NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

THE NUCLEAR DATA REQUIREMENTS FOR FUSION-FISSION (HYBRID) REACTORS

W. C. Wolkenhauer and B. R. Leonard, Jr.
Pacific Northwest Laboratories
Richland, Washington 99352

The fusion-fission or hybrid reactor is generally defined as a Controlled Thermonuclear Reactor (CTR) with a fissionable blanket surrounding it. The concept is based upon the neutron multiplication properties of heavy isotopes in a 14 MeV (deuterium-tritium plasma) neutron flux and the large energy release of neutron-induced fission relative to neutron capture events or neutron absorption in lithium.[1]

While a number of different concepts have been proposed, there appear to be only two distinct classes of hybrid systems. One of these is a system which is optimized for the breeding of fissile fuel for fission reactors. The other concept is the hybrid which is optimized for power production directly.[2]

Because the hybrid concept is not well understood, we will first review the historical development of the concept. We will then develop some of the principle characteristics of the system. After this, a specific hybrid design will be given. A review of the analytical techniques applied to this specific design will then allow for development of the nuclear data required for hybrid reactor design.

1. History of Development

The first suggestion for a hybrid device was apparently made in the early 1950's.[3] A United States patent application describing a hybrid was filed in 1957.[4] A British patent application was filed by Lawson, et al., in 1958 on a similar idea.[5] The first applicable measurements in the open literature appear to have been made by Weale et. al., in 1961.[6] The most systematic study of a hybrid concept which is

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

optimized for the breeding of fissile fuel for fission reactors was carried out by Lidsky.[7] Some of the most recent work on a hybrid concept optimized for power production has been carried out by Lee[8] and by the authors.[1] There does not however, seem to have been a consistent development program on the hybrid concept even though it was first introduced some twenty years ago. Interest in the hybrid may grow, however, when the emphasis in fusion reactor development changes from technical feasibility to engineering and economic feasibility.

2. The Characteristics of a Hybrid Reactor

A hybrid reactor can be defined as a CTR with a blanket which contains fissile or fertile material. Such a machine, independent of the market it is optimized for, has certain characteristics which identify its potential advantages or disadvantages as a source of power.

First of all, consider the characteristics of the plasma of the fusion device employed in the hybrid machine. It is often mentioned that a possible advantage of the hybrid is that, as a result of its energy multiplication possibilities, it can be used with a sub-Lawson plasma which would allow for early exploitation of the fusion reaction. The plasma characteristics of a hybrid can be more accurately defined by pointing out that a hybrid must operate with a sub-Lawson plasma.[9] This conclusion results from engineering considerations. A certain level of energy or neutron multiplication must take place in the blanket in order to breed fuel for the device. For a given blanket design, there is a limit on blanket power density and a limit on fissile fuel depletion rate which can be determined for that design. For known materials, these blanket limits result in plasma limits which are, in all cases surveyed, substantially sub-Lawson in nature. Therefore, the first characteristic of a hybrid machine is that it must operate with a sub-Lawson plasma. This result implies that exotic refractory metals for structure and fuel cladding are not required for hybrid reactors.

Another characteristic of hybrid machines is the nature of the energy multiplication. For a hybrid design with a fissile blanket, the rate of multiplication, or the number of fissions per fusion event, (N) can be estimated by the equation:[10]

$$N = \frac{1}{\nu} \frac{k_{\text{eff}}}{1 - k_{\text{eff}}}$$

where k_{eff} is the neutron balance of the fissile blanket as usually defined by standard reactor physics terminology and ν is the average number of neutrons per fission. From this equation, one can see that very large energy multiplication is possible with values of $k_{\text{eff}} < 1$. Therefore, hybrid fertile/fissile blankets will be subcritical. For a deuterium-tritium plasma, the energy multiplication (Q) of a given design can be estimated by the equation:

$$Q = \frac{200 + 17}{17} \times \frac{1}{\nu} \times \frac{k_{\text{eff}}}{1 - k_{\text{eff}}}$$

MASTER

assuming an average fission energy release of 200 MeV, an average fusion energy release of 17 MeV, and also assuming that all of the fusion energy is available to the energy balance. Therefore, a second characteristic of the hybrid machine can be developed. Not only does the hybrid operate with a sub-Lawson plasma, but also it employs a sub-critical blanket assembly. The design goal, of course, is to develop a machine with the above characteristics which has a favorable output to input energy balance. For a wide range of interesting designs, this appears to be possible.

A third general characteristic of hybrid machines relates to the breeding function of the blanket. If the blanket, in its role as a fissile breeder, utilizes depleted or natural uranium as a fertile material, the bred fissile material is found to be almost all Pu-239.[1] This is due to two phenomena. The hybrid reactor, if it utilizes the deuterium-tritium reaction, gives off 14 MeV neutrons as a primary source. The value of α ($\alpha = \sigma_c / \sigma_f$) approaches zero for Pu-239 above 2 MeV or so.[11] Therefore, the buildup of higher plutonium isotopes in a hybrid reactor can be greatly retarded depending upon the specific concept.

The blanket of a hybrid reactor must perform several functions. It must produce neutron and energy multiplication by means of n , $2n$, $n, 3n$, and fission reactions. It must breed sufficient tritium in order to maintain the fusion reaction. It must breed sufficient fissile material in order to maintain the fission reaction. Finally, it may be used to extract energy by means of neutron moderation and cooling. The two breeding functions and the energy multiplication functions compete with each other for neutrons. One of the difficulties the authors observed in their work was how to suppress breeding in order to obtain the desired energy multiplication. In the case of a graphite moderated blanket, the authors found that it was difficult to achieve all of the requirements with a natural uranium fueled blanket. However, it was found that a slightly enriched blanket provided breakeven breeding for both reactions and a overall system output to input energy ratio in excess of 25. In this case, the results indicate that an additional slight enrichment would provide remarkably short breeding doubling times which are a feature of fusion machines. Thus, two more design characteristics emerge. They are that hybrid blankets would probably operate with a slight fissile enrichment and that the hybrid could have the breeding doubling times characteristic of fusion reactors.[9]

Finally, one can list some of the environmental characteristics of hybrid reactors. The hybrid reactor will contain large quantities of tritium and fission products. A properly designed hybrid will, contrary to fission reactors, contain only small amounts of nonfissile actinides. The tritium inventory will be small compared to that of a fusion reactor. Thus, the ash from a hybrid reactor will be similar to that found in a fully enriched fission reactor. If one assumes that the relatively cheap uranium currently available will be exploited for power, if one recognizes the unique problems associated with tritium containment, and if one recognizes that the higher actinides represent a major waste disposal

problem associated with fission reactors, then it appears that the hybrid reactor might have attractive environmental features.[2]

In summary then, a hybrid reactor is a sub-Lawson plasma coupled to a subcritical fissile/fertile assembly which can produce a positive energy balance. Some of the potential advantages of the device are:

- Has high energy densities associated with fission reactors.
- Has short doubling times associated with fusion reactors.
- Breeds relatively pure fissile material.
- Allows for exploitation of uranium reserves in subcritical assemblies.
- Eliminates major radioactive hazards associated with pure fusion and pure fission devices.
- Development can progress to fruition based on known technology.

The authors have been studying a specific hybrid design based upon the neutron convertor concept.[1,2,9,10] One variation of this approach is shown in Figure 1.

The fissile blanket is divided into a number of regions. These include the neutron convertor, the energy convertor, a reflector, and an outer absorber for tritium production. The design shown here is helium cooled and, at least for the energy convertor, is generally consistent with gas cooled fission lattice design.

The neutron convertor concept is of general interest here as it serves several purposes.[1] It provides direct utilization of the U-238 fission energy by 14 MeV neutron induced fission and multiplication of the 14 MeV neutron source through fission, $n,2n$, and $n,3n$ reactions. The absorption in the convertor of these secondary neutrons and neutrons leaking back from the fission lattice result in further fast neutron fissions and neutron capture in U-238 to produce Pu-239. The lithium serves to breed tritium, inhibit Pu-239 fission and in addition, it decouples neutronically one side of the fission lattice from the other side of the cylinder.

The design shown here is, in general, typical of the studies being carried out on this concept. The hybrid is usually studied somewhat independently of a specific plasma device. However, it is usually based on a deuterium-tritium plasma due to the high potential neutron multiplication of the energetic (14 MeV) neutrons. In addition, a specific blanket design will, as mentioned previously, dictate the desired plasma conditions.

In contrast to this system, Figure 2 shows a spherical design developed by Lee.[8] In principle, this system operates much in the manner of that shown in Figure 1. This type of hybrid probably places more stringent requirements on nuclear data than the coupled convertor-thermal system. In order to analyze this system, one must have continuous data describing the slowing down of neutrons from 14 MeV to thermal energies throughout the system and for all isotopes of the system.

FIGURE 1. HYBRID BLANKET

FIGURE 2. SPHERICAL HYBRID

3. The Analysis of a Hybrid

In order to develop the minimum nuclear data requirements needed to analyze some of these previously described systems, a method of performing an analysis of hybrids will be described. A flow chart of the approach is shown in Figure 3. Other analytical techniques which have been used include Monte Carlo analysis and other computer codes which solve the neutron transport equation directly.

The analysis of a hybrid begins with a microscopic data library for the required isotopes with data being available for the required reactions over an energy range from 14 MeV to thermal. The minimum data requirements are summarized in Figures 7 and 8. In Figure 2, to save computer space, the data are collapsed by means of the neutron transport code ANISN[12] to a 27 energy group set. The THERMOS[13] and HRG[14] codes are used to calculate thermal spatial and resonance absorption spatial effects. These effects are particularly strong with respect to U-238 and Pu-240. The ANISN code is used to calculate the static neutron flux distribution. The ALCHEMY[15] code is used to calculate the burnup rate of the various isotopes. Dashed lines are used to indicate the need for periodic spectral updating of the data as the analysis proceeds to higher neutron exposure. The computer codes used here are generally available and have been used in the analysis of similar devices.[16]

4. The Important Neutron Reactions

The major neutronic reactions involved in the analysis of hybrid blankets are the neutron producing reactions and the fuel breeding reactions. These reactions are reviewed below along with some of the other relevant reactions. The results are then summarized to develop the minimum nuclear data needs for hybrid analysis.

4.1 The Neutron Producing Reactions

The neutron producing reactions for U-238 are shown in Figure 4 as a function of energy. They are the $n,2n$, $n,3n$ and fission reactions and are shown here as a function of energy. The curves were obtained from version 3 of ENDF/B[17] which is the Evaluated Nuclear Data File of the USAEC. If these data are weighted by the specific reaction neutron production, a continuous curve of the number of neutrons produced per neutron absorbed can be developed. This composite curve is shown in Figure 5.[9] If this curve is compared to experimental points, as shown on Figure 5, one can see that the file may not be a best estimate at 14 MeV. While Figure 5 demonstrates the high neutron multiplication which can be obtained from 14 MeV neutrons impinging upon a fissile/fertile assembly, it also indicates some inadequacy in the available data for neutron producing reactions. This inadequacy may, however, be due to inadequacies in the library data file description as opposed to inadequacies in the data themselves. In any case, the nuclear data needs for hybrid reactor analysis not only include specific requirements for nuclear data for energies far above the fission spectrum, but also, there are requirements for data on nuclear reactors often not given emphasis in fission reactors. (i.e., $n,2n$, $n,3n$).

FIGURE 3. AN ANALYSIS MODEL FOR HYBRID REACTORS

FIGURE 4. NEUTRON PRODUCING REACTIONS OF ^{238}U

FIGURE 5. NEUTRONS PRODUCED PER NEUTRON ABSORBED FOR ^{238}U

4.2 The Fuel Breeding Reactions

There are several neutron absorbing fuel breeding reactions associated with the hybrid reactor. Assuming a fusion device based upon the deuterium-tritium reaction, tritium must be bred at a breakeven rate by neutron absorption in lithium. The specific reactions are:[18]

The ${}^6\text{Li}$ reaction is a thermal neutron reaction and is exothermic. The ${}^7\text{Li}_3$ reaction is an epithermal neutron reaction and is endothermic. In a typical hybrid blanket, about one-third of the tritium is bred by the ${}^7\text{Li}_3$ reaction and the rest by the thermal reaction.

Plutonium may be bred in a hybrid blanket to supply fissile fuel either for energy production in the machine itself or in a separate reactor. The pertinent reactions are:

If the fissile fuel is bred by means of neutron absorption in thorium such that ${}^{233}\text{U}$ is bred as the fissile fuel, the reactions are:[19]

The neutron absorption cross sections for the isotopes involved in these reactions must be known over the energy range from 14 MeV to thermal.

4.3 Other Relevant Neutron Reactions

In a hybrid blanket, energy is extracted by moderation of the energetic neutrons. Typical moderating materials include graphite and beryllium. Structural materials which may be used for the vacuum wall and the blanket structure would be alloys of stainless steel in contrast to the exotic metals such as niobium, and vanadium which have been proposed for "pure" fusion reactors. Therefore, inelastic and elastic scattering data are required for these materials, along with neutron absorption data, for the whole energy range from 14 MeV to thermal energies. Supplementary information on the neutron damage characteristics of these materials as a function of energy may also be required.

5. Minimum Data Requirements

The data requirements for hybrid analysis are dictated, in part, by the complexity of the transmutation chain for fertile materials in a 14 MeV neutron flux. Figure 6 displays the uranium transmutation chain in a high energy flux. One can see that such reactions as $n,2n$, which have a threshold in the range of 8 MeV, become important in the hybrid system.

The nuclear data needs for the analysis of a hybrid lattice such as shown in Figure 1 and which uses the uranium burnup chain shown in Figure 6 can be developed for the analysis model shown in Figure 3. Such a compilation of requirements is shown in Figure 7.

The data needs are so extensive in part, because the uranium burnup and transmutation equations have been shown to be quite complex. In addition, one needs to analyze fusion fuel breeding, neutron moderation, neutron production, and possible damage effects. The sum of these requirements leads to the extensive compilation listed in this figure.

Figure 7 itemizes the data requirements for the analytical model. However, there are additional specific data requirements over certain energy ranges which are of special concern. These requirements are shown in Figure 8.

While plasma reaction data is not of great importance directly in hybrid design, there will eventually develop a need for accurately controlling the degree to which the plasma lacks being a breakeven plasma. For fusion reactors, the emphasis has been placed upon knowing the charged-particle reaction cross section in the range of 10-100 keV. Because hybrid reactors require a degraded plasma, accurate data must be obtained in the range of a few keV. Because the cross section is very small and changing rapidly in this energy region, accurate data in this range might be difficult to obtain.[20]

6. Summary

At present, the nuclear data used in hybrid design are found, for the most part, in ENDF/B[17] and other similar data libraries. They are, however, all lacking in some of the required reactions either because it has not been evaluated or because it has not been measured. Immediate requirements are for improved measurements of the minimum indicated reactions as shown in Figure 8 for the indicated energy range. Beyond the basic measurements, the data must be evaluated by data evaluation experts, and just as importantly, it must be placed upon the available nuclear data files.

FIGURE 6. THE URANIUM TRANSMUTATION CHAIN IN A HYBRID BLANKET

REACTION ISOTOPE	n, γ	n, α	n, p	n, 2n	n, 3n	n, n' α	FISSION	ν	ELASTIC SCATTER	INELASTIC SCATTER
$^4\text{He}_2$	X			X					X	X
$^6\text{Li}_3$		X		X					X	X
$^7\text{Li}_3$				X		X			X	X
^{12}C	X	X							X	X
^{16}O									X	X
Fe	X		X	X						
^{234}U	X									
^{235}U	X	X		X			X	X		
^{236}U	X			X						
^{238}U	X			X	X		X	X		
^{237}Np	X			X						
^{236}Pu	X			X						
^{237}Pu		X								
^{238}Pu	X			X						
^{239}Pu	X			X			X	X		
^{240}Pu	X			X						
^{241}Pu	X			X			X	X		
^{242}Pu				X						

FIGURE 7. MINIMUM DATA REQUIREMENTS FOR HYBRID DESIGN

ISOTOPE	REACTION	ENERGY RANGE	COMMENT
^{239}Pu	FISSION	10-15MeV	INTERACTION OF 14MeV AND DEGRADED NEUTRONS WITH ^{232}U , ^{238}U , AND ^{239}Pu LEAD TO NEED FOR IMPROVED DATA
^{238}U AND ^{232}Th	ν	8-15MeV	
	n, 2n	THERMAL-15MeV	
	n, 3n	THERMAL-15MeV	
	INELASTIC SCATTER	8-14MeV	IMPORTANT FARTHER OUT IN THE BLANKET
	RESONANCE CAPTURE	THERMAL- 1MeV	
Fe	CAPTURE	THERMAL- 2MeV	STAINLESS STEEL IS LIKELY HYBRID STRUCTURAL MATERIAL.
	n, 2n	THERMAL-14MeV	
	n, 3n	THERMAL-14MeV	
	ELASTIC SCATTER	THERMAL-14MeV	
	INELASTIC SCATTER	THERMAL-14MeV	
FISSION NEUTRON SPECTRA		4-15MeV	THIS IS NEEDED TO CALCULATE SPECTRA NEAR THE VACUUM WALL.

FIGURE 8. SPECIFIC DATA WHICH NEED IMPROVED MEASUREMENT

7. References

- [1] LEONARD, B. R., Jr., and WOLKENHAUER, W. C., Fusion-fission hybrids: A subcritical thermal fission lattice for a DT fusion reactor, presented at a conference on Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors, University of Texas, Austin, Texas, (November 1972).
- [2] LEONARD, B. R., Jr., and WOLKENHAUER, W. C., Fusion-Fission (Hybrid) Systems, USAEC Report, BNWL-B-162, Pacific Northwest Laboratories, (Feb. 1972).
- [3] POWELL, F., Proposal for a Driven Thermonuclear Reactor, USAEC Report, LWS-24920 (revised), (October 1953).
- [4] BARRETT, L. G., A Fusion-Fission Reactor, KAPL, Report M-LOB-14, (June 1957).
- [5] LAWSON, J. D., THONEMANN, P. C., POOLE, M. J., and TAIT, J. H., Patent Specification 830, 255, United Kingdom Patent, complete specification filed January 15, 1958.
- [6] WEALE, J. W., GOODFELLOW, N., MCTAGGERT, M. H., and MOLLENDER, M. L., Measurements of the reaction rate distribution produced by a source of 14 MeV neutrons at the centre of a uranium metal pile, J. Nucl. Energy, A/B, 14, (1961) 91.
- [7] LIDSKY, L. M., Fission-fusion symbiosis: General considerations and a specific example, Nuclear Fusion Reactors Conf. (September 1969) UKAEA, Culham Laboratory, Abingdon, Berks.
- [8] LEE, J. D., Subcritical fast fission blanket, Thermonuclear Reactor Memorandum 20, LRL (Nov. 1970).
- [9] LEONARD, B. R., Jr., Fusion-fission hybrid systems; a presentation prepared for the staff of the USAEC, Div. of Controlled Thermonuclear Research, BNWL-B-216 (July 1972).
- [10] WOLKENHAUER, W. C., Editor, The Pacific Northwest Laboratory Annual Controlled Thermonuclear Reactor Technology Report - 1971, BNWL-1604, (July 1971).
- [11] Neutron Cross Sections, BNL-325, Second Edition, Supp. 2, (Feb. 1965)
- [12] ENGLE, W. W., Jr, A User's Manual for ANISN, a One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering, K-1693, (March 1967)
- [13] SKEEN, D. R. and PAGE, L. J., THERMOS/BATTELLE: The Battelle Version of the THERMOS Code, BNWL-516, (September 1967).
- [14] CARTER, J. L., HRG-3: A Code for Calculating the Slowing Down Spectrum in the P-1 or B-1 Approximation, BNWL-1432 (June 1970).

- [15] DUANE, B. H., Time-Variant Isotopic Transmutation, GE-HL Program ALCHEMY, HW-80020, (December 1963)
- [16] ABDOR, M , and MAYNARD, C. W., Computational Techniques for Neutronics and Photonics Calculations for Fusion Reactor Blankets and Magnet Shields, FDM3, Nucl. Engng. Report, University of Wisconsin, Madison, Wisconsin, (June 1972)
- [17] HONECK, H. C., ENDF/B, Specifications for an Evaluated Nuclear Data File for Reactor Applications, BNWL-50066, USAEC (1966).
- [18] STEINER, D., The nuclear performance of fusion reactor blankets, Nucl Applications & Tech. Vol 9, (July 1970).
- [19] GLASSTONE, S., and SESONSKE, A., Nuclear Reactor Engineering, D. Van Nostrand Company, Inc., (1967).
- [20] GLASSTONE, S., and LOVBERG, R. H., Controlled Thermonuclear Reactions, D. Van Nostrand Company, Inc., Princeton, N. J., (1960).

LIST OF FIGURES

1. Hybrid Blanket
2. Spherical Hybrid
3. An Analysis Model for Hybrid Reactors
4. Neutron Producing Reactions of ^{238}U
5. Neutrons Produced per Neutron Absorbed for ^{238}U
6. The Uranium Transmutation Chain in a Hybrid Blanket
7. Minimum Data Requirements for Hybrid Design
8. Specific Data which Need Improved Measurement