Comparative Breeding Characteristics of Fusion and Fast Reactors

Abstract. *Expressions are developed to allow ready comparison of a hybrid fission-fusion plant and a fast breeder with respect to the number of thermal reactors that their fissile production could support, both for their feed requirements and for the new inventory needs of an expanding industry. These relations are expressed in terms of the neutron multiplication factor obtained in the fusion blanket, and the analogous quantities represented by the conversion ratios of the fast and thermal fission associated with the comparison. Results are presented graphically both for the steady state and for industries of arbitrary growth rate, and include the influence of tritium production requirements. Even a modest blanket neutron multiplication factor could enable the hybrid fusion system greatly to outperform the fast breeder on this simple basis of material balances.*

Present estimates of uranium ore resources leave little doubt that some supplement to their natural fissile content is essential if nuclear fission is to satisfy world energy needs for more than a few decades (*1*). Although there is, in practice, always some conversion of fertile to fissile material within the cores of all reactor types, this conversion requires further aid if any more than a small fraction of the total source uranium is to produce power. This external aid could be supplied, for instance, by the introduction of a sufficient number of fast breeders, which have the capability to produce more fissile material than they consume. An alternative way of converting fertile to fissile material lies in the possible use of fusion-generated neutrons. The prime aim of this report is to compare these two avenues as fissile factories. A second purpose is to comment on the influence of such a role for fusion on the timing and direction of its development.

Schemes involving combinations of fusion and fission (hybrid schemes) cover a spectrum of proposals, varying from the inclusion of a thermal reactor within the blanket of a fusion reactor to the use of this blanket as far as possible only to convert fertile into fissile material for use in separate fission reactors (*2*). It is this second scheme with which I am primarily concerned here, for it could ease the task of the fusion reactor and make possible a more effective and well-established utilization of the fission process. In this association of fission and fusion, investigators are particularly interested in the generation of ^{233}U from thorium as opposed to the production of plutonium from ^{238}U, for this option much increases the total system power that a given fusion plant will sustain. This increase arises both because use of thorium reduces the fission occurring in the fusion blanket, and also because the ^{233}U-thorium cycle considerably increases the conversion ratio of the associated fission reactors and therefore reduces their need for fissile feed. In particular, the conversion ratio C potentially obtainable in efficient converter reactors such as the high-temperature graphite reactors (HTGR's) operating with ^{233}U ($C = 0.95$) could, in effect, release $[1/(1 - C)]$ or 20 times the fission energy of their feed, which is itself some 11 times that of a deuterium-tritium (DT) fusion event. Such a large boost in ultimately available energy would greatly relieve the pressure for achieving the highest possible energy efficiency otherwise necessary for the success of pure fusion.

The bulk of the total energy produced by the hybrid system comes essentially from the fertile material supplied, in this case thorium, and not from the substantially unlimited source of deuterium alone, which is all the pure fusion plant needs to draw upon. However, the world's fertile (as distinct from fissile) resources are indeed large enough for foreseeable needs. The real issue in evaluating the use of fusion neutrons to activate these fertile resources is how the fusion plant compares with the fast breeder as a fissile factory, for this would most effectively describe their common function.

Consider a fission reactor having an initial fissile loading of N atoms. The required fissile feed per fuel cycle will be given by

$$N - \beta N + G_c N (1 + Z) = N [(1 - \beta) + G_c (1 + Z)]$$

where β is the ratio of fissile material in the discharge to that in the initial loading, G_c is the fractional growth rate of inventory (the total initial core fissile content) per cycle, and Z is the fissile content in the associated storage and processing lines, expressed as a fraction of the in-core fissile inventory. But

$$(1 - \beta) = (1 + \alpha)(1 - C) F$$

where F is the number of fissions per initial fissile atom, and α is the capture-to-fission ratio. Thus the required feed per cycle is

$$N [(1 + \alpha)(1 - C)F + G_c (1 + Z)]$$

Then, the required feed per year is given by

$$N \left[(1 + \alpha)(1 - C) \frac{F}{Y} + G_A (1 + Z) \right] \quad (1)$$

where Y is the number of years per cycle, and G_A is the fractional growth rate per year.

Consider a fusion plant producing N_F fusion events per year. Each fusion event produces one neutron. Let the fusion blanket material (FB) cause C_F new

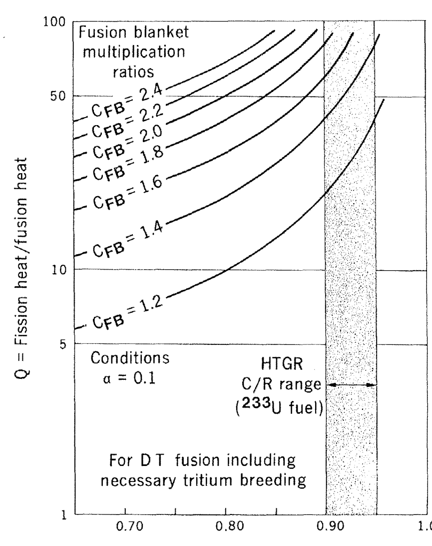

Fig. 1. Ratio of the fission heat produced to the fusion heat required to supply the necessary fuel, under steady-state conditions.

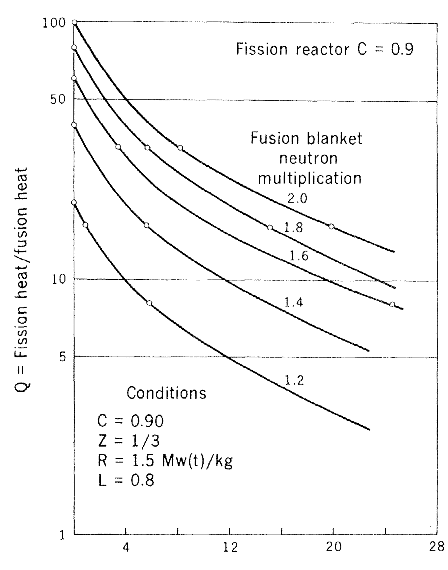

Fig. 2. Growth of fusion-fission reactor association (zero tritium processing delay).

(tritium + fissile) atoms to be produced there by each fusion neutron. Since one replacement atom of tritium is required per fusion, this leaves ($C_{FB} - 1$) fissile atoms per fusion (where C_{FB} is the fusion blanket multiplying factor). So fissile production is N_F ($C_{FB} - 1$) fissile atoms per year. Equating this production to the fission reactor feed requirement of Eq. 1 gives

$$(1 + Z)\, G_A = \frac{N_F}{N}\,(C_{FB} - 1) - (1 + \alpha)\,(1 - C)\,\frac{F}{Y}$$

But one fission produces 10.95 times the heat of one fusion. Thus

$$Q = \frac{\text{fission heat}}{\text{fusion heat}} = 10.95\,\frac{NF}{YN_F}$$

Therefore,

$$G_A = \frac{F}{Y\,(1 + Z)\,Q} \times [10.95\,(C_{FB} - 1) - (1 + \alpha)\,(1 - C)\,Q] \qquad (2)$$

But

$$\frac{F}{Y} = \left(\frac{\text{fissions per year}}{\text{initial fissile inventory}}\right)$$

Thus

$$\frac{F}{Y} = \frac{365}{950} RL = 0.383\,RL$$

(taking 950 Mw-day/kg of fission heat), where L is the load factor, and R is the fission reactor rating, that is, megawatts (thermal) per kilogram of fissile material. Substituting this equality in Eq. 2 gives

$$G_A = \frac{0.383\,RL}{(1 + Z)\,Q} \times [10.95\,(C_{FB} - 1) - (1 + \alpha)\,(1 - C)\,Q] \qquad (3)$$

Equation 3 specifies the annual growth rate provided, assuming a negligible tritium inventory requiring buildup. Under steady-state conditions, with no allowance for system growth, $G_A = 0$ and Eq. 3 reduces to

$$Q = \frac{10.95\,(C_{FB} - 1)}{(1 + \alpha)\,(1 - C)} \qquad (4)$$

It is important to remember that C_{FB} has been defined here as the sum of the tritium and fissile atoms formed per fusion, the justification for mixing these quantities being that either event requires one neutron. Moreover, the energy balances derived are not affected by whether the tritium is actually manufactured in the fusion blanket or in the associated fission reactors, or whether some of the fission also occurs in the fusion blanket. In the interest of easing the design requirements of the fusion plant, it is highly desirable to relegate the tritium breeding function to the associated fission reactors and to reduce the fission heat generated in the fusion blankets to a minimum.

Although the fusion plant has a negligible internal inventory (which is one of its great advantages over a fast breeder as a fuel factory), nevertheless, if there is a long delay time between the production and use of the tritium involved, then the inventory in this "pipeline" has to be considered. Neutrons must be provided to expand this inventory also with the industry growth. Allowance for this expanding pipeline inventory can be made as follows.

Consider a fusion plant burning one tritium atom per year. Let the delay time in tritium processing be D years. There will be D atoms in the pipeline. If the annual growth rate of the industry is G_A, we must supply $D\,G_A$ new tritium atoms for the expansion of this pipeline inventory.

The one neutron that must be used to replace the burnt tritium must be increased to ($1 + D\,G_A$) neutrons, to provide also for the expanding pipeline inventory. The term ($C_{FB} - 1$) in Eq. 3 that ignored this inventory must therefore be replaced by ($C_{FB} - 1 - D\,G_A$); making this substitution in Eq. 3 gives

$$G_A = \frac{10.95\,(C_{FB} - 1) - (1 + \alpha)\,(1 - C)\,Q}{\dfrac{(1 + Z)\,Q}{0.383\,RL} + 10.95\,D} \qquad (5)$$

Equation 5 gives the growth rate when the delay in tritium processing is long enough to allow an appreciable extra inventory to be expanded with the system. Equation 5 reduces to Eq. 3, the case where the tritium inventory is neglected, when $D = 0$, or in practice when

$$D \ll \left[\frac{0.2\,Q\,(1 + Z)}{RL}\right]$$

By virtue of their blankets and processing tritium inventory, the fusion plants by themselves have a maximum growth rate per year given by the result when $Q = 0$ in Eq. 5, which is

$$G_{A_0} = \frac{C_{FB} - 1}{D}$$

This limitation is not serious, however, so long as there is an appreciable multiplication by blanket neutrons and D is not many years.

The total heat produced by the initial fusion (FU) plus that in the associated fission (FS) reactors is ($1 + Q$) multiplied by the initial fusion heat (neglecting heat produced by fission in the blanket). But one unit of heat from the fusion reactor alone could produce an electric output of η_{FU} at an efficiency of η_{FU}.

From the usual definition of a "break-even" factor, we can measure the "effectiveness" of a system as

$$\gamma = \left(\frac{\text{fusion electric energy produced}}{\text{electric energy needed}}\right) \qquad (6)$$

This relationship would require an electric input of (η_{FU}/γ), or ($\eta_{FU}/\eta_{FS}\gamma$) units of input heat, coming from a generation efficiency of the fission reactors of η_{FS}. Thus

$$K = \left(\frac{\text{net useful heat out}}{\text{fusion heat}}\right) = Q + 1 - \frac{\eta_{FU}}{\eta_{FS}\gamma}$$

Figure 1 shows the ratio of the heat produced from thermal reactors to that from the fusion reactor required to supply their fuel, with no surplus for industry expansion, the steady-state case. This ratio is plotted here as a function of the fusion blanket neutron multiplication factor C_{FB}, and the conversion ratio of the associated fission reactors C, for a typical capture-to-fission ratio α of 0.1 in the fission reactor. Some 20 to 50 converter reactors could be maintained by a fusion plant of equal power, which, as will be seen later, is enormously more than a fast breeder could supply.

Figure 2 shows the corresponding case where industry growth rate is taken into account. The conditions specified are typical. A representative result is that a system of some ten converters and one fusion reactor of equal power could be not only fueled but expanded at 12 percent per year, given a fusion blanket multiplier of 1.4.

Figure 3 shows the influence of the tritium inventory, neglected in Fig. 2. The effect is quite small, so long as the industry expansion rate is not too great and so long as the tritium is reprocessed in reasonably less than a year.

Figure 4 concerns net energy flows. It shows the ratio of useful heat to that produced by fusion in the system, on the assumption of varied fusion plant "effectiveness," as defined in Eq. 6. Equal electric generation efficiencies are assumed here. Even a "perfect" fusion plant (one needing no electric power) would score little better on this basis than one consuming ten times the electric power that is produced. This is so, because, although only 17.3 Mev of heat comes from the fusion event, thousands

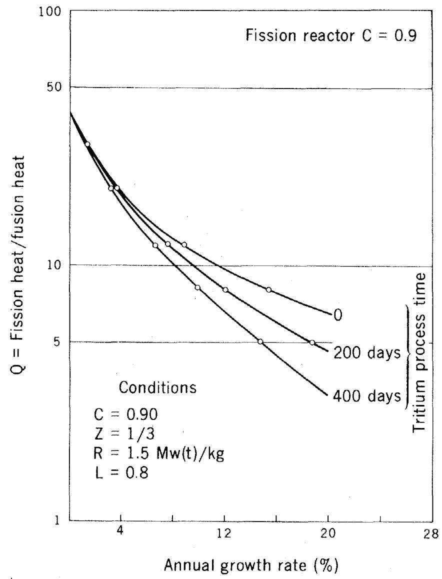

Fig. 3. Effect of tritium process time with a fusion blanket multiplier of 1.4.

of megaelectron volts of heat are released by the $[1/(1 - C)]$ recirculations of the fuel atoms supplied to the fission reactors. Thus the electric supply of even a poor fusion plant looks like a small drain. Indeed, the fusion reactor heat could simply be dumped, with little effect on the useful total output.

In this argument I am concerned with energy balance only and I make no judgment relating to economics. Very expensive equipment might very well be necessary to convert electric power to the form necessary to produce fusion, rendering the real cost of this so-called negligible power quite high.

The fast breeder may be an alternative way of converting fertile resources into the material needed for fission. This device has the advantage of having been already invented, and indeed thus far fairly convincingly demonstrated. Why then should we even consider the unknowns of a fusion plant as competition? There are two very good reasons for considering fusion as a fuel source. First, the fusion plant carries virtually no expensive inventory, which, apart from its financial charges, heavily penalizes the expansion rate of available industry. Second, even unmultiplied fusion provides about 11 times the neutron flux per unit power of a fast breeder. In use as a "fuel factory," this handicap insofar as materials irradiation is concerned is turned to corresponding advantage.

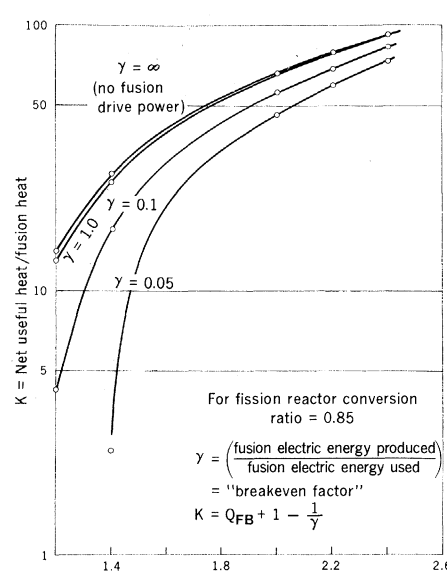

Fig. 4. Fission-fusion power balance.

Just how much these two features affect the practical issue can be shown by reference to expressions analogous to the ones thus far discussed, derived from a consideration of fast and thermal reactor combinations (*3*). In this instance, the additional factors of the fuel rating, out-of-core inventory, conversion ratio, the capture-to-fission ratio, and the fast fission factors associated with the fast breeder, R_B, Z_B, C_B, α_B, and f, respectively, must be introduced. Here

$$f = \left(\frac{\text{total fissions}}{\text{fissions in thermally fissile material}} \right)$$

The ratio of thermal-to-fast reactor heat for a steady industry level, corresponding to Eq. 4, is

$$Q = \frac{1}{k} \left(\frac{C_B - 1}{1 - C} \right)$$

where

$$k = \frac{(1 + \alpha) f}{(1 + \alpha_B)}$$

which is always close to unity. The available annual growth rate, corresponding to Eq. 3 for fission-fusion, is

$$G_A = \frac{0.383\ R_B L\ (1 + \alpha_B)}{f\left[1 + Z_B + \dfrac{QR_B}{R}\ (1 + Z)\right]} \times \left[(C_B - 1) - (1 - C)\ k\ Q \right]$$

For the steady-state case, the only significant difference is that C_B replaces C_{FB}, and, most importantly, the 10.95 ratio of fission-to-fusion heat is absent. In the growth equation the coefficient 10.95 is absent, and, assuming equal out-of-core fractions ($Z = Z_B$), the denominator becomes multiplied by $[(1/Q) + (R_B/R)]$, representing the additional burden of the fast breeder's inventory.

The numerical results are given in

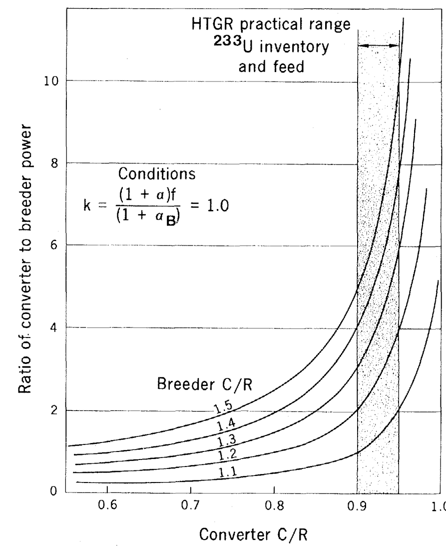

Fig. 5. Fast breeder-converter combination under steady-state conditions.

Figs. 5 and 6, which compare directly with Figs. 1 and 2, respectively (a change in scale is necessary). A comparison of Figs. 1 and 5 and Figs. 2 and 6 indicates the enormously higher number of converter reactors that can be fed by one fusion plant of equal power, and also the much higher growth rate sustainable. This result alone does not mean that the fusion plant will be a more economic proposition, for we know nothing yet about the cost of a yet-to-be-invented plant. But it does indicate how much we can afford to pay for it, considerably more per unit heat output for a fusion plant that could do the necessary duty than for a fast breeder for the same purpose.

In considering hybrid fission-fusion plant systems, the pertinent issue is a

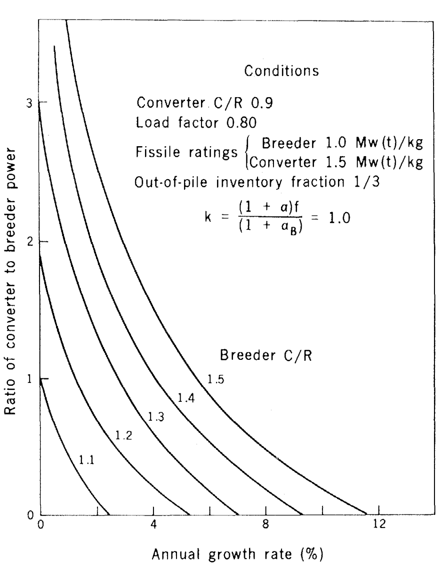

Fig. 6. Fast breeder-converter combination with self-sustaining growth.

comparison of the fusion part of the complex with the alternate use of a fast breeder reactor for this part of the job. In their "fuel factory" role, neither the fusion reactor nor the fast breeder reactor can be properly compared to an enrichment plant. Such a plant is not a synthesizer of new fissile material, but simply an extractor of dwindling natural supplies, which furthermore consumes power rather than produces it as a by-product.

The outstanding characteristic of the fusion plant is its potential ability to supply the feed and new inventory needs of many more associated thermal reactors than a fast breeder can. This advantage arises primarily from the high rate of neutron generation made possible by the relatively low energy release of the fusion event.

In considering an expanding industry, this benefit is much enhanced by the fact that the fusion plant does not require the large fissile inventory that the fast breeder requires. The importance of these features, however, rests entirely on the assumption that the thermal fission reactor will remain the best-adapted, practical prime power source, as evidenced by the costs of its construction, operation, and maintenance, by its reliability, and by its adaptability to specific needs.

If and when a pure fusion power plant can surpass the thermal fission reactor in these areas, it will doubtless displace fission altogether. In the meantime, an association of fusion and fission provides another end use for fusion (that is, as a fissile fuel factory) that must enhance the prospect of practical success. Thus, the pressure to achieve a high ratio of direct energy output to input is greatly relieved; furthermore, the function of tritium bleeding can be relegated much more conveniently to the associated fission reactors, and the need for high-temperature cooling to secure high power generation efficiency is eased. This easement might well permit use of blanket materials in aqueous solution, making possible their continuous extraction, which would represent a further, very great advantage over fast breeders, whose performance is inherently much penalized by the long element residence time of blanket materials. The "fuel factory" function is also more suited than power production to discontinuous operation, which may ease fusion plant design by allowing discontinuous plasma refueling.

All these factors could stimulate development by providing reward for early progress. Insofar as the likely result of such stimulation would be an earlier approach to the final goal of undiluted fusion, the long-range effect of an interim period in which the fusion plant is a producer of fissile fuel might well be to substantially lessen the eventual world pool of fission products.

I would emphasize that the foregoing remarks should not be construed as arguments for discarding the eventual goal of purely fusion-derived power. My intention is only to point out that, until this end is achieved, there remains a task (fissile material production) which could easily become of crucial importance to the continuity of our energy supplies, and to which fusion technology may be applied, perhaps more readily than to its ultimate objective.

PETER FORTESCUE
Advanced Energy Systems, General Atomic Company, P.O. Box 81608, San Diego, California 92138

References

1. P. Fortescue, *Nucl. Eng. Int.* **21**, 71 (October 1976).
2. ———, *Ann. Nucl. Energy* **2**, 29 (1975).
3. ———, *ibid.*, in press.

27 August 1976; revised 22 December 1976

Polarity Transition Records and the Geomagnetic Dynamo

Abstract. *The Parker-Levy approach to reversals of the geomagnetic field predicts meridional transitional paths of the virtual geomagnetic pole (VGP) which pass either through the site of observation or through its antipode, depending upon the site location and the sense of the polarity transition. Comparison with the most detailed transitional VGP path records presently available gives some indication of the above behavior as predicted by the Parker-Levy model. Discrepancies may be due to complexities in the distribution of cyclonic convection cells in the core not considered in the formal mathematical treatment. The predicted variation in transitional field intensity experienced at any given site also is compatible with several reported transition records.*

The behavior of the axial dipole during a geomagnetic polarity transition is sometimes considered to consist of a simple decay followed by regeneration in the opposite sense. Such behavior is predicted by and serves to model the suggestion (*1*) that, given a Bullard-Gellman-Lilley core dynamo (*2*), field collapse occurs when the convection configuration becomes overly symmetric so as to lose the Braginskii condition (*3*). Field reversal then follows when sufficient asymmetry is restored. In contrast, the work of Parker (*4*) and of Levy (*5*) suggests that field reversals are associated with changes in the latitudinal distribution of cyclonic convection cells in the core. In contrast to the field-collapse hypothesis, the Parker-Levy reversing dynamo appears to involve a substantial conversion of the axial dipole field into axial multipole components during a polarity transition. More specifically, according to their approach, reverse toroidal flux, which acts to create a poloidal field that degenerates the existing dipole field, first appears at low latitudes. This reverse flux then extends to higher latitudes, ultimately reversing the sense of the dipole. However, when the poloidal field at low latitudes is opposite in sense to that at higher latitudes, the field experienced on the surface of the earth cannot be that of a simple dipole. A similar suggestion (Fig. 1) has been made with regard to solar field reversals (*6*).

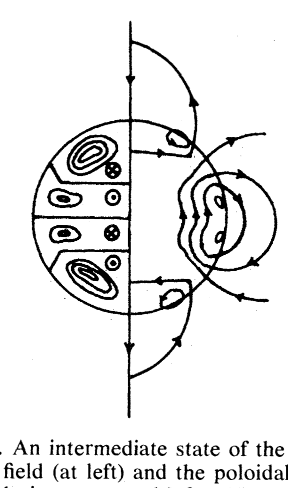

Fig. 1. An intermediate state of the solar toroidal field (at left) and the poloidal field (at right) during a reversal [after (*6*)].

One may develop a crude model of the Parker-Levy reversing dynamo by assigning for a given time at each latitude within the core an axial dipole having a sense consistent with that of the poloidal field being generated. Figure 2 depicts the sequence corresponding to a transition from reverse to normal (R → N) polarity along with the associated magnetic field vectors experienced at sites in both the Northern Hemisphere and the Southern Hemisphere.

The above models make possible the prediction of the transitional paths of the virtual geomagnetic pole (VGP) as ob-