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ABSTRACT

Breeding is expected to become a necessity in about 40 years and in view of the 20 years development time and 30 years service life of breeder reactors, development of such reactors at present is timely. In plutonium breeders, the specific power is inherently low and the doubling time long. This seems to prevent such breeders from furnishing a large fraction of the energy demands of the expanding economy from uranium recoverable at or about present cost. U^{233} breeders can be designed to the requirements of low inventory and short doubling time, but the aqueous homogeneous reactor seems to be the only type which can adequately meet these requirements.

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I. HISTORY AND SCOPE OF THE STUDY

The Oak Ridge National Laboratory has conducted a study regarding breeding on the Th^{232}-U^{233} cycle. Object of the study was, on one hand, the importance of breeding on this cycle and, on the other, a comparison of the various reactor types with respect to their suitability as U^{233} breeders.

The study was prompted, in part, by temporary difficulties in the Aqueous Homogeneous Reactor Program. These difficulties made it advisable to re-investigate the validity of the old reasons which originally made the aqueous homogeneous reactor appear as one of the desirable reactor types, in order to see whether these reasons still hold. Breeding on the Th^{232}-U^{233} was one of these reasons.

During the course of the study, the homogeneous reactor experiment operated in a far more satisfactory manner than anticipated at the time when the study was originated, and this increased expectation that the aqueous homogeneous reactor will be a desirable reactor type even without U^{233} breeding. This made it less important to carry the study to its final form at the present time. On the other hand, enough unexpected phenomena are appearing in the homogeneous reactor experiment to let it seem possible that important parameters for breeding, for instance, poisoning by corrosion products, may turn out differently than anticipated. These uncertainties plus the recently developed large uncertainty in the η of U^{233} will be resolved in the near future. The final form of the study should be postponed until these uncertainties are resolved. This memo serves the purpose of an interim report.

The importance of breeding on the Th^{232}-U^{233} cycle depends primarily on the importance of breeding in general, and secondly on the comparison of the U^{238}-Pu^{239} breeding cycle with the Th^{232}-U^{233} cycle. As to the necessity of breeding in general, E. D. Arnold and J. W. Ullmann have reached conclusions which are reported in ORNL CF-58-8-16.[1] As to the comparison between Pu^{239}

1. E. D. Arnold and J. W. Ullmann, Use of Raw Materials in an Expanding Nuclear Power Economy, ORNL CF-58-8-16, Aug. 4, 1958.

and U^{233} breeding a few remarks are contained in the present memo.

The desire to compare various reactor types as to their suitability as U^{233} breeders resulted in an investigation by A. M. Perry, C. A. Preskitt, and E. C. Halbert on the use of gas-cooled, graphite-moderated reactors for this purpose. This investigation is now being extended to gas-cooled, heavy-water-moderated reactors.

E. Guth, S. Jaye and A. Sauer spent considerable time on the optimization of the aqueous homogeneous reactor for U^{233}-breeding purposes (as contrasted to the much discussed optimization as to cost per kwh). This part of the study is not finished and is most strongly affected by the above-mentioned uncertainties.

II. THE NECESSITY FOR BREEDING

The fuel burnup cost in a straight burner, with present prices, is about 3 mills/kwh. Thus a difference of 10% in breeding ratio amounts to about 0.3 mills/kwh, since a reactor of breeding ratio β could buy fuel amounting to 10% of its burnup for 0.3 mills/kwh and end up with the same amount of fissionable material as a reactor of breeding ratio $\beta + 0.1$. A breeder and a converter of reasonably high conversion ratio will not differ in conversion ratio by more than a small multiple of 10%, and the difference in fuel-burnup cost will thus be smaller than the uncertainty in the estimated power cost of a nuclear reactor. Fuel burnup cost on the basis of present prices will thus not offer a strong reason in favor of breeding.

Any justification for breeding thus involves an element of planning for the future, a consideration of the time when the fissionable material recoverable at reasonable cost will be exhausted and the nuclear-power economy depends on tapping the energy content of fertile material.

The justification for breeding is then analogous to the justification of nuclear-power production in general - nuclear-power production is justified with a view to future depletion of fossile fuel, rather than with a view to present prices. The long-range planning is needed in the nuclear-power field because of the long development and design time - estimated at

20 years - and long life of power plants, estimated at 30 years. Thus, if breeding will be necessary 20 + 30 = 50 years hence, it is not too early to proceed with the development now. Otherwise, we will have, 50 years hence, a large installed capacity which still could be used except for the fact that it burns fissionable material which we can no longer afford to burn. If it is the intention to scrap these reactors before they are worn out, they would have to be burdened by larger depreciation costs during their use.

Any estimate of future supply and demand of fissionable material is very uncertain. Estimate of how much fissionable material will be available, and at what price, depends on guesses as to future discoveries of deposits and also on how much fissionable material the U. S. will be able to import from abroad, or will export to other countries. Demand depends not only on the extremely uncertain requirements of the power economy itself, but to a large extent on the demand for nuclear-powered naval vessels, aircraft, rockets and weapons. Conceivably the latter could even become a source rather than a sink of fissionable material, as within the time periods considered nuclear disarmament and release of stock-piled material could become a reality. On the other hand, some of the uses of nuclear energy could be extremely wasteful of fissionable material. An example for this is the "bomb rocket" intended to propel a large weight into outer space by a large number of "small" nuclear-bomb explosion behind the weight to be lifted.

The impact of fusion on fission reactors is likewise very uncertain. Conceivably, fusion could produce power cheaper than fission and put fission power reactors out of business, or fusion based on the D-D reaction could be a source of neutrons and hence of fissionable material. On the other hand, large-scale power generation by fusion may be uneconomical, or unfeasible, or dependent on outside supply of tritium and hence on fission reactors with good neutron economy.

An accurate prediction of the supply and demand situation with respect to fissionable material is obviously impossible, but it is also unnecessary for the purpose of deciding on the development of a breeder reactor. If there is a reasonable probability of breeding being attractive during the next 50 years, such development would be indicated. In fact, it is quite likely that applications of nuclear energy will be proposed which consume large amounts of fissionable material. The bomb rocket is an example. If there is a prospect of fissionable material becoming scarce, the decision regarding such proposals may very well depend on the feasibility of a suitable breeder. In that case, any effort spent on development of a breeder would pay off in terms of hard information regarding the feasibility of the breeder, and in a firmer basis for the above decision.

Even if breeding were of little interest for the near future in the United States, it may well be important in foreign countries with less native supply of fissionable material. The potential need of foreign countries for power is one of the main justifications for development of nuclear-power reactors. An analogous argument could justify the development of breeders.

It appears that, for a breeder, the doubling time is the more important concept than the breeding ratio. In part this is due to the somewhat philosophical point that breeding ratio is not always easy to define. Breeding ratio is the ratio of the amount of fissionable material available at the end of a fuel cycle to the amount of fissionable material at the beginning of the cycle. If different parts of the fissionable material have different histories, the "cycle" is a somewhat controversial concept. On the other hand, the doubling time, that is the time at which the amount of fissionable material has doubled, is clearly defined.

More important than the above philosophical point is the fact that the doubling time of the reactor can be compared directly with the doubling time of the demand of the fission-power economy. If the reactor doubling time is longer than the doubling time of the demand, then the reactors cannot keep up with demand. A future shortage of the supply of fissionable material will be reflected back to earlier dates.

Doubling time has to defined as the time in which the whole fissionable inventory of a reactor is doubled. This inventory includes fissionable material contained in the reactor core, the blanket, the reprocessing plant, etc. Reprocessing losses have to be taken into account.

In considering the reactor doubling time one should really consider the average over the whole economy. Since there will be a large number of reactors which will not breed(mobile reactors, for instance), the incentive for short doubling time will be high in those reactors which can be made to breed.

As to the actual numbers, Arnold and Ullmann assume a U. S. nuclear-power production which at first increases very rapidly as the nuclear-power production increases its share of the total power production which, in turn, is increasing. Finally, the nuclear-power production is assumed to increase with the same doubling time as the total power production, this doubling time being between 5 and 10 years. Assuming that the United States power production can draw on the ores of the U. S. and Canada, the raw material which could be recovered at up to twice the present cost would last until 1990-2000. From this, Arnold and Ullmann concluded that breeding will not be necessary for about 30 to 40 years.

As has been discussed above, a case can be made for the development of breeder reactors up to 50 years ahead of the time when breeding is necessary. Thus the figures of Arnold and Ullmann seem to show that development of breeders is quite timely at present. This conclusion is made even stronger if consideration is given to the possibility that the non-power use of fissionable material, export of Canadian ore to other parts of the world, etc., could advance the date at which breeding will be a necessity.

Since the power economy is expected to have a doubling time of 5 to 10 years, the doubling time of the breeders should be the same, or preferably shorter to make up for non-breeding uses of fissionable material.

Arnold and Ullmann point out, however, that other factors are more important than breeding. Among these factors is high thermal efficiency, which means high operating temperature of the reactor. This deserves underlining. A reactor with high thermal efficiency, which does not breed, uses a relatively small amount of fissionable material, and, though it does not convert sufficient fertile into fissionable material, it leaves the energy content of some fertile material untouched, to be available for future users who are ingenious enough to extract it. A low-thermal-efficiency breeder replaces the fissionable material it uses, but it uses a relatively large amount of fissionable, and hence fertile atoms, and whatever is wasted is gone forever. In this respect, high temperature reactors, like the liquid-metal fuel reactor and the molten-salt reactor are more desirable even if they are no breeders.

Another parameter of great importance in an expanding nuclear-power economy is, as Arnold and Ullmann point out, a low inventory. Low inventory is closely connected with short doubling time, the importance of which has beenmentioned above. A further drastic example of this will be mentioned below.

Arnold and Ullmann emphasize that there is an enormous supply of uranium, estimated at 100,000,000 tons for the U. S. and Canada, which could be recovered at up to \$100/lb U_3O_8. This supply will not be exhausted within a foreseeable future, and even if a breeding program fails to produce enough fissionable material for the energy requirements, only an increase in power cost,but no catastrophic power shortage,will result.

III. COMPARISON OF PLUTONIUM AND U^{233} BREEDING

From a practical viewpoint, the main difference between plutonium and U^{233} breeding lies in the inventory of fissionable material. This inventory is much larger for plutonium breeders than for U^{233} breeders. Large inventory is connected with low specific power (kw/kg of fissionable material) and long doubling times. The large inventory is mainly a consequence of basic physical facts: because of the energy dependence of the η of Pu^{239}, plutonium breeders have to operate at high neutron energies where the cross sections are small and where it takes many plutonium atoms to catch a neutron with sufficient probability before it escapes or slows down. A contributing cause of the large inventory is the intricate core structure of fast breeders and the resulting large hold-up of fissionable material external to the reactor.

The specific power of the Enrico Fermi Fast Breeder Reactor is 149 kw/kg of total inventory of fisssionable material,[2] or approximately 1 kw/kg of natural uranium (assuming that essentially all U^{235} contained in natural uranium could be used in the reactor). The U. S. and Canadian uranium resources recoverable at present prices are, according to Arnold and Ullmann, 550,000 tons, which would allow the production of 550,000 Mw (thermal), or 1.6×10^{16} Btu/year. The time when this would have covered the total energy* input of the United States alone has, according to Putnam,[3] passed around 1910.

At a given specific power, the energy production can increase only at a rate determined by the doubling time. At 149 kw/kg, the time of 100% burnup would be 14 years. Hence, with any reasonable breeding gain, the doubling time of the reactor, and hence of its power production, would be around 100 years. In practice the non-breeding uses of fissionable material would more than use up the small yearly production of plutonium in the breeders.

With the above figures, the plutonium breeders could supply only a small part of the energy requirements of the U. S., and because of their long doubling time, they would fall further and further behind the rapidly increasing demand.

The U^{233} breeders, on the other hand, operate best in the thermal region where the cross sections are large, and fewer atoms suffice to prevent an adequate number of neutrons from escaping. More important, atoms other than fissionable ones can be used to do a large part of the neutron scattering and

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2. Technical Progress Review, Power Reactor Technology 1, No. 3, 57(1958), quoting Enrico Fermi Fast Breeder Reactor Plant, APDA 115, Nov. 1956.

3. P. C. Putnam, Energy in the Future, p. 75, Fig. 4-3, D. Van Nostrand Co., Toronto, New York, London (1953).

*Thus when other power sources were used up and we had to rely on the above uranium resources and the above specific power, we would have to revert to the 1910 standard of total energy consumption. Total energy means all the energy, including the part now derived from fossile fuel for space heating, vehicle propulsion, etc.

escape preventing. Neutron-energy degradation by these "other atoms" does not have to be prevented and is in fact desired. Thus, the critical mass and inventory in a U^{233} breeder can be made very low, and the specific power very high. (The design parameters of a 300 Mwe aqueous-homogeneous reactor station call for about 4500 thermal kw/kg of fissionable material.[4] With this specific power a breeding gain of 8.2% would correspond to 5 years doubling time.)

Unless these design data are upset by low η values resulting from new measurements, or by unexpected changes necessitated by new experiences with the homogeneous reactor experiment, the power generated from the available U^{235} resources could be considerably higher than with the fast plutonium breeder, and after conversion to U^{233} the doubling time would be in line with the doubling time of the nuclear-power economy.

The above is not meant to imply that the specific power of the Enrico Fermi Fast Breeder Reactor is the maximum that can be achieved in a fast plutonium breeder. However, in view of the somewhat fundamental considerations which lead to low specific power in this type of reactor, it is unlikely that the specific power can be raised by a large enough factor to satisfy the expanding power economy, and to compete in this respect with thermal U^{233} breeders. At the very least, it seems considerably simpler to achieve the required specific power with thermal U^{233} breeders.

Another important point of comparison for the breeding cycles is the availability of the fertile materials, U^{238} for the plutonium cycle and Th^{232} for the U^{233} cycle. For the world as a whole, the amount of high grade ore are about the same for uranium and thorium.[3] The largest deposits of thorium are, however, in Brazil and India, and both countries have at present embargoes against the export of thorium. Whether this is serious for the time period under consideration in this Study is debatable. The

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4. Computed from "Fluid Fuel Reactors" (J. A. Lane, H. G. MacPherson and F. Maslan, Editors), Addison-Wesley Publishing Co., Inc., Reading, Mass., (1958), Table 9-9, p. 508. To the fissionable inventory quoted in the table, 16 kg have been added to allow for holdup in the "Chem Plant", etc. This was done on the basis of oral communication from R. B. Korsmeyer.

North American continent, U. S. and Canada, have about 200,000[5] tons of high grade thorium ore, which is a fraction of the high grade uranium-ore supply but still of the same order of magnitude and very substantial. If all converted into energy this supply would correspond to 17×10^{18} Btu which is quite comparable to the whole fossile fuel supply of the U. S. and Canada. It would cover, according to Arnold and Ullmann's figures, the anticipated U. S. requirement of electrical energy well beyond the year 2000. Considering the U. S. alone, the known thorium supply is relatively small, but this is probably largely due to the lack of interest in finding thorium.

In summary of the supply situation there are considerably less thorium deposits in the U. S. than uranium deposits; but if thorium were needed, it could be found in sufficient quantities either by further exploration or by import from Canada, if not from India or Brazil.

As far as price goes the U^{238} is obviously cheaper than thorium because it is obtainable from the tailings of U^{235} production which is needed by users other than commercial power plants. However, the price of the fertile material makes an insignificant contribution to the cost of power derived from a breeder.

Both recycled thorium and plutonium are radiation hazards. However, there seems to be no significant difference in the handling of the two substances.

A strong case can be made for parallel development of the plutonium and U^{233} breeding cycles. Neither cycle has been demonstrated to give breeder reactors of sufficiently low inventory and doubling time. Gambling on one cycle - with the possibility that the other cycle would have been the only successful one - would be dangerous to the extent that breeding is necessary. More important, the optimum development might very well involve a start with a low-inventory, short-doubling-time U^{233} breeder which would allow, with a limited supply of fissionable material, to produce a substantial amount of power and a substantial yearly increase in the power production. With the fissionable material supply increased by these breeders, high inventory plutonium breeders could be put into operation in order to tap the U^{238} supply.

5. J. C. Johnson, Resources of Nuclear Fuel for Atomic Power, Second United States International Conference on Peaceful Uses of Atomic Energy, Geneva Paper A/Conf. 15/P/192.

IV. COMPARISON OF DIFFERENT REACTOR TYPES FOR U^{233} BREEDING

As mentioned in Section I, Perry, Preskitt and Halbert investigated the use of gas-cooled, graphite-moderated reactors for U^{233} breeding. The breeding gain turned out to be small, if not negative, mainly because of the dilemma between, on one hand, large C:U ratio and large absorption in graphite, and, on the other hand, a smaller C:U ratio with insufficient moderation and lower η-values corresponding to higher neutron energies. The inventory was of course large. With respect to breeding, the gas-cooled, graphite-moderated reactors are not competitive with the aqueous homogeneous reactors.

The same authors are now investigating gas-cooled, D_2O-moderated reactors, with some misgivings about the absorptions in the zirconium-pressure tubes. Liquid-metal fuel reactors and molten-salt reactors are bound to have large inventories and, at best, low breeding gains, and are no good as breeders for this reason. Their high-thermal efficiencies speak, however, in their favor, even if conservation of fissionable and fertile material is made the primary consideration (see Section I).

In view of the uncertainty in the η-values, it is not planned to extend in the immediate future the calculations regarding U^{233} breeders, other than the aqueous homogeneous reactors, beyond the already scheduled computations of the gas-cooled, D_2O-moderated reactors.

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