneumatic or electrostatic injection mechanisms appear feasible.

The Driver

The ignition source, or driver, is required to convert electrical, chemical, or thermal forms of energy into a beam of sufficiently intense pulses suitable for initiation of thermonuclear reactions. The characteristics of the beam should be such as to optimize energy transfer to the fuel. Clearly, these characteristics must be determined in conjunction with the fuel-pellet design.

A second set of requirements is dictated by energy-balance and economic considerations; these are related to efficiency, repetition rate, reliability, and cost. The driver efficiency should be greater than 5% (however, efficiencies as low as 1% may be acceptable for pellet gains greater than 100), the repetition rate in the range of 1 to 10 pulses/s, and the lifetime at least 10^9 pulses. In addition, the design should allow convenient waste-heat removal, which means that the medium in which the energy is converted should be a fluid.

At the present stage of laser development the CO_2 gas laser appears most suitable to meet the commercialization requirements if improvements are made in the following technology areas: (a) electron-beam cathode and window materials (to increase lifetime), and (b) optical window materials (to increase transmission, lifetime, and reliability).

At the present stage of particle-beam driver development, electron and light-ion systems are nearest to fulfilling commercialization requirements, with technological development needed most in the areas of cathode and anode materials, and high-current switching techniques.

Beam Transport System

The energy beam generated in the driver must be transported to the reactor cavity and delivered onto the fuel pellet surface. In the case of laser drivers the transport of beams from the driver to the last optical surface does not pose any technical difficulties; it can be accomplished in vacuum tubes with optical prisms and mirrors. In the case of particle beam drivers, production of electron and light ion beams at the diodes can be very efficient. These beams can be efficiently transported from the diodes to the target by using ionized channels in gas at atmospheric pressure. The pointing-accuracy requirements will depend on pellet size and design; for currently considered sizes it is about 1 μrad. Special apparatus must be developed to maintain such accuracy at repetition rates of between 1 to 10 Hz, in the presence of vibrations encountered in the neighborhood of heavy machinery (turbines, generators, pumps, etc.) and those from the reactor containing pulsed microexplosions.

In the case of electron-beam drivers the problems of a suitable electron-beam transport has not yet been solved.

In the case of laser drivers, for which sufficiently detailed conceptual designs exist, the beam energy to initiate the fusion reaction in the fuel pellet is directed into the cavity with the last optical surface. Therefore, the requirements for this element of the system are similar to those imposed on the first wall of the vessel, but mitigated by the fact that this optical surface can be located significantly farther (at least twice as far) from the microexplosion than the first wall. The beam-aiming and focusing functions of the last optical surface, however, impose additional requirements dictated by considerations of beam quality and accuracy, and of surface reflectivity and lifetime.

For CO_2 lasers the need for maintaining high optical quality of the beam requires that the last mirror (as all others) does not deviate from the true optical surface by more than a quarter of the wavelength of light that it is reflecting and focusing; this requirement translates into a surface tolerance of 2.65 μm. However, the need to prevent the formation of surface damage sites (hot spots) reduces this tolerance to 0.025 μm for research and test-type operations, and to 0.002 μm (20 Å) for high-repetition-rate or continuous operation when lifetime considerations dominate.

In particle-beam systems, there is no last optical surface; however, the protection of the electron-beam diode, which must stand off from the microexplosion, requires attention.

The Power Supply System

The design of a suitable power supply for the driver of the ICF reactor offers a major challenge for the technology developments mainly because of the need to switch hundreds of kilovolts with an efficiency higher than 90% several times per second for many years.

In the current technology the spark-gap switches have a lifetime limited to 10^5 to 10^6 pulses (less than one day's operation at 10 to 50 pulses per second), and the capacitors have a lifetime of 10^7 to 10^8 pulses (approximately one month at the required frequency of operation).

Therefore, the lifetimes of spark-gap switches and capacitors must be extended more than 100-fold. These goals may be achieved by either: (a) derating the presently available components to operation at lower voltages at the expense of size and cost, or (b) by investigating the potential advantages of semiconductors or ignition pulse transformers in place of spark-gap switches and identifying a new energy storage system in place of capacitors and inductors.

Tritium Recovery and Purification

During operation of ICF reactors tritium concentrations in structural materials and blanket regions will range from 0.1 to 10 ppm. Current lithium refining technology appears adequate to ensure the necessary recovery and purification to less than 1% impurity content. This impurity level should be low enough to keep radiobiological hazards from activated impurity components reasonably low. Development is required in the adaptation of current laboratory processes and techniques to large-scale and long-time industrial operations and to meet the reliability standards dictated by radioactivity levels. Research in these areas is already under way in magnetic fusion energy programs.

Balance of Plant

Balance of plant auxiliary systems, e.g., turbogenerators, heat exchangers, and pumps for an ICF reactor are similar to those for the magnetic-confinement fusion reactors and will require development of methods and procedures for the remote replacement and maintenance of activated components and of safeguard systems for shutdown (e.g., maintaining lithium in the liquid state), tritium containment, and control of lithium fires for the protection of the public, personnel, and the plant.

A unique requirement for the ICF reactor is the large amount of electric power necessary to start up the plant after a shutdown (black start); this demand is a consequence of the relatively low driver efficiency, which requires a significant recirculating power fraction to operate the reactor.

Currently available remote maintenance technology, as well as safety and environmental protection systems developed for fission reactor plants, are more than adequate for fusion plants. A large amount of the vast liquid sodium technology developed for LMFBRs is directly applicable to liquid lithium requirements. Low-cost gas-turbine generators now used to meet peak power demands are available for a black start; however, bootstrap methods for start-up should be considered early in the design of large multicavity ICF reactors. Therefore, the only new developments for the remainder of the plant are the verification of engineering design parameters for tritium extraction and containment, lithium heat exchanger, steam generators, pumps, etc.

PROGRAM REQUIREMENTS

The above discussion shows that the scientific and technological requirements for commercialization of ICF cannot be separated: they must be blended into a program plan in which research results are used continually to indicate expected or feasible advances and in which technology development investigations indicate what is desirable or even necessary for successful commercialization. In this section we will discuss briefly the general requirements imposed on the planning of the ICF program by its dual nature of research and technology development.

Because a new energy source is urgently needed, and because of the large effort associated with its introduction and integration into the national economy, it is necessary to carefully plan the commercialization of ICF. However, the program is currently research-based, making the successful attainment of its goal depend more on the advances in understanding of yet unexplored areas of physics than on coordination of technology developments.

Therefore, to ensure success, i.e., to minimize the possibility of failure, the program strategy should be based on the following principles:

- Investigate several approaches in parallel (Nd:glass, CO_2 gas, new gas lasers, electron beams), with provisions to change emphasis without excessively perturbing the overall program when the results indicate the utility of such action;
- Establish milestones leading to an understanding of basic phenomena that opens the paths to further progress beyond special, specific, nongeneralizable results, and avoid committment to expensive experiments that may

produce nonscalable (or unfavorably scalable) results and thus not lead to practical applications;

- Establish and maintain interactions and compatibility between the research and technology development phases of the program for their mutual benefit; and
- Establish intermediate objectives along the path to commercialization that will be realized and will have practical value before the ultimate goals are attained.

Adherence to the above principles of program planning will not only maximize the probability of success for the ICF program, but also ensure that the planned objectives are attained in the shortest time and with the minimum expenditure of resources.

SUMMARY

The results of the considerations discussed in this presentation are summarized in the following conclusions:

- Current status of the ICF program is research-based in the sense that its success depends more on results of basic investigations in unexplored areas of physics (e.g., radiation matter interaction at high energy and matter densities) than on coordination of technology developments;
- Program strategy is correctly based on parallel investigations of the potential of four ignition sources: Nd:glass, CO_2 gas, new gas lasers, and electron beams;
- Generic and specific ICF reactor designs have been investigated in sufficient detail to determine the technology requirements for their commercialization;
- Technology development requirements are straightforward but challenging, some requiring long lead times; and
- For successful commercialization of ICF, the long lead time technology developments can and should be compatibly integrated into the program in parallel with the research efforts.

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MR. NEFF: Thank you very much, Larry.

Are there any questions?

DR. SCHULTZ: Ken Schultz from General Atomic Company.

I wonder could you expound a little bit on your second bullet on the third viewgraph that made the point that you felt technical breakthroughs rather than technical evolution were needed. That is sort of a scary thing. You can't legislate or even plan breakthroughs but you can legislate and plan evolution.

DR. BOOTH: Yes. I tried to qualify that when I had the viewgraph up there, that I think a better word would have been "understanding."

At this point in time, we are not able to study the laser-matter interactions in the appropriate regime to really know whether the predictions of the higher gains are really valid. And that is what is meant by breakthroughs. We are going to have to understand an unexplored regime of physics in order to get to the scientific feasibility stage.

DR. BERWALD: Dave Berwald, Exxon Research.

I have a question about the failures of pellet delivery systems. In most of the designs I have seen, they assume a reflected laser light fraction of about 10 percent. Now, if the pellet delivery system fails, all of the laser light will impact against the first wall. So, do you think that these kinds of fractions are realistic in first wall designs?

DR. BOOTH: Well, I think that is part of technology development. There are certainly ways that one can determine whether or not the beams should be fired. Now, if you are talking about missing the pellet -- is that what you are talking about?

DR. BERWALD: Yes. Well, there will be a certain fraction of misses, I assume.

DR. BOOTH: Okay. Given a certain fraction of misses, the X-ray outputs are likely to be of the same order as the laser beam energy; that is, X-ray outputs of the pellet. The first wall protection scheme will protect against the X-rays.

DR. BERWALD: But the deposition depth for the reflected laser light is much thinner, isn't it?

DR. BOOTH: Yes, in general, but when you get down to a certain energy level or a certain pulse width, then it is pretty much energy independent.

ALTERNATE FUSION CONCEPTS
FOR HYBRID SYSTEMS

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I would like to talk about alternate fusion driver concepts, and in particular some that may have applicability to hybrid systems. The questions of exploratory alternate fusion concepts has gotten alot of attention during the last year. As some of you probably know, there was a rather formal review of all of the exploratory alternate concepts by ERDA.(1) The review was done in a rather complex, essentially a science court, procedure. Some people liked it and others didn't. However, some of the results have taught some of us some important lessons.

Twelve exploratory concepts were rated on the basis of physics, technology and desirability as fusion reactors. Figure 1 shows the summary from that review. As can be seen, the three linear concepts, the linear theta pinch, the laser solenoid, and the E-beam solenoid, rated very well in physics. In fact, the laser solenoid was rated tops in physics, which meant that there is general agreement in the community that the physics of the linear laser solenoid fusion system, and linear systems as whole, is reasonably well understood.

With respect to technology, linear fusion systems were rated in the middle of the group, which, to me reflected a lack of detailed technology work on the concept. Technology confidence is really a matter of how much the various technological aspects have been thought out.

With respect to reactor desirability, linear systems in general didn't rate too well. They were all judged to be in the lower half of the group and that reflected the fact that the designs were all very long. Containing a high value of plasma Q in a linear machine, requires very long lengths, and that is the subject I would like to talk about.

Since the exploratory concepts review, there has been another significant event in the linear fusion systems community, and that has been a recognition of the importance of the subject of end stoppering, i.e., how are you going to close up the ends of these open-ended machines. The mirror proponents have been conscious of this for years. The answer to how you are going to accomplish end loss reduction is of utmost importance to the question of how to make a "desirable reactor out of a linear, as well as a mirror, fusion machine?"

There was a workshop/meeting in Santa Fe(2) recently where the subject of end loss reduction was discussed in great detail. Most of the researchers in the linear fusion community put their ideas and current progress together and out of that meeting came a new appreciation of where the field really stands. Most of us who attended feel that it stands pretty well, particularly, when you consider applications to hybrid fusion/fission systems. Figure 2 is a plot of plasma Q equals two fusion machines, in a length/density space, with the various end stoppering techniques superimposed on the length/density grid.

One can immediately see that for free streaming end loss, you have to have very high density in order to bring the length down below a kilometer. The required densities are beyond the range of magnetic confinement and must resort to wall confinement. For solid end plugs, recent work in Scylla IVP(3) at Los Alamos Scientific Laboratory is very, very encouraging. Material end plugs, i.e., just putting material plugs at the ends of a theta pinch were used to stop the flow to see whether it is possible to achieve heat conduction, i.e., classical heat conduction, controlled containment time. It is not possible to say that this has been proven, but the results are very encouraging.

If thermal conduction confinement control can be achieved then the length of linear systems comes down to the second line. This line is an ideal classical heat conduction end condition. Now it is possible to talk about machines, for instance, if you consider laser heated machines (which are the highest density linear machines, as opposed to shock heated theta pinches which are much lower density machines) which are less than one kilometer long. Shock heated theta pinches fusion reactor designs have generally been in the 10^{16}/cc region while laser heated fusion machines, at least, the past designs, have been in the 2 x 10^{17}/cc density region.(4) All these comments apply to Q equals two machines as shown in Figure 2. It can be seen that such machines can be about 500 meters long, if we can use material end plugs. We like to think that probably they can no more 2- to 300 meters if we can learn how to reduce the thermal conductivity by a small factor. This comment has been made considering the potential of one kind of end plugs, i.e., material end plugs, which is the area which has had the greatest amount of research.

I would maintain that in all of the fusion reactor buildings that you have been shown in this meeting, for Tokamaks, mirror machines and pellet laser fusion reactors, there are dimensions of at least 200 meters. Every one of those reactor buildings is large and it just depends on how you lay out your reactor in it. I think that a dedicated research program in end loss control is the proper way to attach the question of reactor desirability for linear fusion systems.

There also are other, more advanced end plug concepts. One of these is the Multiple mirror. There are also very encouraging experiments.(5) However, these experiments were performed in a very low density regime, far from the conditions needed for reactors. The experiments were also specific for a configuration, the so called minimum average B configuration, that may not be very applicable to reactor end stoppering. As a result the utility of multiple mirrors is still a major question. However, the possibilities are good. The line drawn for the effectiveness of mirrors in reducing reactor length is drawn for a mirror ratio of 2, but the experimental data is not yet in a regime where one can count on this performance for a reactor.

Cusp end conditions would also be exciting. Here the critical question is, what is the hole size in the cusp? There are some data from Japan(6) and some from UCLA(7) that indicate that the hole in the cusp should be the so-called hybrid radius, i.e., the average between the ion and electron gyro radius. That is a question which is not yet settled. Some people say the hole should be the ion radius, in which case, cusps confinement will not be very good. If the hole turns out to be the hybrid radius, then cusps make very exciting end plugs. The line in Figure 2 is drawn for the hybrid radius.

Finally, there are also some new ideas on how to apply field reversal as an end plug for a linear reactor. Loren Steinhauer and Bill Grossman have developed the so-called Field Reversal Multiple Mirror Reactor Concept(8). This work is presently strickly theoretical, but, so is most of the field reversal work. There is very little experimental data beyond the achievement of field reversed conditions.(9) All field reversed reactor concepts are extrapolated from this data.

If field reversed multiple mirrors can be utilized, then the game in terms of linear machines really changes. Length could be reduced by more than an order of magnitude, and the question of reactor desirability would be settled at that point.

I think I have made the points I really wanted to make. I had more slides, but this makes the point as well as I can in five minutes. There are some limited experimental data available for all of these concepts. Some of the data looks very good and there is a good probability that the performance we expect from a material end plug will be feasible. Some of the other ideas discussed have more potential, and are also being worked on. When you put the whole story together linear reactors, as a family, really appear to be highly desirable for a hybrid reactor.

CONFIDENCE IN PHYSICS		CONFIDENCE IN TECHNOLOGY		REACTOR DESIRABILITY	
Concept	Score	Concept	Score	Concept	Score
Laser Heated Solenoid	38	Elmo Bumpy Torus	6.7	LINUS	770
Theta Pinch	29	LINUS	5.0	Fast Liner Reactor	760
Reversed Field Pinch	8.3	Fast Liner Reactor	3.8	Elmo Bumpy Torus	690
TORMAC	4.2	TORMAC	3.4	TORMAC	560
SURMAC	3.9	Laser Heated Solenoid	2.2	SURMAC	560
Ion Rings	2.1	Ion Rings	2.1	e-Beam Heated Solenoid	550
e-Beam Heated Solenoid	2.0	Theta Pinch	1.6	Reversed Field Pinch	520
LINUS	1.80	e-Beam Heated Solenoid	1.5	Laser Heated Solenoid	500
Fast Liner Reactor	0.88	Reversed Field Pinch	0.85	Ion Rings	480
Multiple Mirror	0.49	Multiple Mirror	0.46	Multiple Mirror	420
Elmo Bumpy Torus	0.43	SURMAC	0.27	Theta Pinch	420

Figure 1. Summary of Scores of DMTE Exploratory Concepts Evaluation

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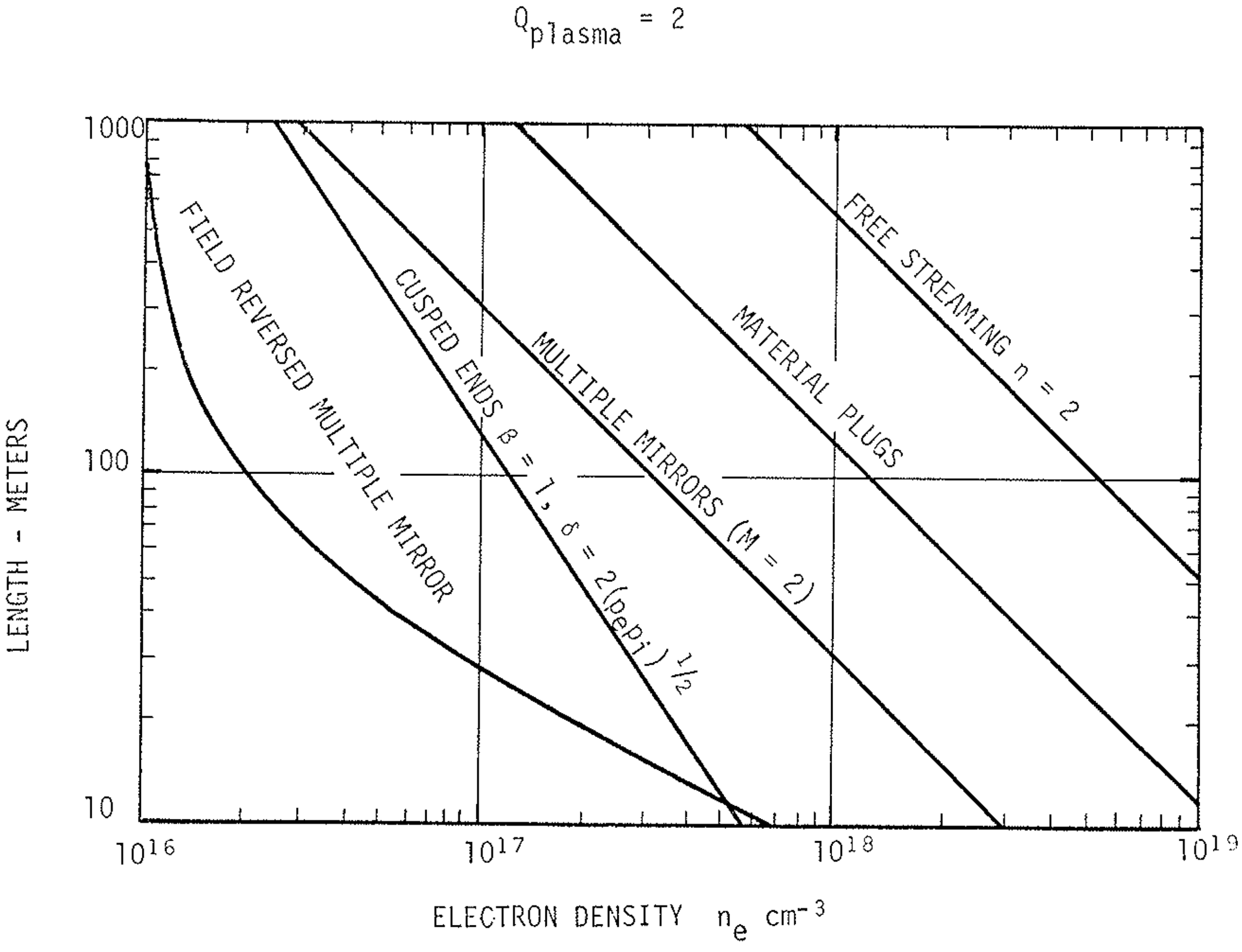

$T_e = T_i = 5$ keV

$a = 2$ cm

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Figure 2. Fusion-Fission Hybrid Reactor Length

MR. BOGART: Are there any questions?

DR. MOIR: I don't think that length, per se, is such a big thing except as it relates to a high cost. If a kilometer long is cheap, it may be okay, but I doubt it.

DR. ROSE: The only concrete answer I can give you with respect to cost is that under an EPRI contract we have estimated system costs. I have to put very very large quotation marks around "cost" because it was estimated--really estimating, nothing that is in any way competitive with the kind of cost estimates that you have heard here about the mainline machines. I don't remember the exact length, but it was of the order of a kilometer--was evaluated and the cost was not out of sight. Most of the costing was done on an analogous basis, i.e., analogous to other cost estimates, so we were trying to use the same techniques. As a result, we shouldn't be too far off. Now my claim is that the machines are going to be a factor of about 5 shorter, and I think cost-wise, although there just hasn't been any analysis, some of the major cost items will be smaller and consequently there should be a significant gain. How much I cannot say. There just has not been enough work on these machines to get good cost estimates.

You should not make an a'priori argument that the cost is going to be high, one argument that has always been made against linear machines. Linear machines consist of simple cylindrical constructions. The fission engineers love it because they see structures that are similar to the kind of devices that they are used to, that they have done before.

For linear fusion reactors we can talk about modular construction, modules that are made in a factory and trucked to the site. Those are constructions that I don't know how to put a number on right now, but they represent pluses. So I think with respect to cost, linear machines if they can be made of reasonable length, are going to do very well.

A TOKAMAK DEMONSTRATION HYBRID REACTOR

V. L. Teofilo, Battelle, Pacific Northwest Laboratories

In 1975, during the fusion reactor development planning exercises, Kulcinski and Conn(1) had proposed the design and construction of a facility to test and demonstrate fusion-fission hybrid reactor operation. Battelle-Northwest, in cooperation with the University of Wisconsin has performed a preliminary conceptual design of a Tokamak Demonstration Hybrid Reactor (TDHR). A fuel breeding blanket has been designed and adapted to the fusion driver system of the Tokamak Engineering Test Reactor (TETR)(2) which has been designed by the University of Wisconsin to produce a high neutron wall loading for engineering and materials testing. The design is based upon near-term technological developments for a system that could be operating in the late 1980's. The U. S. tokamak fusion reactor development program could provide the physics and technology base for proceeding with the design and construction of TDHR upon successful operation of TFTR and its predecessors.

FUSION DRIVER

Amongst the major design features of the TETR fusion driver system is a plasma whose parameters are listed in Table 1. It is operated in the TCT mode(3) with some elongation to increase beta, neutron power, and wall loading (1.4 MW/m^2). Impurity control in the plasma is maintained by a double null poloidal divertor operated in the unload mode in addition to a carbon curtain first wall liner. The magnet system consists of NbTi superconducting TF coils ($B_{max} = 8.5T$) together with high conductivity aluminum OH coils operated at cryogenic temperatures. The normal VF and divertor and shaping coils are water cooled copper and are placed within the TF coils to minimize the current requirements needed for shaping and maintaining vertical stability. The first wall structure is made of 316 SS cooled to 250°C in order to operate in a regime where the first wall need not be replaced during the lifetime of the reactor due to radiation damage.

TABLE 1. TETR Plasma Parameters

R	3.24 m
a	0.6 m
A	5.4
ELONGATION	2.0
I_p	2.5 MA
B_T	4.2 T
q (a)	2.4
$\bar{n}_e$	7.7 x 10^{13} cm^{-3}
$\bar{T}_e$	11.3 keV
β_p	3.8
$\bar{n}_e \tau_E$	8 x 10^{12} cm^{-3}-sec
Q	1.78
BEAM POWER	150 MW
NEUTRON POWER	214 MW
PULSE DURATION	60 sec
DUTY FACTOR	0.83

BLANKET DESIGN

A cross sectional view of TDHR is shown in Figure 1. The modular blanket assembly layout which has been designed(4) assumes a 65 cm blanket the thickness of which is restricted by a minimum of 10 cm proximity to any normal shaping or vertical field coil as seen in Figure 2. The 316 SS modular assemblies are interchangeable with respect to the horizontal midplane. There are 32 modular assembly slices, two per TF coil, which allow for assembly and disassembly.

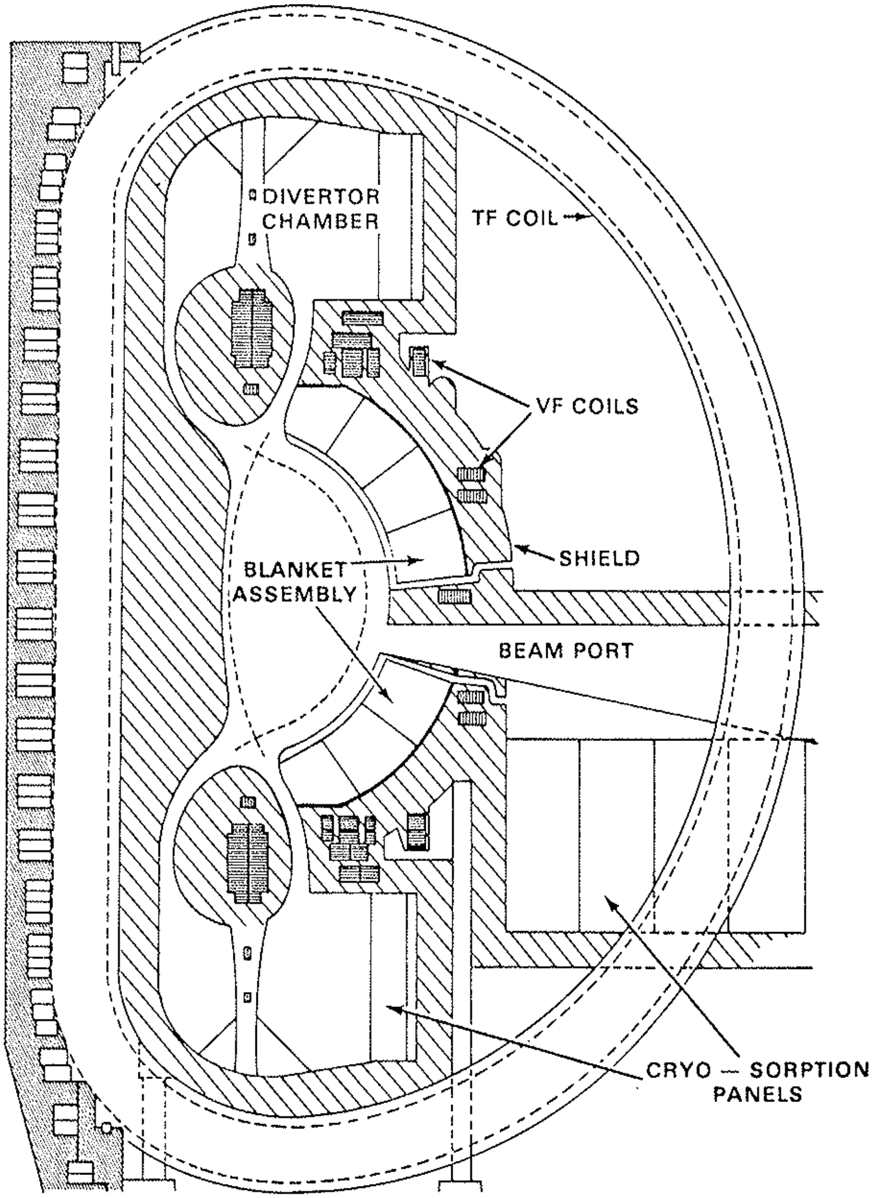

FIGURE 1. Modular Blanket Assembly Layout

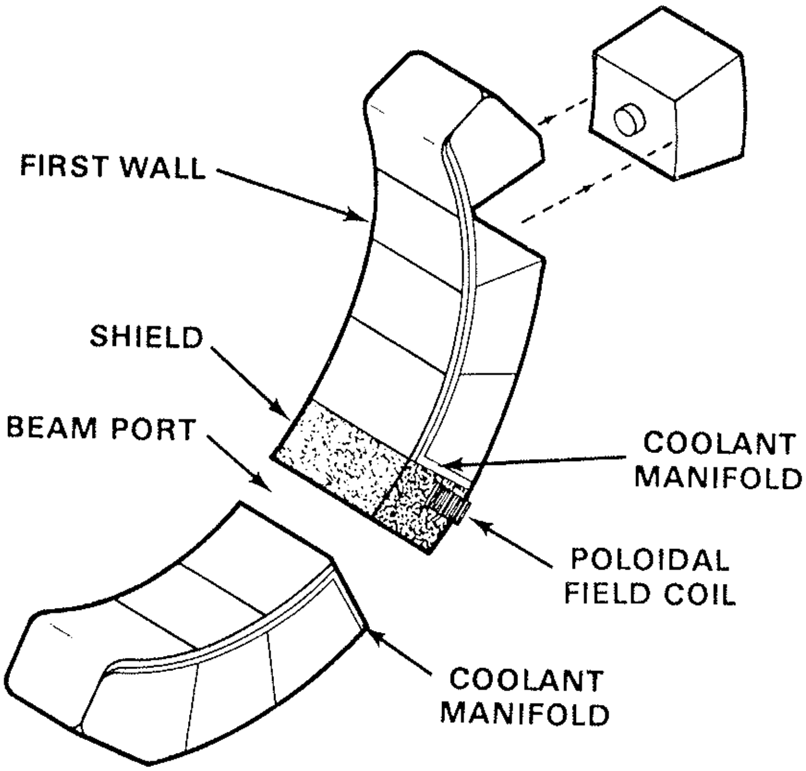

FIGURE 2. Hybrid Blanket Assembly Schematic

In light of the requirement of implementing near-term technology, the fertile breeding fuel selected is natural uranium oxide pellets encased in 316 SS clad fuel pins.

The cross section of a module and plenum chamber shown in Figure 3 indicates its double wall construction to allow cooling of the structural walls by the incoming helium fluid, T_{in} = 600°F. Each module contains 2520 UO_2 fuel pins clad with 316 SS. The pins are 61 cm long and 1 cm in diameter. The return flow of heated fluid is contained in a flow channel which is surrounded by the incoming flow of cold helium coolant. The structure of the inner flow channel will see cyclic temperature variations but should have very small pressure loadings. However, the outer wall, which is subjected to very high pressure loadings, will be cooled by the cold incoming fluid so that it should see little if any cyclic temperature variations. The thermal hydraulic analysis of the module cooling system, using the COBRA-IV-I code(6) for the power density distribution determined by neutronic computations, indicate an outlet temperature at the end of the fusion burn cycle of 1200°F at 700 psia with a 2.5 psi pressure drop along the fuel rods.

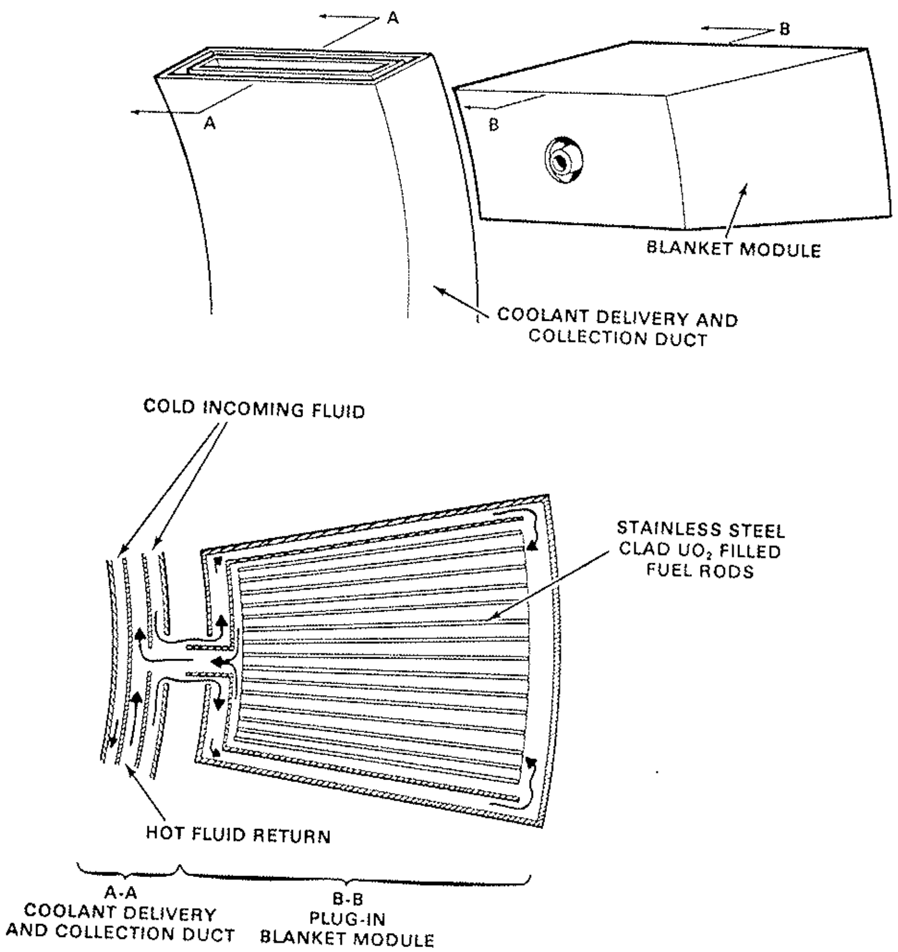

FIGURE 3. Blanket Module Cross Section

The structural analysis of the blanket modules was performed with the 2-D BOSOR4 Code(7) a minimum of 5.27 cm of 316 SS is needed for structural integrity of this outer wall unless some external structural support is provided. The inner wall, which is supported by the coolant delivery ducting, would not require this large thickness. Nevertheless, this wall should be made as thin as possible (e.g., by using double layered wall) in order to improve the neutron economy.

The neutronics analysis of the TDHR system(8) was performed using the ANISN neutron transport code run in 1 D vertical cylindrical geometry with the results corrected for isotopic buildup and burnup as computed by the ORIGEN code. The resulting relevant blanket parameters computed are shown in Table 2. Similar calculations for technologically yet underdeveloped fuels show increased Pu and power producing rates which compared to UO_2 are approximately 10% greater for UMo fuel, 20% greater for UC fuel, and 25% greater for U_3Si fuel.

TABLE 2. Pu Breeding Blanket Parameters

FUEL	316-STAINLESS STEEL CLAD PINS UO_2 PELLETS
FISSIONS PER FUSION	0.35
Pu ATOMS PRODUCED PER FUSION	1.15
Pu PRODUCTION IN ONE YEAR	740 kg
AVERAGE BLANKET POWER DENSITY	15.6 W/cm^3
HELIUM COOLANT:	
INLET TEMPERATURE	600°F
OUTLET TEMPERATURE	1200°F
PRESSURE	700 psi(a)
INITIAL BLANKET POWER	780 MWt
BLANKET POWER AFTER ONE YEAR	975 MWt

For the simultaneous breeding of tritium with Pu the Pu breeder was reduced to 26 cm while the rest of the blanket contained tritium breeding canisters of Li_2O enriched to 90% ^6Li, and carbon. In addition, in order to utilize those fusion neutrons (>50%) which penetrate the inner toroidal shield and thereby achieve T breeding ratios >1, liquid natural Li coolant is used in the inner shield. An illustration of the resulting ANISN and ORIGEN computations are displayed in Table 3. The Pu production rate is reduced by more than 50%, while the blanket power is reduced

TABLE 3. Pu/Tritium Breeding Blanket

FUEL	UO_2 316 SS CLAD PINS Li_2O 316 SS CLAD CANISTERS Li IN INNER SHIELD
FISSIONS PER FUSION	0.20
Pu ATOMS PRODUCED PER FUSION	0.54
T ATOMS PRODUCED PER FUSION	1.10
Pu PRODUCTION IN ONE YEAR	330 kg
INITIAL BLANKET POWER	560 MWt
BLANKET POWER AFTER ONE YEAR	630 MWt

by but 30%. This, together with the other beam, neutronic and photonic power dissipated in the walls, shields and divertor chamber is sufficient to power the system which requires ~400 MWe including the pumping power for the helium coolant.

For the Pu breeding blanket, however, the generated blanket power (800 MWt) together with the power deposited in the walls, shields, and divertor burial chambers (350 MWt total) is more than enough to provide the necessary recirculating power (400 MWe) for the overall system to make it a net generator of electric power.

TDHR COSTS

The added cost to the TETR system for the fabricated modular blanket structure has been estimated to be $22,450,000 U. W. (1976) or $100,250 per module including the cost for fuel assembly fabrication. To this must be added the nuclear material cost of $50-100/kg of natural UO_2 for the 251,400 kg which are needed, or $12,570,000-$25,140,000. These costs, including the costs of cladding, end caps, and other module hardware are based upon FFTF 316 SS component costs. The fuel fabrication process cost estimates for commercial PWR elements in the Fuel Element Fabrication Cost (FEFC) computer code.

With this estimate a preliminary capital cost of the TDHR as determined from the base cost of TETR is $600M including the cost for the power conditioning and generator facilities. This, together with the annual operating and maintenance ($25M) and tritium fuel costs ($44M), fixes a price for the 740 kg Pu produced per year at $200/gm. This amount of Pu produced is enough to fuel 1.6 LWRs(9) in the same manner and provided that LWR fuel reprocessing should be implemented.

CONCLUSIONS

The TDHR based upon the TETR fusion driver system could demonstrate sensible fuel and power production rates at a reasonable cost for the practical demonstration of the fusion fission/hybrid concept. It is anticipated that such a demonstration would be practical with proliferation resistant blanket designs which may or may not require fuel reprocessing. An important question is whether such a demonstration should be made with or without accompanying tritium production in the hybrid blanket for the overall system to be technically as well as economically viable.

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University of Wisconsin Hybrid Studies

Greg Moses

My comments will be very brief and they are simply a point of information. In addition to this study here, we are also conducting a study for EPRI on a laser fusion hybrid reactor design, and this is, in fact, the second part of a study which they funded, beginning in January 1976. We have currently just completed a pure laser fusion reactor design and are now going on to look at the relaxation requirements necessary, let's say, in laser fusion systems to produce a viable hybrid design. Bob Conn asked me to simply make that comment here since this is a review meeting on the hybrid activity in this country. Since we will be devoting a great deal of effort to this over the next year, he felt that it would be appropriate to at least interject into the proceedings the fact that there is a new group involved in hybrid reactor design.

We have been involved in pure laser fusion design reactor conceptual designs, as you may know, but this is our first real attempt at a hybrid. Thanks.

REACTOR STUDIES OF TOKAMAK HYBRIDS

by
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During the last two years one of the tasks of the Reactor Studies Division of PPL has been a systems study of a fusion-fission hybrid reactor.[1] The objectives of the study were twofold: first, to assess the commercial feasibility of a hybrid reactor with a "TCT style" neutral beam driven tokamak as the fusion core; second, to assess the suitability of the TFTR device, now under construction at PPL, to serve as a test bed for such a fusion core. The assessment of the hybrid role for the TFTR was negative.[2] The approximately 1 second burn time for the TFTR was judged too short to provide the experience deemed necessary to evaluate how to make and maintain a plasma burn of some 1000 seconds, a burn time that we consider desirable for a commercial hybrid reactor, and the addition of a blanket forces a substantially different machine for which the TFTR cannot be considered a prototype.

To evaluate the commercial feasibility of a tokamak hybrid reactor we considered the economics of a "nuclear park" consisting of both the hybrid reactor and the satellite fission burners supported by the fissile fuel (plutonium) bred in the hybrid. The only product of the park was assumed to be electricity. The figure of merit for a particular hybrid design was the cost of producing electricity at the one and only bus bar of the nuclear park.

To evaluate the tokamak hybrid reactor we developed physical models for the tokamak device itself, its plasma properties, coil configuration, blanket and shielding layout, and for the uranium bearing blanket enclosing the plasma. An economic model was developed for the hybrid reactor accounting for the capital cost of the entire plant, the operating and maintenance costs and the fuel cycle costs. Both the direct and so called indirect costs were accounted for. (Capital cost = 1.93 x direct costs) The pressurized LWR (1 GW(e) net) was taken as the fissile fuel burner and its known economics modified to represent a Pu burning reactor. (A parity of 0.6 was assumed for the Pu.)

Our modeling allowed the physical and economic properties of the nuclear park to be completely specified by six parameters: three plasma parameters, two geometrical, and one related to the blanket. The parameters are: the plasma temperature, the injection energy of the neutral beams, the ratio of the density of energetic injected ions in the plasma to the plasma electron density, the major radius of the inner leg of the toroidal magnetic field coils, the minor radius of the plasma and the gross electric output of the hybrid reactor. (In our plasma modeling both the average pressure and the discharge current were functions solely of the geometry.) Certain constraints were also imposed such as the nature of the plasma confinement and stability, penetration requirements for the neutral beams and the neutronic limits of blanket performance.

Our search for the "best" hybrid design consisted of exploring the six dimensional parameter space for the particular "6-vector" that specified the hybrid producing the cheapest electric power for an assumed price of fissile fuel. Our early calculations indicated that the larger the gross power level of the reactor the cheaper the electricity. Consequently, our analysis has proceeded in terms of specifying the gross power and then searching over the remaining five dimensional parameter space for the "best" hybrid.

We can search the parameter space in either of two ways: by selecting a set of discrete values for each parameter and surveying over the entire set of 5-vectors so defined; or by using an "optimization calculation" by which a certain number of randomly selected 5-vectors are evaluated and the "best" 5-vector selected as a starting point for a numerical search, using a 5-dimensional gradient, for the minimum of the cost of electricity function. The survey technique is faster, hence cheaper, but less precise than the optimization technique. One survey over some 107,000 hybrid designs takes about three quarters of the time to find seven "optimized" hybrid designs.

Some survey results are shown in Fig. 1. These results are for rather conservative assumptions of a low pressure plasma ($\beta \sim 1\%$) in a so called single null configuration (the plasma cross section is somewhat elongated in the horizontal dimension due to the presence of a null in the poloidal magnetic field at the inner edge of the plasma). However they reflect several features that characterize the results under more optimistic assumptions. The curves are the bus bar cost of electricity, e, for the best hybrids as a function of an assumed price of plutonium. (The correlation in prices of Pu and U_3O_8 assumes a parity of 0.6 for Pu and the enrichment of U235 via the diffusion process at a cost of separative work of \$60/kg.) The intersection of the curves with the LWR line specifies the economics for possible nuclear parks. The intersections are labeled with the number of LWR's in the park supported with make-up fuel by the hybrid reactor. We make several observations:

First, the park value of fissile fuel is in competition with other sources of fissile fuel. This competition will determine when the use of hybrids will become economically attractive as a source of fissile fuel.

Second, the park cost of electricity is in competition with alternative energy sources. This competition will determine when the use of hybrids will become economically attractive as a source of electric power.

Third, it is estimated that U_3O_8 can be obtained at approximately \$100/lb from the relatively low grade, but plentiful, Chattanooga Shale type of ore. Therefore, if the hybrid is to prevent the large scale mining of this low grade ore, hybrids of about 6 GW(e) gross power levels appear to be required. This power level is probably too large for any utility to handle. Gross power levels of about 3 GW(e) is perhaps as large as can be expected to be useful. Therefore if there is to be a hybrid competition with Chattanooga Shale, there is a premium on reducing the size of the hybrid reactors.

Fourth, high prices for fissile fuel produce best hybrid designs that breed more net fissile fuel than the best hybrid designs found for low prices of fissile fuel. Consequently since cheap electricity will be made by the nuclear park at low values of fissile fuel the most interesting hybrid reactors may well be designed to make power rather than fissile fuel. The 10 GW(e) curve in Fig. 1 illustrates the extreme of this argument.

The results shown in Fig. 1 can be improved upon to some extent by searching for best hybrids by the "optimization calculation" technique rather than by the survey technique. In Fig. 2 are shown some results using the optimization calculation. For comparison two survey curves from Fig. 1 are also shown. A modest reduction in e is found.

Reduction in e can be sought by changing some of the assumptions of the reactor model. Herein lies the strength of the systems analysis. Five examples of changes in assumptions are shown in Fig. 2. In three cases the neutral beam penetration requirement has been changed. In the "strict penetration" case the mean free path for ionization of the neutral beams is taken to be one half of the distance between the magnetic axis and the edge of the plasma. For the "ripple" case the penetration requirement is entirely removed. In one of the ripple cases the assumed plasma pressure is increased by a factor of $\sqrt{10}$. One case has a flatter pressure profile than the "standard" cases. To create the "super blanket" the number of uranium fissions in the blanket per 14 Mev DT neutron has been increased by 50%. Significant changes in the cost of electricity are made by most of these different assumptions. We have not had time to explore the synergistic effects of these various assumptions. There is evidence, not shown here, of an optimum in plasma pressure.

The effect these different assumptions produce on the physical size of the hybrid reactor is shown in Fig 3. The reduction in physical size from the "standard" sizes is striking. We note, however, that the assumptions producing the smallest size reactor shown in Fig. 3 result in an <u>increase</u>, not a decrease, in the cost of electricity compared to the "standard" reactor. This increase is the result of the interplay of many factors. In this particular case, imposition of both the strict penetration requirement and the enhanced plasma pressure produce a reduction in both the physical size of the plasma and the energy multiplication factor of the blanket. These reductions produce an increase in the breeding ratio for fissile fuel and a savings in some capital costs. However, the reduction in size reduces the confinement properties of the plasma which in turn requires an increase in the beam power delivered to the plasma. The increase in beam power causes the net electric power to be reduced and the cost of the beam injectors to increase. On balance, the cost of electricity for the hybrid increases. This discussion serves both to underline the complexity of interaction between the various factors that make up the cost of electricity and to highlight the importance of simultaneously exploring the effects of changes in many parameters.

Finally, in Fig. 4 we show the correlation between the park cost of electricity and the gross electric power of the hybrid reactor for a variety of assumptions about the confinement properties of the plasma. The confinement property of the plasma is one of the most influential factors in determining the cost of electricity for a hybrid plant. Note for the 3 GW(e) gross hybrid reactors a quite striking change in e is produced for different degrees of optimism applied to the so called trapped electron mode scaling of the plasma confinement time.

The effect of assuming the plasma shape to have a so called double null configuration (the plasma cross section is elongated in the vertical dimension due to the presence of a null in the poloidal magnetic field at both the top and bottom of the plasma) is also shown in Fig. 4.

The combination of assuming the double null configuration and assuming the "Alcator scaling" for the confinement of the plasma produces the cheapest electricity found to date in the range of parameters explored. Such a hybrid at the 3 GW(e) gross level produces a best hybrid curve that almost coincides with the 6 GW(e) curve plotted in Fig. 1. This result is the first one that begins to look economically interesting.

We note that the more optimistic scaling for the plasma confinement produces cheaper electricity. The optimism also produces ignited tokamaks. The perhaps surprising conclusion is that the ignited tokamak hybrid will be more attractive economically than will the driven tokamak hybrid. This conclusion requires more study.

As a final topic on fusion-fission systems we consider some different ways in which the hybrid can be used primarily as a source of electric power. In Fig. 5 we show the material flows for several conceptual hybrids. Success will depend upon the energy multiplication factor of the blankets. The hybrids we have discussed above correspond to the top left corner of the figure. The feedstock is uranium (depleted or natural), lithium and deuterium. The lithium is required to breed the tritium that is required to sustain the DT fusion reaction in the plasma. Some of the bred Pu is burned in the blanket and some is sold.

The promise of a light water (moderated blanket) hybrid reactor [3] (LWHR) is higher blanket multiplication of the fusion energy without fear of criticality. The equilibrium condition of the uranium may have an atom percent of Pu239 equal to the atom percent of U235 in natural uranium. Hence reconfiguration cannot produce a critical mixture.

If the energy multiplication of the light water moderated blanket is high enough, the energy produced in the hybrid blanket can be used to drive a semi-catalyzed deuterium reactor (SCD-LWHR) [4]. Here the plasma is to be fed only with deuterium plus the tritium produced by the DD reactions in the plasma. Adding a "fission plate" to the blanket may increase the neutron density sufficiently to further increase the blanket multiplication and/or allow physically smaller machines. Perhaps the neutron density can be made high enough to make actinide burning in the blanket attractive, although this may not prove desirable.

Finally, there is the concept of using the semi-catalyzed deuterium plasma to drive a thorium bearing blanket and burning the bred U233 in situ. The last two concepts have the promise of meeting all the objections to fission plants (criticality, diversion, actinides) and to fusion plants (high tritium inventory). High energy multiplication in an inherently sub-critical blanket is the key.

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Figure Captions

Fig. 1. Bus bar cost of electricity, e, versus f, price of Pu, and U_3O_8 for "best" tokamak hybrids and a Pu burning light water reactor (LWR).

Fig. 2. Bus bar cost of electricity, e, versus price of fissile fuel (Pu) for selected variations of the hybrid model. "Ripple injection" applies to both data symbols O and ▽ .

Fig. 3. Hybrid reactor sizes displayed as circles depicting the major and minor radii of the hybrid plasma. The circle labeled "$\alpha = 1.3$" corresponds to the "flatter profile" point in Fig. 2. The circle labeled "scaled-strict pen." results from using the strict penetration requirement together with an increased (scaled) plasma pressure.

Fig. 4. The bus bar cost of electricity, e, versus the gross electric power, P_g, of the park hybrid reactor for different scaling laws for the plasma confinement parameter $n\tau$. For the (+) data $n\tau = 5\times10^{13}$ sec cm^{-3} for all hybrids. The (o—·—o) data is for a double null configuration.

Fig. 5. Material flows in a variety of electric power producing hybrid concepts.

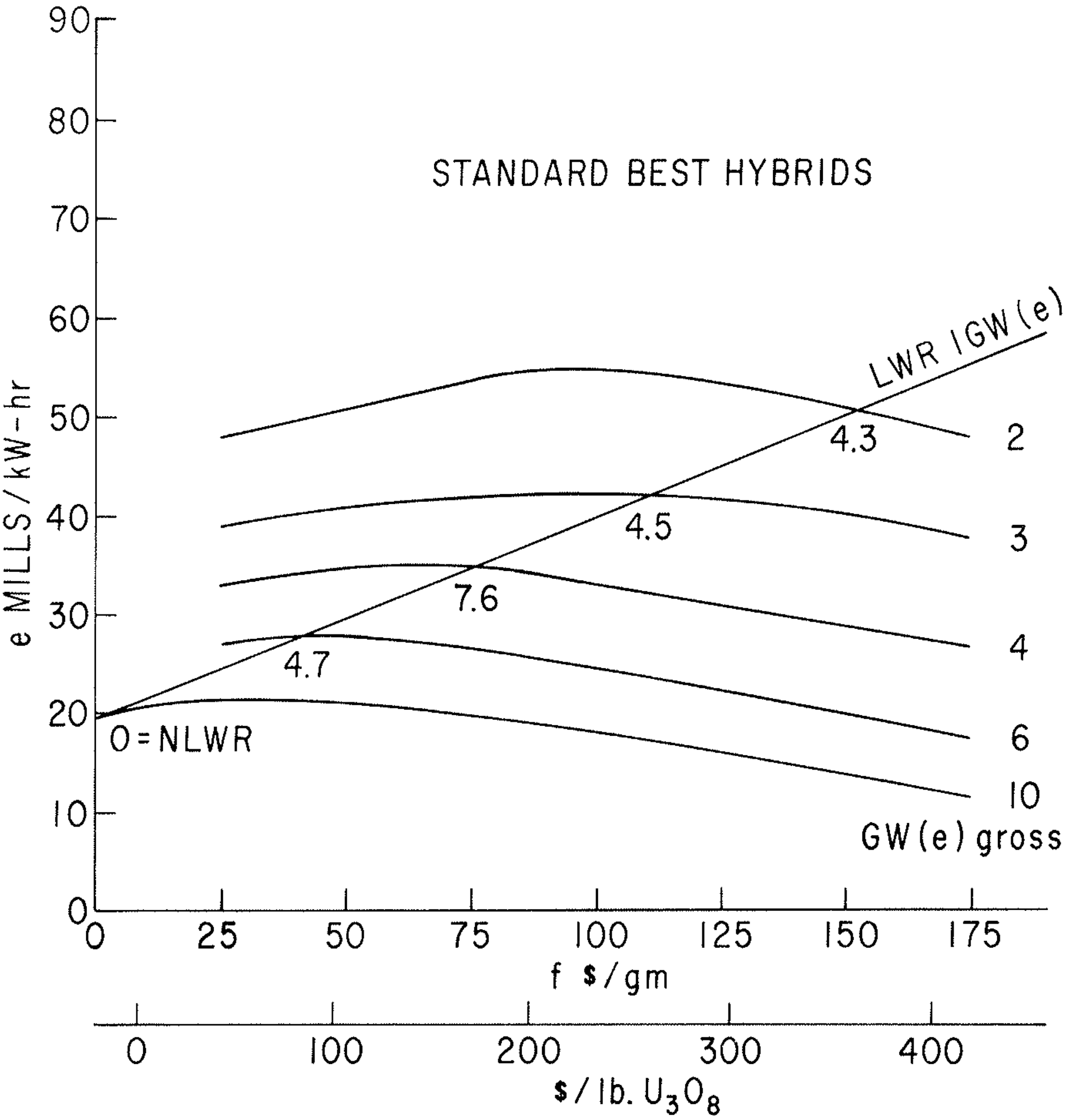

Fig. 1. Bus bar cost of electricity, e, versus f, price of Pu, and U_3O_8 for "best" tokamak hybrids and a Pu burning light water reactor (LWR).

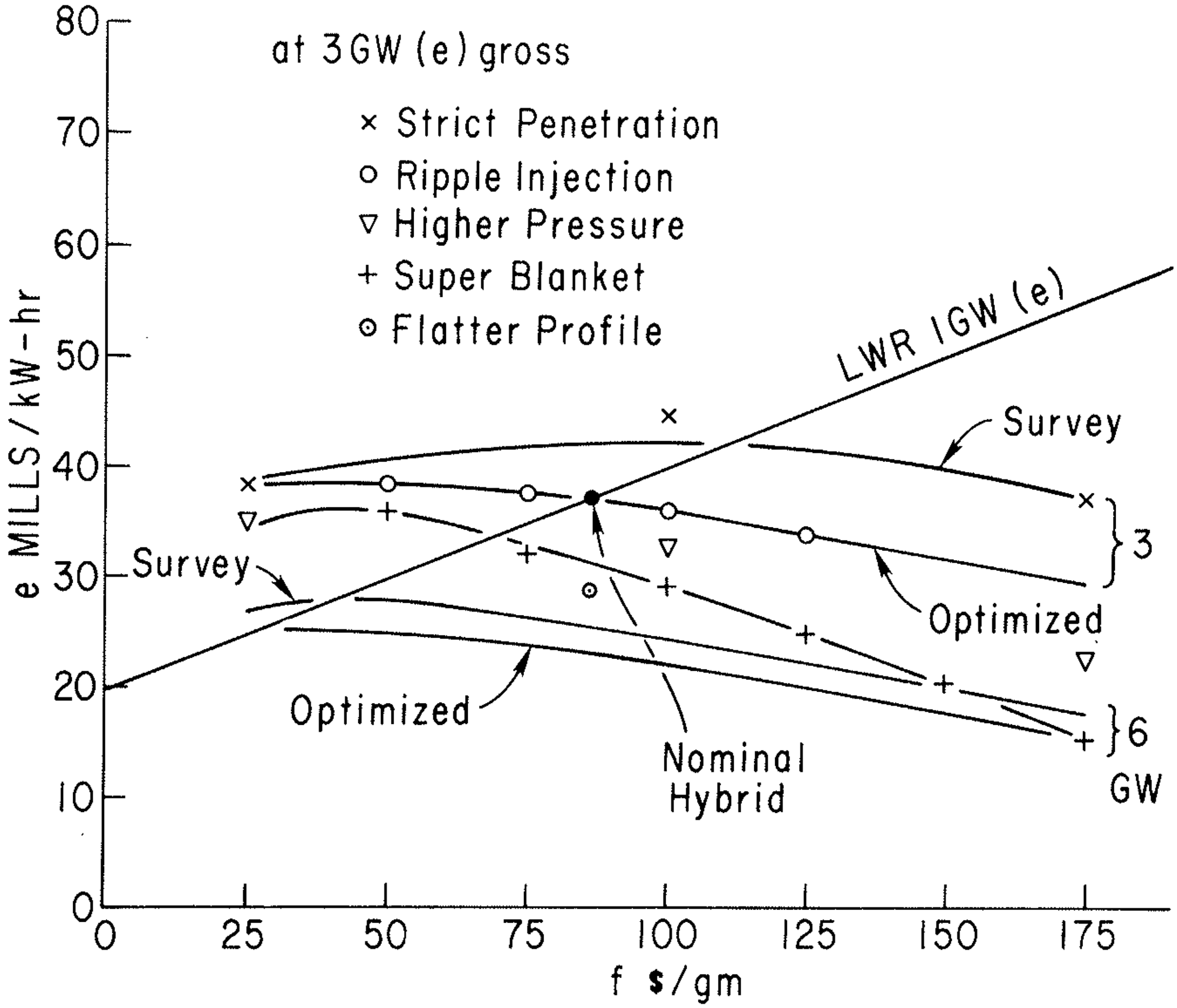

Fig. 2. Bus bar cost of electricity, e, versus price of fissile fuel (Pu) for selected variations of the hybrid model. "Ripple injection" applies to both data symbols O and ∇ .

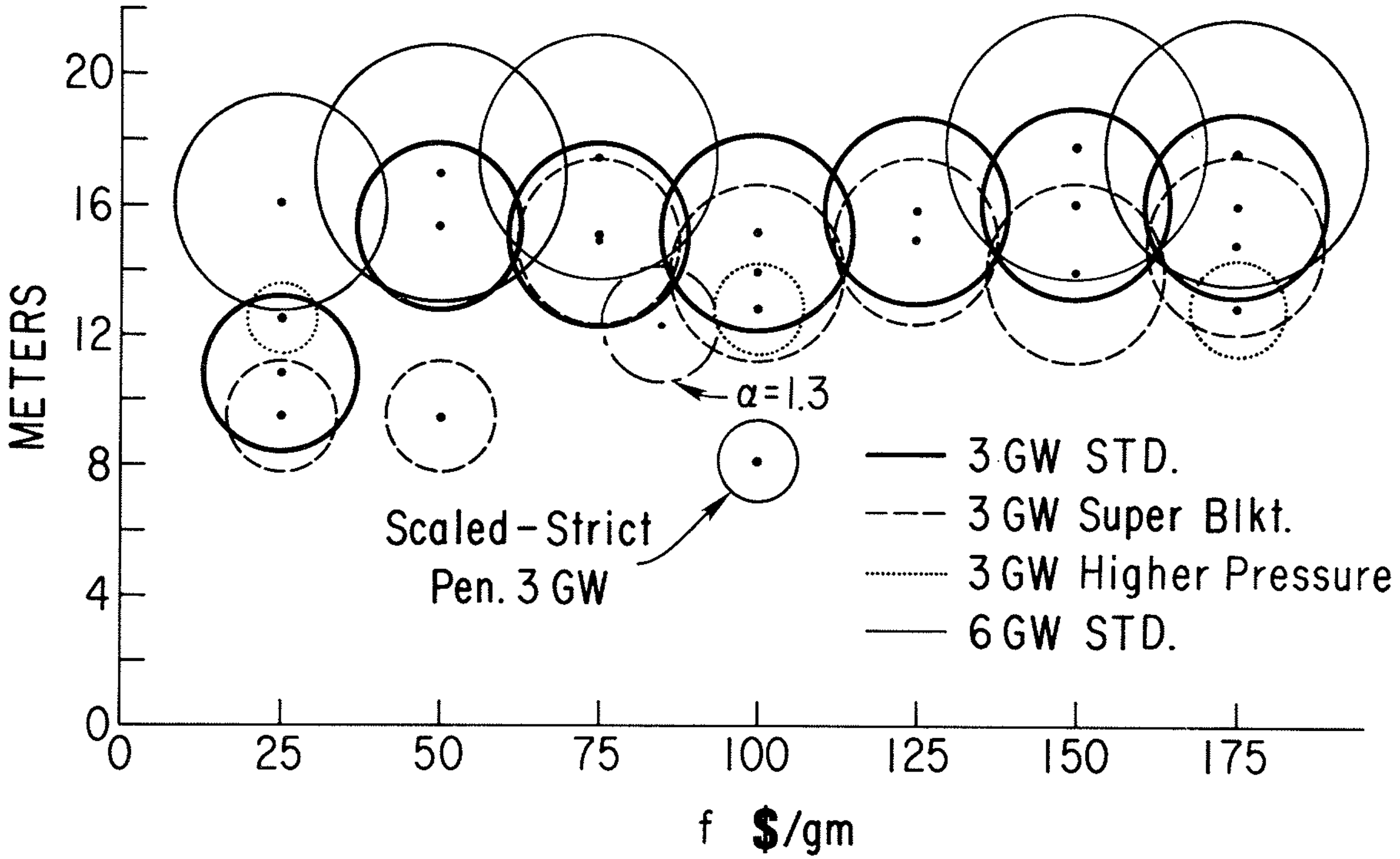

Fig. 3. Hybrid reactor sizes displayed as circles depicting the major and minor radii of the hybrid plasma. The circle labeled "$\alpha = 1.3$" corresponds to the "flatter profile" point in Fig. 2. The circle labeled "scaled-strict pen." results from using the strict penetration requirement together with an increased (scaled) plasma pressure.

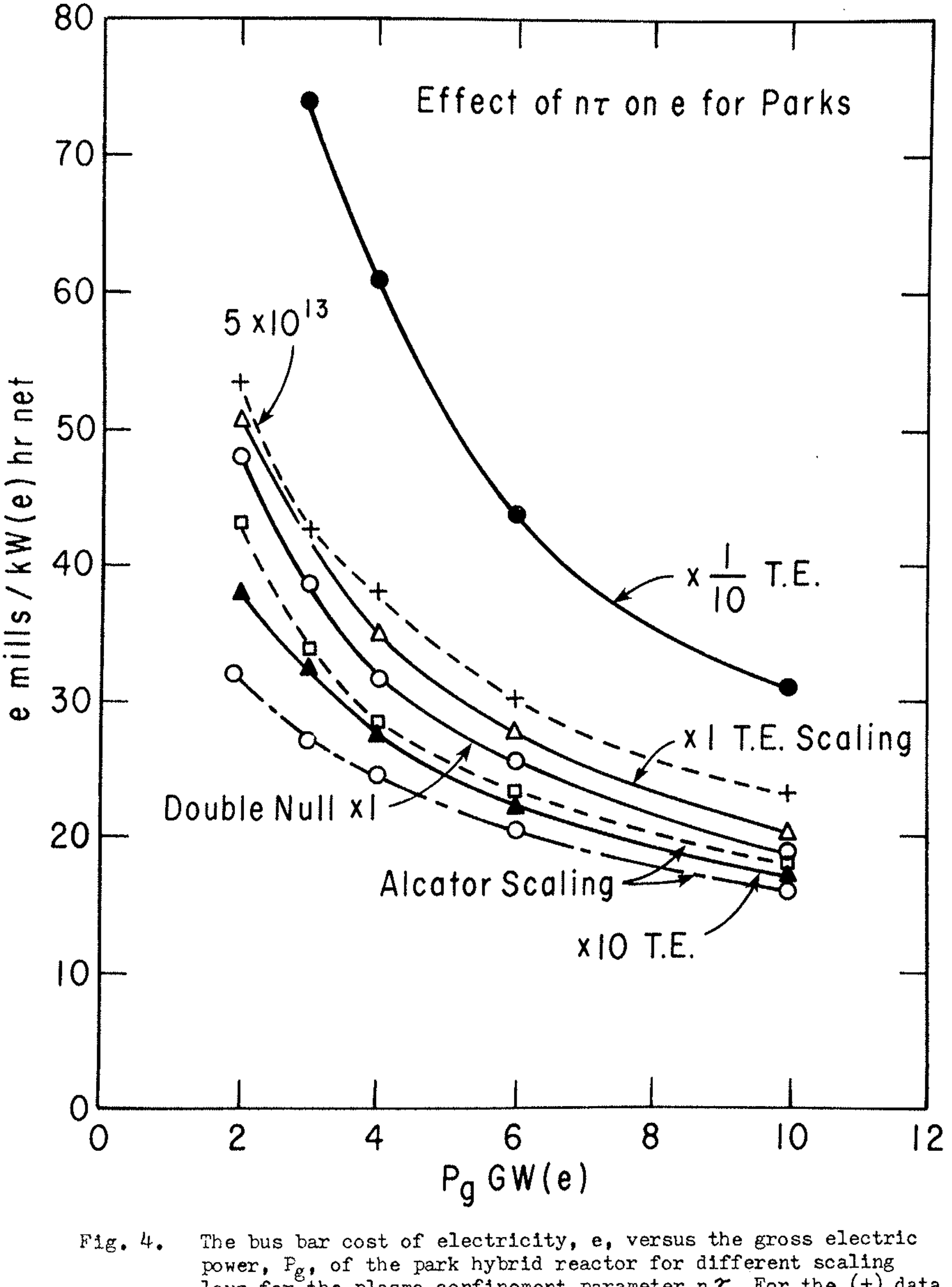

Fig. 4. The bus bar cost of electricity, e, versus the gross electric power, P_g, of the park hybrid reactor for different scaling laws for the plasma confinement parameter $n\tau$. For the (+) data $n\tau = 5 \times 10^{13}$ sec cm^{-3} for all hybrids. The (o—·—o) data is for a double null configuration.

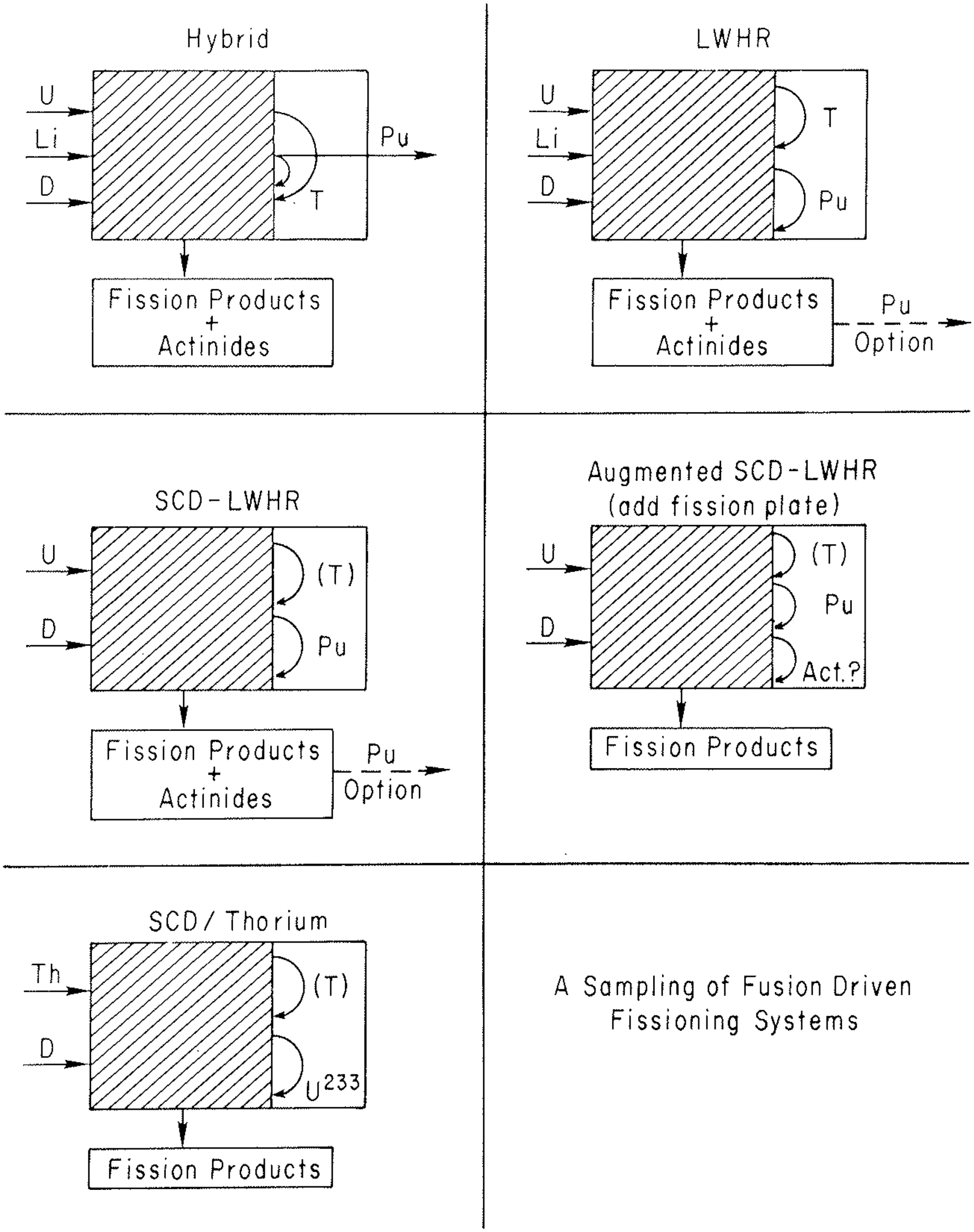

Fig. 5. Material flows in a variety of electric power producing hybrid concepts.

MR. BOGART: I think that there will be questions on that. If nobody from the audience has one, I do.

Are there any questions?

DR. BENDER: Lawrence Livermore Lab, Fred, why the strong influence on the size of the reactor? As the reactor got larger and larger, the cost of electricity --

DR. TENNEY: I think that was because our balance of plant estimate and capital cost was such that the larger the power level you went to, the cheaper it was. Basically, that was it.

MR. BOGART: I will ask my question.

Were those curves for a beta of 1 percent?

DR. TENNEY: Not all of them. These original curves were, right. If you up the value of beta by a factor of 3, you could get a small drop in these economic curves. You get a big change in the machine size but the kind of thing that seems to happen is that you up the power density in the plasma by increasing the density. The machine size then shrinks for economic reasons and when it shrinks, one loses the confinement capability of the plasma. It is hard to confine a small plasma. Since the confinement property goes down, you have to increase the beam drive in order to satisfy the energy balance. This then ups the recirculating power, reduces your net power and increases the cost of projectors. So you sort of go back where you started from. So, the economic impact isn't so great. The size impact is large.

We use positive beams, incidentally, and cost them at $300/kw. These are the same as Ralph Moir's early figures.

Advantages and Limitations of High-Gain, Mixed-Cycle Hybrid Reactors

by

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I. Introduction

A High-Gain, Mixed-Cycle (HGMC) hybrid reactor has two distinguishing characteristics. High-Gain implies that the "fission-plate" located either very near or immediately adjacent to the blanket first wall contains a significant percentage (∿8%) of fissile isotopes. The term, Mixed-Cycle, connotes the use of U-238 and Pu-239 in the fission-plate for neutron and energy multiplication together with a thorium-containing region in which U-233 is produced. Both U-233 and power (in some form) are produced for sale in a HGMC reactor and the performance characteristic of such a plant may be attractive, especially for relatively near-term applications.

II. Fuel Cycle Trade-Offs

Values of eta, neutrons produced per absorption, are listed in Table I for the combination of Th-232 and U-233 on the one hand and for U-238 and Pu-239. The values are energy dependent and those listed are for neutron spectra representative of thermal and fast reactors and for 14 MeV neutrons. Eta is defined somewhat differently at low energies and high energies, but the differences in definitions do not affect the conclusions that can be drawn from the values in Table I.

It is clear that U-233 is the superior fuel for thermal reactors insofar as neutron economy is an important consideration. If we assume that η-1.2 is approximately the maximum achievable conversion ratio, then it is concievable that a thermal reactor fueled with U-233 could breed provided other features for conserving neutrons are also incorporated. The Light Water Breeder Reactor (LWBR), Molten Salt Breeder Reactor (MSBR), and some designs of the pebble-bed reactor[1] are examples of such efforts.

In a fast spectrum the situation is reversed. Not only are eta values for Pu-239 significantly greater than those for U-233, but equally important, the eta values for U-238 are greater than those for Th-232. It is particularly noteworthy that the latter difference amounts to about 40% at 14 MeV. The eta values at 14 MeV represent the combined effects of a number of reactions including fission, (n, 2n), and (n, 3n). Fission is by far the most important component, however, and the higher values reflect both higher fission cross sections and higher ν values (neutrons produced/fission).

If a hybrid is to be designed to produce fuel for a fast breeder (or near-breeder) reactor, the choice is clear - the U-Pu cycle is superior on all counts. If, however, a hybrid is to supply thermal reactors with fuel, there are trade-offs involved. The improved performance of U-Pu in the hybrid must be weighed against the advantages of U-233 in thermal reactors. The motivation for considering a HGMC hybrid is the possibility of utilizing the best features of both cycles, i.e. fast neutron and energy multiplication from U-Pu and production of U-233 to fuel thermal reactors.

III. Figures of Merit

One of the difficulties involved in comparing hybrid reactor designs is the lack of uniformity in the types of results reported. This, in turn, may reflect a lack of consensus about which figures-of-merit are most meaningful. Ultimately, of course, cost-benefit comparisons will dictate the degree of market penetration achieved by hybrids. Hybrid designs are still, however, very preliminary and nothing has been actually constructed, not even experimental devices. Cost estimates are, therefore, very uncertain. At the present time the fusion driver remains as the critical element and for this reason it is meaningful to reference figures of merit to plasma performance.

The two products of a hybrid are energy and fissile fuel. The two parameters which express hybrid output relative to plasma performance are the energy multiplication, M,

$$M = \frac{\text{energy produced in the blanket (MeV)}}{\text{14 MeV}} \quad ,$$

and F, the net number of fissile atoms produced per fusion. It can be argued that the reference energy for M should be greater than 14 MeV since most pure fusion blankets will produce more than 14 MeV per fusion. There is no other value, however, that is an obvious choice and it is possible for a pure fusion blanket to produce less.

Another widely reported result can be called the net specific fissile production rate, P. This quantity can be computed from M and F,

$$P = 5.56 \frac{F}{M} \qquad \frac{\text{kg fissile}}{\text{MW}_{\text{th}} - \text{yr}} \quad .$$

The quantity P is often considered a figure of merit because it relates net fissile production to the total thermal power and the latter can sometimes be correlated with the total cost of the plant. Although P is clearly a useful term, its validity as a figure of merit is questionable. There is no obvious relationship between the thermal power produced in a hybrid and the net electrical power (or other form of energy) available for sale. This relationship depends on both conversion efficiencies and the circulating power fraction. Furthermore, use of this ratio as a figure of merit implies that the power produced directly in the hybrid has no value.

For an overall figure of merit it is probably more meaningful to consider a weighted sum of M and F rather than a ratio of these two quantities. An obvious choice for weighting coefficients would be the energy conversion values,

$$R = 14M + 200F \qquad \text{(MeV/fusion)} \quad .$$

The quantity R represents the total energy yield per fusion of which 14M MeV is produced immediately in the hybrid blanket and 200F MeV is produced subsequently when the fissile atom is fissioned. The latter term actually underestimates the total potential energy yield represented by one fissile atom. If the fissile fuel is burned in a reactor having a conversion ratio, C, and which is part of a system including fuel reprocessing, the conversion of fertile material leads to an effective enhancement in the energy released per original fissile atom by the factor $(1-C)^{-1}$. This suggests a definition of F which is a function of C,

$$R(C) = 14M + \frac{200F}{(1-C)} \qquad \text{(MeV/fusion)}.$$

This expression can be very useful in comparing the performance of various hybrid designs. It is a measure of not only direct performance, but also of the benefit obtained in a larger system which represents the most likely application for a hybrid.

IV. Results and Conclusions

Results of analyses of a large number of fusion-fission hybrids have been reported in the literature. A representative sample of some of these results is given in Tables II and III. The results are categorized by the types of energy spectra characterizing most of the blanket, by the type of fuel cycle involved, and by fissile content in the fission-plate.

In addition to the data reported in the literature, Tables II and III include total yields in MeV/fusion computed as described above for two different conversion ratios for the accompanying system of converter reactors. Conversion ratios of approximately 0.5 are typical for thermal reactors now in operation regardless of the type of fuel employed. Conversion ratios of 0.9 can be considered readily achievable for thermal reactors fueled with U-233 or in derated fast reactors fueled with Pu-239.

Hybrids having a thermal spectrum typically display relatively high energy multiplication (reflecting relatively high values of k_{eff}) and mediocre fissile production rates. If hybrids were to function as "once-through, stand-alone" (no fuel reprocessing) plants, thermal systems would deserve consideration. They are less attractive as fuel sources for systems of converter reactors.

The performance of hybrids having a fast spectrum depends very heavily on the type of fuel cycle involved. Thorium fueled designs are singularly unattractive on all counts. This is not surprising in view of the eta values noted earlier. Designs involving U and Pu tend to have lower energy multiplication than thermal systems, but improved fissile production rates. They could be attractive as sources of fuel for a system of fast breeders which required an external source either due to rapid expansion or as a result of derated performance. The performance of this class of hybrids is markedly improved by the addition of Pu to the blanket as shown in the results of Maniscalco and Steinhauer. Since the Pu concentration will increase with time (up to $\sim$8%), a wide range of choices exists in terms of refueling patterns and equilibrium configurations.

The HGMC results are not very different from those for U-Pu designs having similar fissile concentrations. The results from Su, et al, and Steinhauer, et al, corresponding to a Pu concentration of 8% in the fission-plate are particularly noteworthy, because this is approximately the equilibrium concentration. Concentrations greater than 8% are of interest, however, because it is possible that Pu produced in converter reactors could be recycled to the hybrid. The important difference between HGMC hybrids and U-Pu designs is in the type of fissile fuel produced, U-233 instead of Pu-239.

A system of thermal converter reactors fueled by U-233 from an HGMC hybrid offer some very compelling advantages over other alternatives. Table IV lists annual fissile make-up requirements representing several types of thermal reactors. It is realistic to consider fueling a relatively large number of thermal reactors with U-233 from a single HGMC. As noted by Angenstein[14], the economics of such a system can be very attractive and relatively insensitive to the capital cost of the hybrid. Furthermore, for basically the same reasons, such a system offers significant safety, environmental, and proliferation advantages. A small number of hybrids together with the necessary fuel reprocessing facilities can be centered in perhaps one or two energy centers which feature a high level of security and isolation. These centers and the associated dispersed thermal reactors constitute a system that may be far more acceptable than other breeding alternatives. This is especially true if the fuel for the thermal reactors leaves the energy center in a form that is considered acceptable from a proliferation standpoint.

Finally, it is important to note that the high-gain aspect of an HGMC hybrid makes it possible to use fusion drivers with lower plasma gains. This concept, therefore, probably represents the nearest term application of fusion power.

Table I

η Values

	^{232}Th	^{233}U	^{238}U	^{239}Pu
Thermal	--	2.26	--	2.04
FBR	∿0.39	2.31	∿1.28	2.45
14 MeV	2.34	4.07	3.25	4.53

Table II

Results of Thermal-Spectrum Hybrid Analyses

Reference Design	M Energy Mult.	F Net Fissile Atoms / Fusion	KG Fissile / MW(TH) - Yr	R - Total Yield[A] (MeV/Fusion) R(0.5)	 R(0.9)
U-Pu					
Leonard[2]	31.0	0.29	0.05	550	1.01(3)[B]
Maniscalco[3]	25.0	1.04	0.23	766	2.43(3)
	23.6	1.05	0.25	750	2.43(3)
	25.1	0.94	0.21	727	2.23(3)
	18.7	1.03	0.31	674	2.32(3)
	35.4	1.05	0.16	916	2.60(3)
Wolkenhauer[4]	39.8	0.33	0.05	689	1.22(3)
Th-^{233}U					
Krakowski[5]	31.3	0.23	0.04	530	898

[A] $R(C) = 14M + \frac{200F}{(1-C)}$

[B] $1.01(3) = 1.01 \times 10^3$

Table III

Results of Fast-Spectrum Hybrid Analyses

Reference Design	M Energy Mult.	F Net Fissile Atoms / Fusion	KG. Fissile / MW(TH) - Yr	R - Total Yield[A] (MeV/Fusion) R(0.5)	R(0.9)
U-Pu					
Braun & Lidsky	6.1	0.83	0.76	417	1.75(3)[B]
Lee[7]	14.4	2.34	0.90	1138	4.48(3)
	9.4	1.54	0.91	748	3.21(3)
Parish & Draper	3.2	0.67	1.16	313	1.38(3)
Su[9]	8.6	1.45	0.94	700	3.02(3)
Maniscalco[3]	10.0	1.95	1.08	920	4.04(3)
	10.4	1.99	1.06	942	4.13(3)
	11.4	1.96	0.96	944	4.08(3)
	7.0	1.34	1.06	634	2.78(3)
Steinhauer[10]	8.1	1.39	0.95	669	2.89(3)
High-Gain					
Maniscalco					
(9.5% Pu)	80.2	4.58	0.32	2.96(3)	1.03(4)
Steinhauer[10]					
(4% Pu)	23.1	2.06	0.50	1.15(3)	4.44(3)
(2% Pu)	11.8	1.62	0.76	813	3.41(3)
Th-^{233}U					
Parish & Draper[11]	1.4	0.31	1.23	144	640
Maniscalco[3]	2.2	0.61	1.54	275	1.25(3)
High-Gain, Mixed Cycle					
Su[9] (8% Pu)	81.5	3.53	0.24	2.55(3)	8.20(3)
Steinhauer[10]					
(8% Pu)	80.4	3.63	0.25	2.58(3)	8.39(3)

[A] $R(C) = 14M + \frac{200F}{(1-C)}$

[B] $1.75(3) = 1.75 \times 10^3$

Table IV
(From Refs (12) & (13))

Fuel Requirements for Thermal Reactors

Annual Fissile Make-Up Requirements	(kg/yr)[A]	Thermal Reactors[B] / Hybrid
Current Designs		
PWR - Pu/UO_2	590	3.4
PWR - $^{233}U/ThO_2$	310	6.4
HTGR - $^{233}U/ThO_2$	270	7.4
Advanced Designs		
PWR - $^{233}U/ThO_2$	120	16.7
Pebble Bed - $^{233}U/Th/O_2$	40	50.0

[A] 1000 MWe with recycle

[B] Hybrid fissile prod. rate - 2000 kg/yr

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MR. BOGART: Are there any questions?

DR. LEE: Gene, I am curious about two things -- or one thing, really. You mentioned the fact that the thorium system breeds U-233. It could fuel a lot of fission reactors probably the HTGR type. But then, you said that it also had the advantage of proliferation resistance. Now, I assume those high reactor support numbers did not include the fact that to make it proliferation proof, you would have to denature it, which would have a very strong effect on the conversion efficiency of those reactors.

One other quick comment: the best figure of merit for the combined plutonium breeding or uranium breeding into energy is mills per kilowatt hour of the combined systems.

DR. WOODRUFF: Well, I am not sure that you are looking for an answer there, right?

DR. LEE: I am looking for an answer to the first question. Do you have proliferation scenario that includes the effect of denaturing the cycle?

DR. WOODRUFF: No. What you see is what you get here. Those are the fissile make-up requirements, and if you are turning out 2,000 kilograms per year, you can satisfy that many plants...

DR. LEE: But that isn't the proliferation resistant system?

DR. WOODRUFF: That is true. I mean, I don't know what is ultimately going to be considered acceptable as a proliferation resistant cycle. Whether the denatured cycle is better than spiking plutonium, I couldn't say.

A SIMPLE ECONOMICS PARAMETRIC ANALYSIS OF FISSILE FUEL PRODUCTION BY FUSION-FISSION REACTORS

By

R. A. Krakowski
A. S. Tai*

ABSTRACT

A simplified but general analytic model is formulated and evaluated to relate all major elements of fissile-fuel production by fusion-fission (hybrid) reactors on basis of simple economic constraints. The hybrid reactor performance is examined in terms of its fissile-fuel conversion ratio, blanket multiplication, and intrinsic efficiency. A stationary, equilibrium fissile-fuel/energy market is assumed, and the economically constrained performance is evaluated parametrically as a function of burner-converter conversion ratio, plant capital costs, and ratio of fissile-fuel to energy costs. The model and results presented herein can be applied to other means of fissile-fuel production (e.g. electronuclear breeders).

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1. INTRODUCTION

Systems that propose the generation of fissile fuel by the interaction of thermonuclear 14.1-MeV neutrons with a fertile blanket are comprised of the following three essential elements: a) the efficiency by which the fusion driver generates thermonuclear neutrons, b) the neutronic characteristics of the breeding/multiplying blanket (including tritium breeding), and c) the neutronic characteristics of the fission burner-converter system that is sustained by the fusion-fission system. These three elements interact through a set of economic and socio-political constraints. A major part of the literature that has been published on this subject focuses either on the neutronic design of a specific blanket or range of blanket configurations,[1-3] or couple such studies to specific fusion driver concepts upon which cost estimates are made.[4] Relatively detailed cost/benefit economic evaluations,[5] using present-worth criteria, ascertain the merits or demerits of a generalized fusion-fission system in comparison to other more conventional energy sources. The complexity of the fusion-fission/burner-converter interaction generally has forced past studies to focus onto one element of the problem. A simplified but general model is formulated herein to relate all elements of this problem on the basis of simple economic constraints. Both the fusion-fission system and the burner-converter system are characterized by a minimum number of performance parameters and are then related to each other through stationary, common fuel and energy markets. The simple analytic expressions given by the model are evaluated over a realistic parameter range, and general conclusions are drawn therefrom. Unlike more commonly used methods of economic evaluation, this model specifies the fuel and energy cost and then examines the range of fusion-fission and burner-converter system parameters where economically interesting operation may occur. By straightforward reinterpretation of fusion-fission system parameters, the economic constraints associated with other means of fissile-fuel generation, e.g. accelerator-driver breeders, can be investigated. Although the "lumped-parameter" approach used here may over-simplify the problem, this model presents the merits of transparency and the simplicity of a generalized and analytic solution, which is considered an asset insofar as establishing trends and pointing towards answers to complex questions (i.e. the economic desirability of fissile fuel vs power production, explicit blanket neutronic constraints, etc.).

2. MODEL DEVELOPMENT

2.1 Fusion-Fission and Burner-Converter System Model

A simple but relatively comprehensive model is developed to join explicitly all of the aforementioned elements of this complex problem. Firstly, the neutronic characteristics of the fissioning/breeding blanket associated with the fusion-fission (or accelerator-breeder) system are specified by a conversion ratio [CV], defined as the net fissile-fuel production per fusion event, and an energy multiplication M, defined as the ratio of in situ energy generator relative to the pure fusion case; 20 MeV/n is taken as an energy worth of a D-T fusion neutron in a typical (pure) fusion blanket. Secondly, the efficiency Q_E of the fusion driver (or accelerator breeder) is taken as the ratio of total electrical power generated when M=1 to the recirculating power needed to sustain the fusion reaction. Thirdly, the burner-converter systems are assumed to operate at a total power level that is commensurate with the total fissile-fuel output from both the fusion-fission system and from sources inherent to the burner-converter system with an intrinsic conversion ratio $[CV]^*$. Hence, the fuel and energy market is assumed to be stationary and in equilibrium.

Each kilogram of fissile fuel is taken to correspond to 2.5 MWt y of thermal energy, and the ratio of annual fissile-fuel production (kg/y) to the in situ thermal energy production for the fusion-fission system is given by

$$R(\mathrm{kg/MWt\ y}) = 3.83\,[CV]/M \qquad (1)$$

Figure 1 gives a schematic diagram of the fusion-fission/burner-converter interaction. The total engineering Q-value for the fusion-fission system is $Q = Q_E M$, where the recirculating power fraction is $\varepsilon = 1/Q$. Figure 1 depicts the cases where Q is either greater or less than unity. The ratio of total thermal power P^*_{TH} generated by the burner-converter system to the total thermal power P_{TH} generated by the fusion-fission system is easily shown to be

$$P^*_{TH}/P_{TH} = 2.5\ R/(1-[CV]^*) \tag{2}$$

For like quantities the star (*) superscript is used to designate the burner-converter system. Figure 1, Eqns. (2) and (3), and the quantities [CV], [CV]*, M and Q_E, therefore, represent all key, non-economic system parameters.

2.2 Economics/Cost Model

As noted previously, both the fusion-fission and burner-converter systems share the same fuel and energy markets, which, respectively, are characterized by the costs c_f(\$/kg) and c_p(\$/MWe y). The capital costs for power and fissile-fuel production by the fusion-fission system are designated C_P(\$/MWe) and C_F(\$/kg/y), respectively. Similar capital costs for the burner-converter system are designated by C^*_P and C^*_F. Letting η^*_{TH} (~ 0.4) represent the thermal-to-electric conversion efficiency for the burner-converter system, the annual revenue derived by this system is given by

$$[REV]^*(\$/y) = 2.5\,\eta^*_{TH} R\ P_{TH} c_p/(1-[CV]^*) + [CV]^* P^*_{TH} c_f/2.5\ , \tag{3}$$

where fissile fuel bred by the burner-converter is sold on the fuel market at the prevailing price c_f(\$/kg). The annual cost of the burner-converter operation is composed of investments on the power generation system, fuel handling payments, both being incurred over the pay period T*(y), and fuel costs. Hence,

$$[\text{COST}]^{*}(\$/y) = 2.5\ \eta_{TH}^{*}\ R\ P_{TH}(C_P^{*}/T^{*})/(1-[\text{CV}]^{*})$$

$$+ [\text{CV}]^{*}P_{TH}^{*}(C_F^{*}/T^{*})/2.5 + R\ P_{TH}c_f/(1-[\text{CV}]^{*}) \quad . \tag{4}$$

For a $Q > 1$ fusion-fission system the sale of fuel and energy represents the annual revenue and is given by

$$[\text{REV}]_{Q>1}(\$/y) = R\ P_{TH}c_f + \eta_{TH}P_{TH}(1-1/Q)c_p \quad . \tag{5}$$

The annual costs for the fusion-fission system are made-up of payments on capital investments associated with the power system, the fissile fuel handling and the fusible fuel supply (~ 49 g/MWt y for tritium, assuming a fusion energy worth of 20 MeV/n). Hence, designating C_{FF}($/ g/y) as the fusible fuel cost,

$$[\text{COST}]_{Q>1}(\$/y) = \eta_{TH}P_{TH}C_P/T + R\ P_{TH}C_F/T + 49(P_{TH}/M)C_{FF}/T \quad . \tag{6}$$

The fusible fuel cost can in principle be decomposed into a component for D_2 and Li purchases and a component associated with special blanket features required for tritium breeding and for tritium extraction. These quantities cannot be quantified without specifying the blanket details and are neglected for the sake of simplicity. Equation (6), therefore, becomes

$$[\text{COST}]_{Q>1}(\$/y) = \eta_{TH}P_{TH}C_P/T + R\ P_{TH}C_F/T \quad , \tag{7}$$

where C_P($/MWe) includes all costs associated with fusion driver not directly attributable to the processing of fissile fuel. Clearly, the blanket costs *per se* fall into a "grey zone," in that specific components may simultaneously serve fuel and power handling functions.

For the $Q<1$ fusion-fission case (Fig. 1) only the sale of fissile fuel generates revenue, whereas, the need to purchase energy from the energy market presents an added cost. Hence, for $Q<1$

$$[\mathrm{REV}]_{Q<1} = R\,P_{TH}c_f \tag{8}$$

$$[\mathrm{COST}]_{Q<1} = [\mathrm{COST}]_{Q>1} + \eta_{TH}P_{TH}(1/Q-1)\,c_p \tag{9}$$

A revenue-to-cost ratio, $[\mathrm{REV}]/[\mathrm{COST}] = 1+\Delta$ and $[\mathrm{REV}]^*/[\mathrm{COST}]^* = 1+\Delta^*$, defines a return-on-investment (or profit), Δ and Δ^*, for the fusion-fission and burner-converter systems, respectively. Combining Eqns. (3) and (4) with Eqns. (5) and (7) or Eqns. (8) and (9), for the same common market prices (costs) for fuel and energy, c_f(\$/kg) and c_p(\$/MWe y), the following economics-constrained relationship between [CV] and M can be written

$$[\mathrm{CV}] = \alpha + \beta M \tag{10}$$

where,

$$\alpha_{Q>1} = \frac{\eta_{TH}}{3.83\;Q(\rho - B\;C_F/C_P)}$$

$$\alpha_{Q<1} = \alpha_{Q>1}(1+\Delta)$$

$$\beta_{Q>1} = \frac{\eta_{TH}(B-1)}{3.83(\rho\;-B\;C_F/C_P)}$$

$$\beta_{Q<1} = \beta_{Q>1}(B - (1+\Delta))/(B-1)$$

$$B = \left(\frac{1+\Delta}{1+\Delta^*}\right)\left(\frac{T^*}{T}\right)\left(\frac{C_P}{C_P^*}\right)\frac{1 + (\rho/\eta^*_{TH})(\gamma^* - (1+\Delta^*)/2.5)}{1 + (\gamma^*/\eta^*_{TH})(C^*_F/C^*_P)}$$

$$\gamma^* = [\mathrm{CV}]^*/2.5(1-[\mathrm{CV}]^*)$$

$$\rho = c_f/c_p \quad ,$$

with the condition $B<\rho/(C_F/C_P)$ imposed to insure that $[\mathrm{CV}]\geq 0$. It is noted that all major variables which determine the relationship between the fusion-fission blanket parameters, [CV] and M, appear conveniently as ratios. Equation (10) is evaluated as a function of $Q_E = Q/M$ and the fuel-to-energy cost ratio $\rho = c_f/c_p$,[+] with the assumption that $C_F/C_P = C_F^*/C_P^* = \rho$.

Although the approximate nature of this economics model does not warrant its use to determine the absolute value of specific costs, such an evaluation in some instances has been made to insure same degree of validity over the parameter range studied. Hence, for $Q > 1$, the fissile fuel cost is given by

$$c_f(\$/\text{kg}) = (1+\Delta^*)(1+(\gamma^*/\eta_{TH}^*)(C_F^*/C_P^*)) \quad (\rho C_P^*/T^*)/(1+\rho g^*) \ , \tag{11}$$

where $g^* = (2.5\gamma^* - (1+\Delta^*))/2.5\,\eta_{TH}^*$. Equation (11) explicitly gives the dependence of c_f on major capital costs and the fixed fuel-to-energy cost ratio, ρ.

The allowable ratio of capital costs C_P/C_P^* for the fusion-fission system relative to the burner-converter system represents an important parameter, and is given by

$$(C_P/C_P^*)_{Q>1} = (C_P/C_P^*)_{M=\infty} - K/MQ_E \tag{12A}$$

$$(C_P/C_P^*)_{Q<1} = (C_P/C_P^*)_{M=\infty} - K((1+\Delta)/MQ_E - \Delta) \quad , \tag{12B}$$

where, $(C_P/C_P^*)_{M=\infty} = K(1 + \rho R/\eta_{TH})$ and

$$K = \left(\frac{1+\Delta^*}{1+\Delta}\right)\left(\frac{T}{T^*}\right)\left(\frac{1 + (C_F^*/C_P^*)(\gamma^*/\eta_{TH}^*)}{1 + (C_F/C_P)(R/\eta_{TH})}\right)\left(\frac{1}{1+\rho g^*}\right) . \tag{13}$$

[+] Although this ratio is not dimensionless, for $\eta_{TH} = 0.4$ the conversion of 1 kg of fissile fuel to 1 MWe y of electrical energy actually allows ρ to be considered as the fraction of the total energy cost corresponding to fuel costs. That is, for $\eta_{TH} = 0.4$, kg/MWe y = 1.0.

Because of the condition $B<\rho/(C_F/C_P)$ needed to insure $[CV]\geq 0$, the maximum allowable value of C_P/C_P^* is given by

$$(C_P/C_P^*)_{MAX} = \frac{\rho}{C_F/C_P}\;\frac{1 + (C_F/C_P)(R/\eta_{TH})}{1 + \rho(R/\eta_{TH})}\;(C_P/C_P^*)_{M=\infty} \quad , \qquad (14)$$

in order to assure the designated or specified economic constraints.

3. EVALUATION OF MODEL

Equation (9) has been evaluated for $T/T^* = C_P/C_P^* = 1$, $C_F/C_P = C_F^*/C_P^* = \rho$, $\Delta = \Delta^* = 0.15$, and $\eta_{TH} = \eta_{TH}^* = 0.4$. The conversion ratio for the burner-converter system, $[CV]^*$, is expected to be in the range 0.6 to 0.8, and ρ is varied in the range of 0.2 to 0.3. Without a detailed cost breakdown the assumption that ρ equals C_F/C_P and C_F^*/C_P^* cannot be tested, although a direct relationship is expected.

Figures 2-4 depict Eqn. (10) for a range of Q_E and for representative combinations of $[CV]^*$ and ρ values. Shown also on these figures are lines of constant R(kg/MWt y) and P_{TH}^*/P_{TH} (Eqns (1) and (2)) as well as the region where $Q = Q_E M<1$. On the basis of the summary of neutronic blanket designs given by Woodruff,[1] values of R much in excess of unity seem unlikely, which exclude large regions of the M-[CV] parameter space; most notably, operation of economic $Q<1$ systems does not appear possible.

Figures 2-4 are based on the assumption that $C_P = C_P^*$. Because of the technologically more complex fusion-fission system, C_P/C_P^* may likely exceed unity. Figure 5 reproduces the conditions of Fig. 2 ($[CV]^* = 0.6$, $\rho = 0.3$), except that the fusion-fission system now costs 20% more than the burner-converter system ($C_P/C_P^* = 1.2$). Only by a significant increase in M and/or [CV] (within the previously noted neutronic constraint $R\lesssim 1$) can the fixed values of ρ and profit Δ be maintained.

Equation (11) has been evaluated in Fig. 6, which gives the dependence of fissile fuel cost on burner-converter capital cost for $\rho = 0.2$ to 0.3, and $[CV]^* = 0.6$ to 0.8. For a given burner-converter capital cost and fuel-to-energy cost ratio, the allowable fuel cost is only weakly sensitive to $[CV]^*$.

Lastly, Fig. 7 gives the dependence of M on C_P/C_P^* (Eqn. (12)) for $\rho = 0.2$, 0.3 and $[CV]^* = 0.6$, 0.8. This figure quantitatively exhibits the small latitude of the fusion-fission capital cost C_P to exceed the burner-converter capital cost C_P^* and for the overall system to remain economically interesting. For the non-profit case ($\Delta = 0$) shown on Fig. 7, the allowable capital cost C_P cannot exceed 45% of the burner capital cost C_P^* for $M \leq 10$ (R = 0.23 kg/MWt y). In addition, this figure shows clearly that a fusion-fission system operating with $Q = Q_E M < 1$ is economically unrealizable ($C_P < C_P^*$) under the conditions used for this analysis.

4. CONCLUSIONS

The following conclusions can be drawn from the limited evaluations depicted on Figs. 2 to 7.

a) Fusion-fission systems which must be driven by external power sources (i.e. $Q = Q_E M < 1$) are economically possible only for very large values of [CV] and $\rho = c_f/c_p$. For a relatively wide range of fusion-fission blankets subjected to neutronic analysis[1] the required [CV] and M values have not been found, and the high ρ values required appear unrealistic. Hence, externally driven symbiotes ($Q<1$, $M \simeq 1$) appear economically unacceptable for the assumed conditions (Figs. 2-4).

b) The curves of constant Q_E shown on Figs. 2-5, as expected, converge to the $[CV] = 0$, $M = 1$ point as Q_E increases, the rate of collapse to this pure fusion operating point depending strongly on the magnitude of $\rho = c_f/c_p$ and $[CV]^*$. Generally, for $Q_E \gtrsim 3$ the pure fusion system becomes attractive and preferable. Given that $R(\text{kg/MWt y}) \simeq 1$ at best, symbiotes (i.e. $M \simeq 1$) are feasible only for [CV] values that are considerably below unity and for fusion-driver systems of reasonable efficiency ($Q_E \gtrsim 2$). Unless the burner-converter system has a very low conversion ratio, $[CV]^*$, and the fuel cost becomes an appreciable fraction of the total energy cost, and in view of conclusion a), pure symbiotes do not appear feasible for this combination of neutronic and economic reasons.

c) For the same values of [CV] and M, either increasing $[CV]^*$ or decreasing ρ forces the required fusion-fission system efficiency Q_E to higher and higher values. Low-efficiency fusion drivers are economic only if the fissile fuel cost becomes high and the burner-converter in themselves are poor generators of fissile fuel. In other words, for high values of $[CV]^*$ and low values of ρ, economic considerations force the fusion-fission to generate more electrical power in order to remain competitive (a constraint imposed throughout this analysis).

d) Figure 6 indicates that the fissile fuel produced by the fusion-fission system would be attractive, according to the fissile fuel costs expected for the coming years, if the fuel-to-energy cost ratio ρ is sufficiently low ($\lesssim 0.3$). The realization of this condition depends on technology advancement (high Q_E and M) and the difficult requirement on capital cost ($C_P/C_P^* \lesssim 1.3$).

e) Given that $R(\text{kg/MWt y}) \lesssim 1$ and that a kilogram of fissile fuel represents a potential thermal energy of 2.5 MWt y, the fusion-fission system will generate a quantity of <u>in situ</u> energy comparable to the energy content of the fissile fuel produced. For the more likely value of R = 0.4 kg/MWt y, the <u>in situ</u> "real" energy generation equals the "virtual" energy production of the bred fissile fuel. According to Eqn. (2), however, the power P_{TH}(MWt) accompanying the production of $R\,P_{TH}$(kg/y) of fissile fuel by the fusion-fission system is multiplied or amplified by a factor of $2.5\,R/(1-[CV]^*)$ when this fuel is consumed by a burner-converter system with an intrinsic conversion ratio $[CV]^*$. The effect of the number $N = P_{TH}^*/P_{TH}$ of equivalent burner-converter systems supplied by the fusion-fission system on the total capital cost associated with power generator C_{PT}($/MWe) is readily seen from the following expression

$$C_{PT}/C_P^* = \frac{C_P/C_P^* + (\eta_{TH}^*/\eta_{TH})(T/T^*)N}{(1-1/Q) + (\eta_{TH}^*/\eta_{TH})N} \qquad (15)$$

$$\simeq (C_P/C_P^* + N)/(1-1/Q + N) \quad .$$

When Q is less than unity, the quantity (1-1/Q) must be set equal to zero. For the conditions assumed throughout this analysis, increasing N beyond ~5 has little effect on the total capital cost C_{PT} relative to the intrinsic capital power costs C_P^* of the burner-converter system. In effect the cost of the fusion-fission system is spread over the cost of N burner-converter systems and the ratio C_{PT}/C_P^* deviates little from unity.

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6. FIGURE CAPTIONS

Figure 1. Schematic representation of fusion-fission/burner-converter model used to evaluate economically constrained flow of fissile fuel and energy. Quantities with starred (*) superscripts refer to burner-converter parameters, whereas quantities without a superscript refer to the fusion-fission system.

Figure 2. Economically-constrained relationship between [CV], M and Q_E for $[CV]^* = 0.6$ and $\rho = c_f/c_p = 0.3$ (Eqn. (10)).

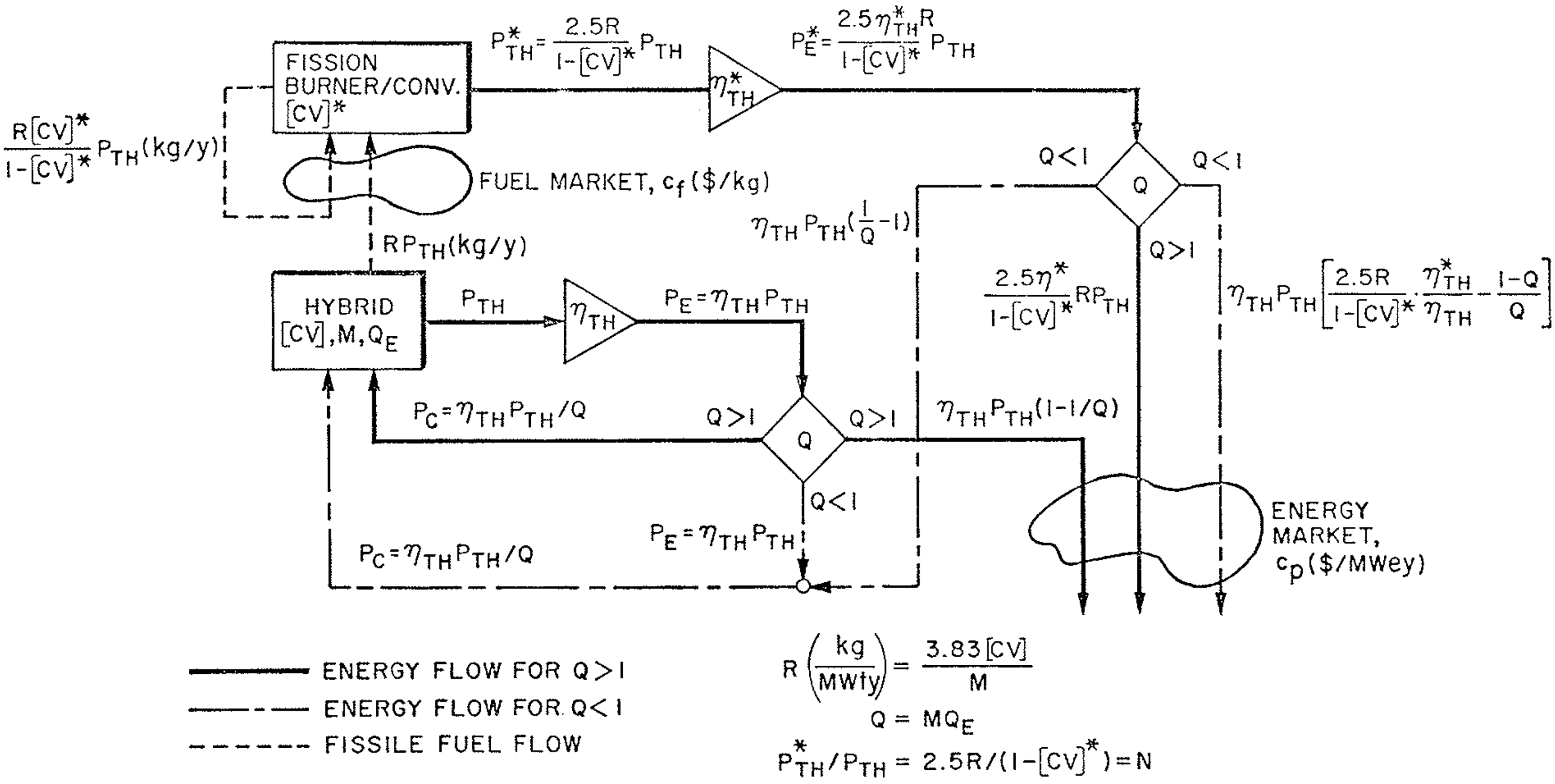
Figure 3. Economically-constrained relationship between [CV], M and Q_E for $[CV]^* = 0.8$ and $\rho = 0.3$ (Eqn. 10)).

Figure 4. Economically-constrained relationship between [CV], M and Q_E for $[CV]^* = 0.8$ and $\rho = 0.2$ (Eqn. (10)).

Figure 5. Economically-constrained relationship between [CV], M and Q_E for $[CV]^* = 0.6$ and $\rho = 0.3$ (Eqn. (10)), but with $C_p/C_p^* = 1.2$.

Figure 6. Dependence of fuel cost c_f($/kg) on capital cost payments of the burner-converter system C_p^*/T^* ($/MWe y) for $\rho = 0.2, 0.3$ and $[CV]^* = 0.6, 0.8$.

Figure 7. Dependence of required fusion-fission multiplication M for [CV] = 0.6 on the ratio of fusion-fission to burner-converter capital costs C_p/C_p^* for $\rho = 0.2, 0.3$ and $[CV]^* = 0.6, 0.8$ (Eqn. (12A)). A non-profit case (Δ=0) is also shown.



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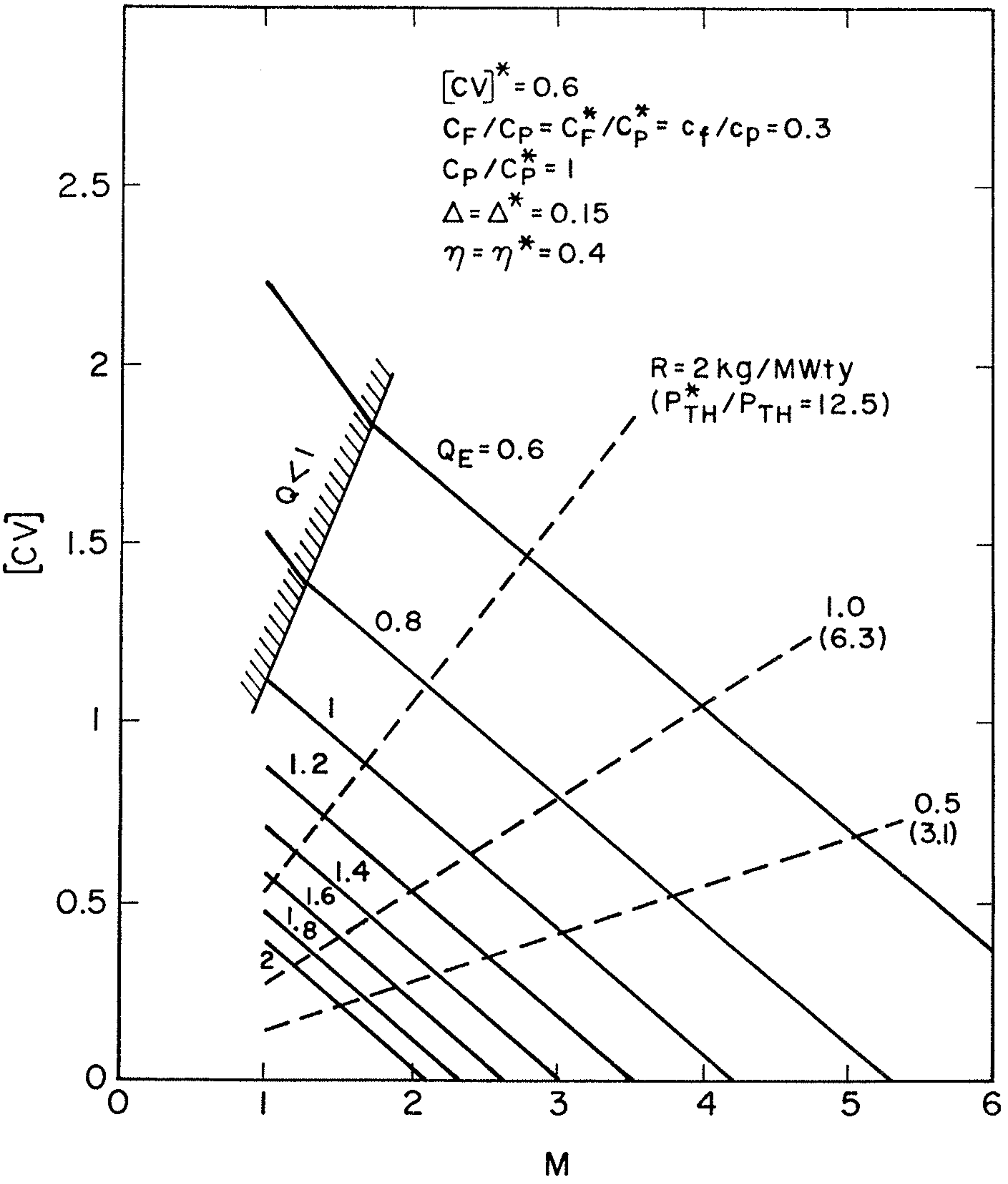

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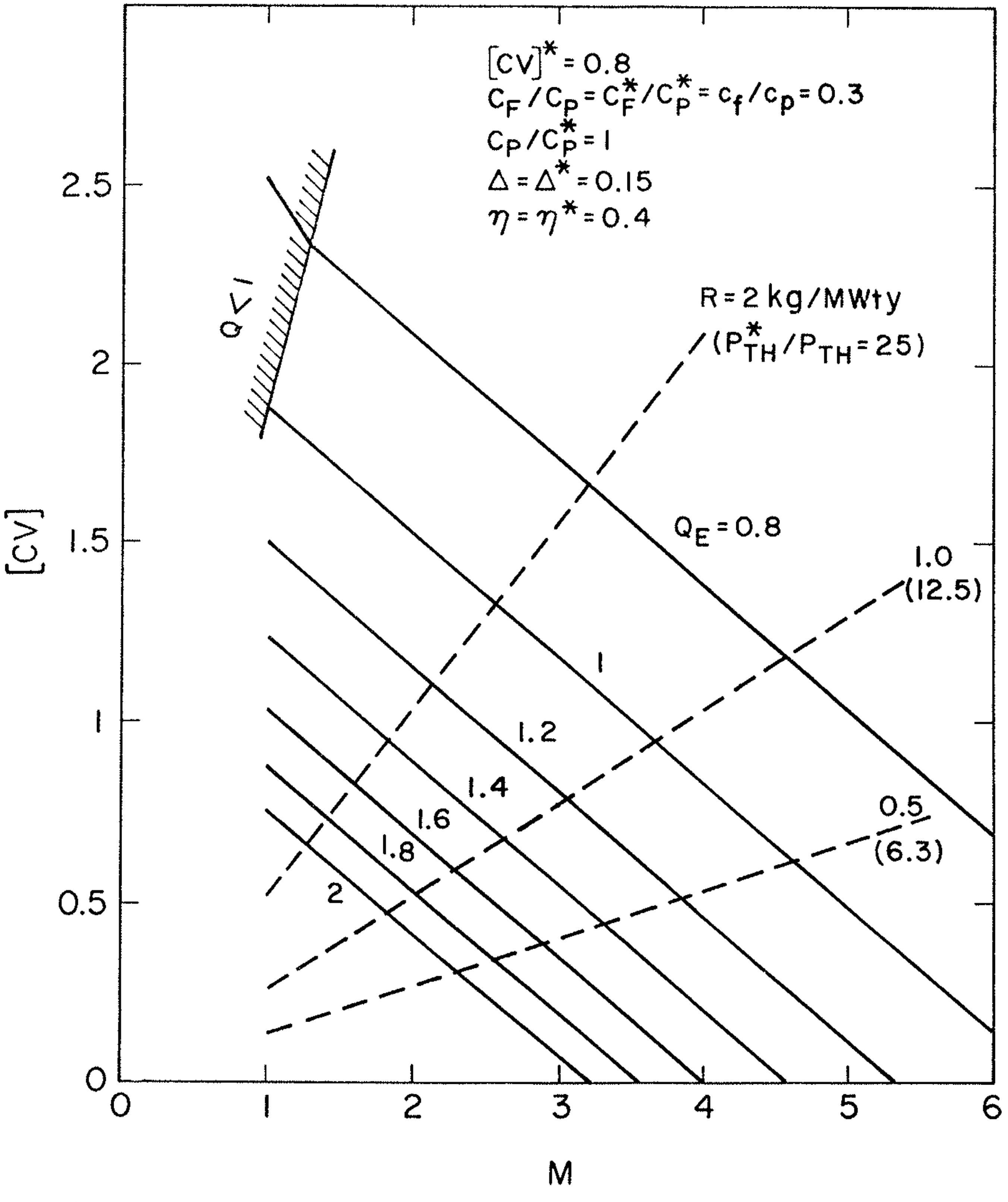


Figure 3. Economically-constrained relationship between [CV], M and Q_E for $[CV]^* = 0.8$ and $\rho = 0.3$ (Eqn. 10)).

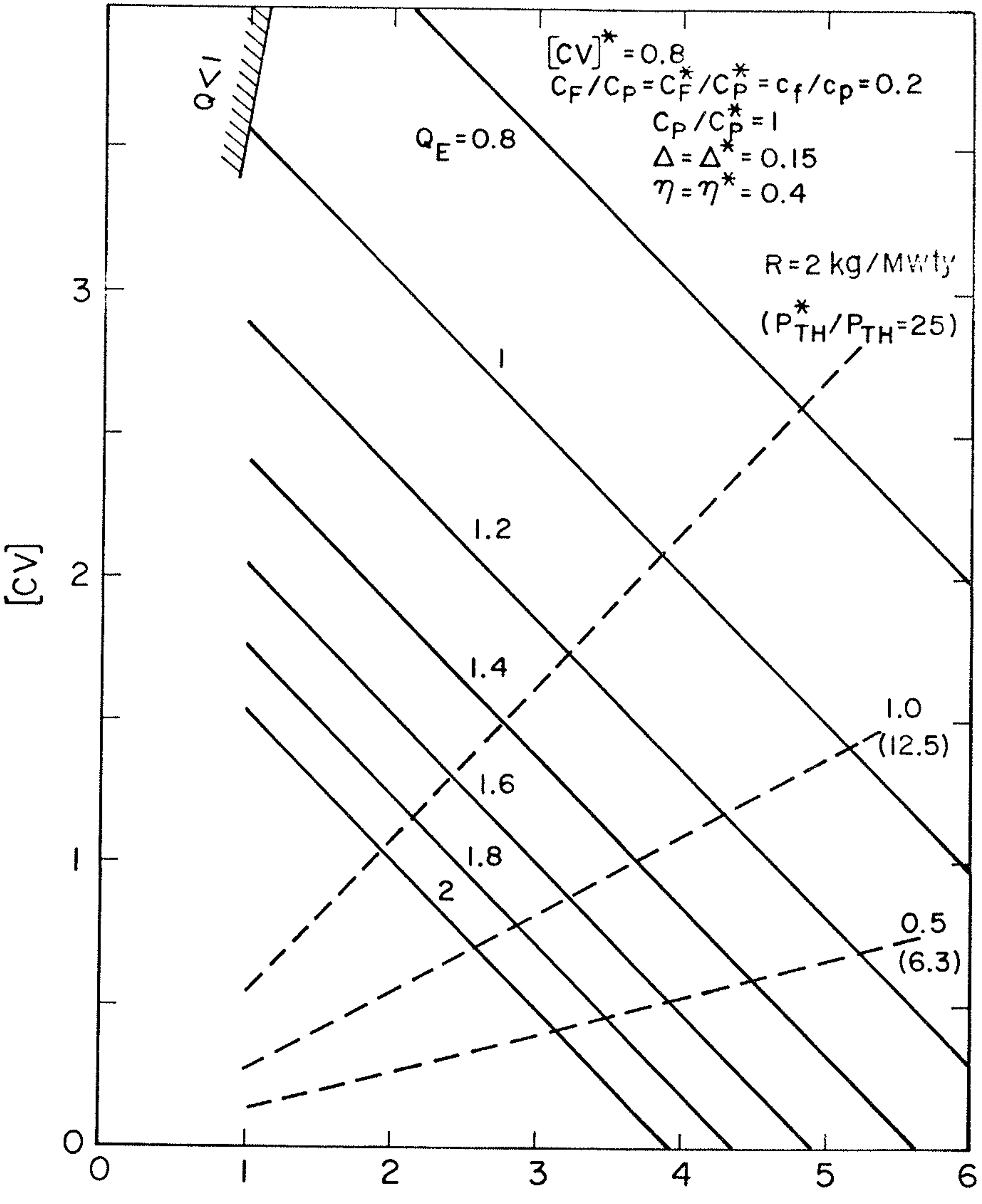
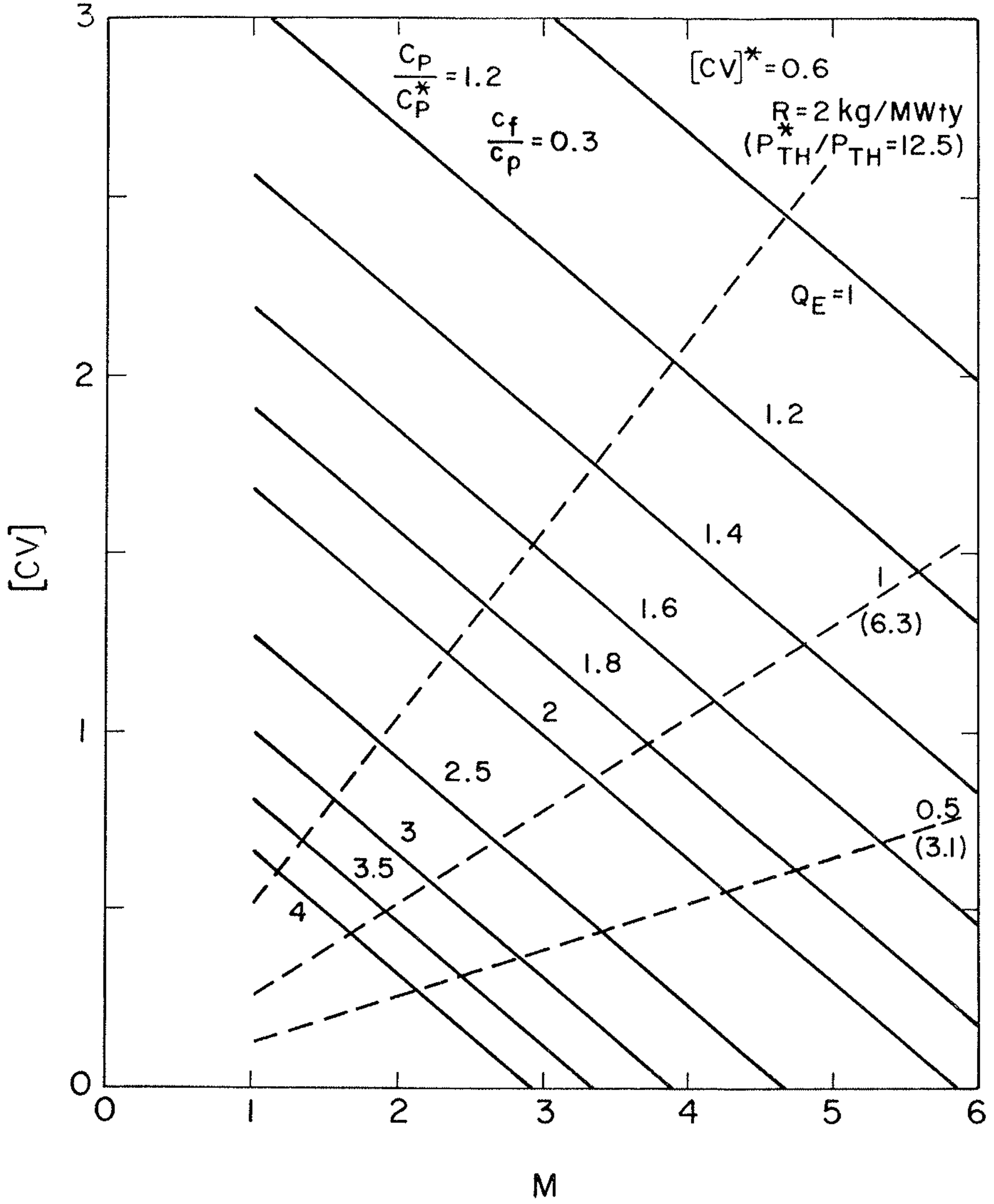


Figure 4. Economically-constrained relationship between [CV], M and Q_E for $[CV]^* = 0.8$ and $\rho = 0.2$ (Eqn. (10)).



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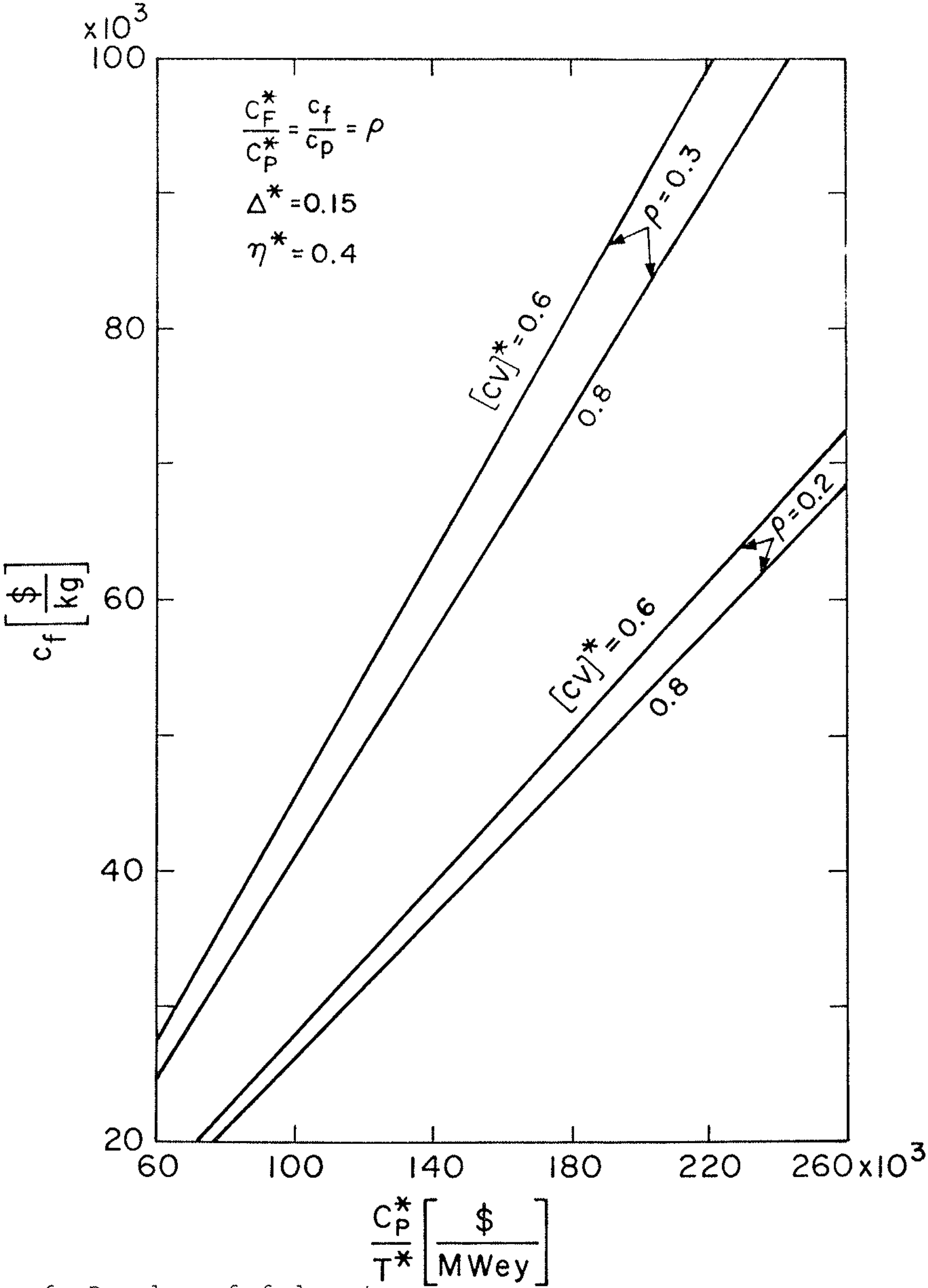

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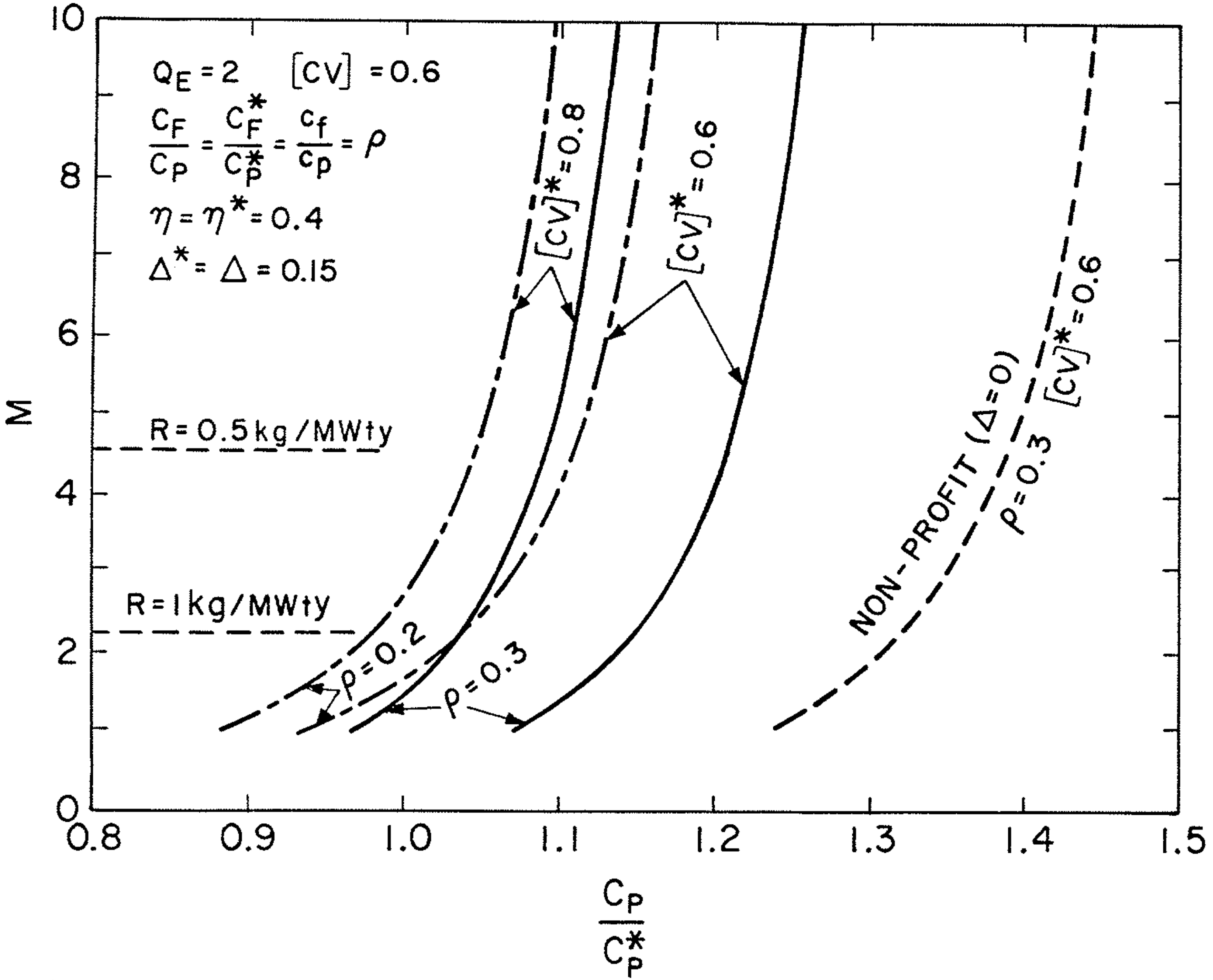

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MR. BOGART: Questions?

DR. TENNEY: I concur with your final conclusion.

DR. KRAKOWSKI: Thank you.

MR. BOGART: I will observe though, that the power-producing hybrid must be a pretty well-developed machine. It will have to be reliable for the utilities to buy it.

DR. TENNEY: The fusion program has got to build reliable machines. Otherwise, it is not going to float no matter what.

DR. KRAKOWSKI: I know at other meetings there has been split opinions as to whether hybrids ought to have to generate power, and our conclusion is that they really must generate power if they are to look at all economic, particularly for low Q machines.

DR. MANISCALCO: It seems to me the emphasis on power production is being misplaced here. Hybrids generate power so that they can make fissile fuel cheaper. I thought you were stating that it was the power that was the prime product.

DR. KRAKOWSKI: It is.

DR. MANISCALCO: I don't see the leverage there.

DR. KRAKOWSKI: You look at these R values, the kilograms per megawatt year. It is very rare that R is going to exceed one. Do you agree to that? -- at least on the summary table that Gene has presented.

DR. MANISCALCO: That you are only going to get about a kilogram of fissile fuel per megawatt year?

DR. KRAKOWSKI: For every kilogram, you are going to generate to one in-situ megawatt year.

DR. MANISCALCO: Then, I produce a kilogram of fissile per megawatt year of energy:

DR. KRAKOWSKI: That is right.

DR. MANISCALCO: I agree with that

DR.KRAKOWSKI: So, that means that for every megawatt -- assuming 2.5 megawatt years per kilogram, if you burn this fuel.

DR. MANISCALCO: How much?

DR. KRAKOWSKI: 2.5.

DR. MANISCALCO: Do you mean in an advanced conversion reactor, say, in an HTGR with a conversion ration of .8?

DR. KRAKOWSKI: If you burn it anyplace. No, forget about the conversion ratio.

DR. MANISCALCO: I want to burn the fuel in a real system. That is the whole issue. For example, an HTGR could burn it at about .1 kilogams per megawatt year. So, I can fuel 10 HTGRs.

DR. KRAKOWSKI: I am not arguing with that. I mean, if you have a conversion ration of .8, granted that one kilogram can feed many reactors, and that is a very strong economic edge. Okay, I am not debating that.

DR. MANISCALCO: The 2-1/2 kilograms per megawatt year?

DR. KRAKOWSKI: But in general, I mean, one kilogram of uranium, sitting right here, would generate 2-1/2 megawatt years. And so, for that virtual energy, represented by the one kilogram of uranium, you have in situ, at least one megawatt year of energy. So, the systems will, in fact, be power generators. I mean, you can't get around that particular problem.

DR. MANISCALCO: I think you are leaving the conversion ratio of the burner reactors out of your argument and I don't think you can do that.

MR. BOGART: Let me interrupt by saying that this is an argument, for those of you not in fusion-fission, that has been raging for as many years as I have been in the program and it still has not been resolved.

DR. KRAKOWSKI: Unfortunately.

MR. BOGART: We need a group here to sit down and write a definitive explanation of power versus fuel production, given the fact that you have a machine that produces a lot of both. Does anybody have a reference they can refer the audience to?

DR. TENNEY: The study that we did at Princeton addressed itself to just that question. One can debate whether the blanket design is an optimal blanket design or not, but the conclusion we came to is that if the price of fissile fuel is low, the economics is going to have you make power producers. And look at that first figure I showed. If you want to get under 30 mils per kilowatt electric for your electricity, and under $50 per gram for the fissile fuel, our economics indicate you want to make power producers.

Proliferation Resistance Vs. Cost

Ralph Moir

I would like to really address this to people who aren't in the audience, for example, people from the Executive Branch of Government, the State Department, and so forth. The thesis is this: We can have fission power and no reprocessing. And people assess that this is a virtue and I concede that this is for proliferation resistance. We can spike our fuel and further increase the proliferation resistance and raise the cost of electricity from the fission system even more.

I think it would be very helpful to people in this audience if there is some quantification of what the virtues are. We can find out how much it is going to cost to do these technical fixes but, on the other hand, how much is it worth to society to do that? What I am afraid is going to happen is that people in high places in government give out orders to have people do the technical work. The answers will come in with the cost estimates -- how much it costs to get how much proliferation resistance, and what-have-you, and they will pick the maximum resistance that it seems like people can afford. Thus the cost of power going up happens in kind of an accidental way.

So, how much do we need and how much can we afford is a question I throw out and I would be pleased to see work in that area.

Utility Observation on the Value of Cost Benefit Analysis

Robert Goodrich

A couple of items would have been helpful to me, as I was listening to the talks on economic analysis that were given today, and I think they would be helpful to anybody who is in the utility business and who is trying to make a decision as to whether or not they should support fusion.

We need to know the economic consequences for our own particular utility of installing a fusion-fission hybrid. There are two, maybe three, scenarios which should be considered. One is where a utility would build a fusion-fission hybrid unit. They would then use the electrical power from it and would use or sell the fissile fuel that has been bred. Presumably they would use their own units, if they had enough light water reactors.

A second scenario is where the hybrid unit would be basically a breeder and the electric output would be sort of incidental. Certainly, the electric energy would significantly reduce the cost of operation or the cost of the fissile fuel. This can be considered as two additional situations. One is where private capital builds this very high capital cost unit, and the other is where the government builds it. Each of these scenarios will have different financial assumption both for cash flow and carrying charges.

It seems to me that depending upon which one of the three scenarios you are looking at, you may arrive at different answers. Therefore, when you do an economic analyses of fusion-fission it would be worthwhile indicating which of the three scenarios you are talking about.

The economic analyses that I saw today were made, I believe, assuming government financing, (i.e., no taxes, a relatively low cost of money) which implies the government will be the builder and operator of the plant.

MR. BOGART: Questions or statements?

DR. SCHULTZ: Ken Schultz, General Atomic Company.

As you all should recognize, I am a ardent proponent of hybrid reactors, and I am also firmly convinced that somehow and somewhere there is a way that we can use fusion energy for direct production of chemical reactions, principally, hydrogen production. But I am a little concerned with the suggestion made by Tom Varljen from Westinghouse that a combination hybrid/chemical producer may be the way to go.

As part of General Atomic's participation in the small mirror reactor project for the EPRI, I looked into the ideas of chemical production using a very simplistic system model. It turns out that because of the high importance of the fast spectrum neutrons in the hybrid blanket for production of fuel, because of the spectral degradation that occurs when you put in something extraneous, such as a chemical compound, in that blanket it may not make sense. Because the direct use of the fusion energy for chemical production seems to be very strongly related to radiation energy, not to thermal energy, it appears that if you wish to take a hybrid blanket and put some sort of chemical compound in it, you lose perhaps as much as M times the thermal energy for one unit of chemical energy produced. Conclusion: It is disadvantageous to have combination chemical and hybrid systems. And I would be interested in receiving any feedback from anybody else who has looked into this area.

MR. BOGART: Equal time, Westinghouse?

DR. SHAPIRO: It just seems to me that to make assumptions with regard to the specific system that one has in mind and then to criticize it, it doesn't make much sense to me. And I think one has to know more about what we would have in mind before one can draw such conclusions.

DR. WOODRUFF: Since he was short, can I throw in a quick one?

The key element is whether or not you degrade the spectrum. I think that to the extent Ken says that you don't want to degrade the spectrum, that is absolutely correct. Once you degrade the spectrum below 14 MeV, all these desirable properties tend to go away. But there is more than one way to skin a cat here. There are other things you can do to make chemical fuels that don't require that. You can put things behind the fission converter, for example, and the advantage of being able to run the hybrid off-line is something I think the utility people will appreciate very much. So, I don't think that should be lightly dismissed.

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