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THE INFLUENCE OF NUCLEAR DATA UNCERTAINTIES ON THORIUM FUSION-FISSION* HYBRID BLANKET NUCLEONIC PERFORMANCE

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The fusion-fission hybrid blanket proposed for the Tandem Mirror Hybrid Reactor employs thorium metal as the fertile material. Based on the ENDF/B-IV nuclear data, the ^{233}U and tritium production rate and blanket energy multiplication averaged over the blanket lifetime of about 9 MW-yr/m^2 are 0.76 and 1.12 per D-T neutron and 4.8, respectively. At the time of the blanket discharge, the ^{233}U enrichment in the thorium metal is about 3%. The thorium cross sections given by the ENDF/B-IV and V were reviewed, and the important partial cross sections such as (n,2n), (n,3n) and (n,γ) were found to be known to ±10–20% in the respective energy range of interest. A sensitivity study showed that the ^{233}U and tritium production rate and blanket energy multiplication are relatively sensitive to the thorium capture and fission cross section uncertainties. In order to predict the above parameters within ±1%, the Th(n,γ) and Th(n,νf) cross sections must be measured within about ±2% in the energy range 3–3000 keV and 13.5–15 MeV, respectively. The present level of uncertainty in these data is ±10 and 5%. This indicates that although presently adequate for preliminary design, additional cross section measurements to improve the accuracy of the Th(n,γ) and Th(n,νf) cross sections in these energy ranges may be needed in order to accurately calculate the blanket performance thorium-base fusion-fission hybrid reactor blankets.

(Fusion-fission hybrid blanket, Th(n,2n), Th(n,3n), Th(n,νf), Th(n,γ), tritium breeding, uranium production, blanket energy multiplication, cross section uncertainty, cross section sensitivity)

Introduction

A wide variety of fusion-fission hybrid system concepts have been recently suggested and evaluated by many investigators.[1] The concept of placing a blanket of fertile material around a fusion plasma to form a hybrid system is most attractive because of the flexibility such a system can have to produce either thermal power or fissile fuel, or both. In these concepts, the blankets consist of either a ^{238}U or ^{232}Th fertile zone which serves to multiply the fusion neutrons via (n,2n), (n,3n) and (n,νf) reactions, to enhance the thermal power output through fission reactions, and/or to produce fissile fuels (^{239}Pu or ^{233}U) from ^{238}U(n,γ) or ^{232}Th(n,γ) reactions. In general, the uranium-base blankets produce a large amount of thermal power, multiplying the incident fusion neutron energy by about a factor of 10 by fast fission of the ^{238}U. They also produce up to two fissile atoms per D-T neutron in addition to the breeding of adequate tritium to sustain the system (T/n $\geq$ 1). The thorium-base blankets produce more modest amounts of thermal power which is generally only two or three times that of the incident fusion neutrons. The fissile atom production rate in these blankets is not more than one per D-T neutron if the self-sustaining tritium production is to be maintained.[2,3] When either uranium or thorium blanket is exposed to the fusion neutron environment the bred fissile fuel concentration accumulates so as to increase the fissioning rate and thus the thermal power output. The net fissile fuel production rate changes relatively little, however, until very high fissile concentrations (~10%) are reached, whereupon production and fission tend to equilibrate.

Because of the higher blanket thermal output in the uranium or fissile enriched blankets which is mainly due to fission reactions, the fission product and actinide inventories in these blankets can be large. The local nuclear heating and after-shutdown decay heat are thus high compared to those of the thorium-base blankets which possess more modest blanket thermal output. The fission product decay heat can cause meltdown of the fuel if a loss of coolant flow accident occurs, which is a severe concern from the safety point of view and necessitates use of diverse and redundant blanket auxiliary cooling systems. Assuming only adiabatic heating, the afterheat meltdown time for a high power density uranium-base blanket can be as short as one minute. For the lower power thorium-base blanket designs, the afterheat adiabatic meltdown time can be as long as one hour under similar loss of cooling circumstances.[4]

Thorium-base hybrid blankets are also attractive because of the bred fuel. ^{233}U is superior to ^{239}Pu for use in a thermal spectrum burner reactor.[5] In addition to superior fuel cycle performance ^{233}U offers the possibility for isotopic denaturing with ^{238}U which may improve proliferation and diversion resistance.

In the Tandem Mirror Hybrid Reactor (TMHR) study,[4] a helium-cooled thorium metal blanket was chosen as the gas-cooled blanket candidate based on the consideration of better bred fuel (^{233}U versus ^{239}Pu), good fuel production and economics, positive net electricity production and reasonable tolerance of the loss of coolant flow accident.[6,7]

The performance of thorium blanket concepts for fusion-fission hybrid systems depend on the neutron and energy multiplication in the blanket through (n,2n), (n,3n) and fission reactions. The thorium cross section uncertainties and their effect on the blanket nucleonic performance are naturally of concern from the blanket design point of view. The thorium partial cross sections such as (n,2n), (n,3n) around the D-T neutron energy range and (n,γ) in the intermediate energy range are expected to be subject to uncertainties of about ±10–20%. The thorium fast fission cross section is also known to ±5% only. A sensitivity study of these cross section uncertainties is the main purpose of this paper. From the results of this study, the desired accuracies of the related partial cross sections can thus be recommended for the accurate computation of the performance of thorium fusion-fission hybrid blankets.

The blanket configuration and nucleonic performance are described briefly in the next section. A

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review of the status of the thorium nuclear data is then given, followed by a discussion of the sensitivity study of the thorium cross section uncertainties to the nucleonic performance of this blanket. The concluding remarks and recommendations of this study are summarized in the last section.

Thorium Fusion-Fission Hybrid Blanket Model

The helium cooled thorium metal TMHR blanket consists of a 10 mm first wall, a 0.11 m thick thorium metal zone, a 0.4 m Li_2O zone and a 0.1 m 316 stainless steel reflector/hot shield. The blanket configuration and material compositions are tabulated in Table I.

Table I. Thorium Fusion-Fission Hybrid Blanket Configuration and Material Compositions

Zone	Thickness (m)	Composition	Remarks
1	1.90	Vacuum	Plasma
2	0.10	Vacuum	Vacuum
3	0.01	Inconel 718	First wall
4	0.11	6.5% Inconel + 10% helium + 83.5% thorium[a]	^{233}U production
5	0.40	6.5% Inconel + 10% helium + 83.5% Li_2O[a]	Tritium breeding
6	0.10	10% helium + 90% 316 SS	Reflector/ hot shield

[a]90% of the theoretical density of this material is considered to account for the packing effect.

The neutronic calculations were performed using the one-dimensional discrete ordinates transport code, ANISN[8] with P_3S_6 approximation in cylindrical geometry. All the nuclear data except thorium are from the DLC-37[9] library which is based on ENDF/B-IV and were collapsed into 25 neutron and 21 gamma-ray group structure using an 1/E weighting spectrum. The group energy boundaries are the same as given in Ref. 10. The thorium nuclear data and all partial cross sections studied in this paper are from the DLC-41[11] library which used ENDF/B-IV data and were also collapsed into the same group structure using the same weighting spectrum.

The resonance self-shielding correction of thorium cross section is not treated in this study. The effects of the group collapsing weighting function and resonance self-shielding correction are not known. However, from the published results of the ^{238}U blankets,[12,13] it is known that the effect of the weighting function is very small[12] and the resonance self-shielding correction may reduce the $^{238}U(n,\gamma)$ reaction rate by about 4%.[13] It is believed that the results of this sensitivity study will still apply to the case when the weighting function and resonance self-shielding correction are treated.

When the blanket is fresh without neutron irradiation, the thorium metal zone contains no ^{233}U, and only fast fission of the thorium metal contributes to the blanket energy multiplication, which is defined as the ratio of total blanket nuclear heating to the incident D-T neutron energy. As the neutron irradiation proceeds, the ^{233}U concentration increases and its fissioning also adds to the blanket energy multiplication. The $Th(n,\gamma)$ reaction rate also increases due to the increase of neutron population in the blanket. However, ^{233}U fission burns the ^{233}U atoms and results in a slight decrease of the net ^{233}U production rate. The tritium production rate, which relies on the $^{6}Li(n,\alpha)$ and $^{7}Li(n,n'\alpha)$ reactions with the neutrons leaking into the lithium zone from the thorium zone, increases as the ^{233}U concentration in the blanket becomes larger. The irradiation lifetime of the blanket module is limited by the burnup limit of the thorium metal. This burnup design limit is about 1% at the peak location, which occurs immediately behind the first wall and corresponds to an accumulated first wall neutron exposure of about 9 MW-yr/m^2. After the 9 MW-yr/m^2 blanket lifetime is reached, the ^{233}U concentration in the thorium metal is about 3%. The blanket is then discharged and replaced with fresh blanket modules. The nucleonic performance of the thorium fusion-fission hybrid blanket at the beginning and end of life are presented in Table II. Note that in this table the time averaged tritium breeding ratio is about 1.12, adequate for tritium self-sufficiency, although it is 1.00 at the beginning of life and increases to 1.24 tritons per D-T neutron at the end of life. The net ^{233}U production rate which is 0.80 and 0.73 at the beginning and end of life, respectively, is time-averaged to be 0.76 atoms per D-T neutron. The blanket energy multiplication, which is about 2.7 at the beginning of life, increases to 7.1 at the end of life, with a time-averaged value, $\bar{M}$, of about 4.8.

Table II. Nucleonic Performance of the Thorium Fusion-Fission Hybrid Blankets at the Beginning and End of Life (Reactions per D-T Neutron)

Nucleonic Performance Parameter	Beginning of Life (No ^{233}U)	End of Life (3% ^{233}U)
$^{6}Li(n,\alpha)$	0.8995	1.1407
$^{7}Li(n,n'\alpha)$	0.1018	0.1021
Tritium breeding ratio	1.0013	1.2428
$Th(n,\gamma)$	0.7983	0.9429
Th(n,2n)	0.3208	0.3114
Th(n,3n)	0.1083	0.1044
Th(n,f)	0.1005	0.1105
$Th(n,\nu f)$	0.3611	0.3798
$^{233}U(n,\gamma)$	—	0.0208
$^{233}U(n,2n)$	—	0.0031
$^{233}U(n,3n)$	—	0.0003
$^{233}U(n,f)$	—	0.2641
$^{233}U(n,\nu f)$	—	0.6942
Net ^{233}U production	0.7983	0.6546
Blanket energy multiplication[a]	2.7	7.1

[a]Defined as the ratio of blanket thermal output to incident D-T neutron energy.

As stated in the previous section, this blanket concept utilizes the neutron and energy multiplications from Th(n,2n), Th(n,3n) and thorium fast fission as well as ^{233}U fission reactions when ^{233}U atoms accumulate. From Table II we see that the additional number of neutrons coming out of the Th(n,2n) and Th(n,3n) reactions is about 0.54 per D-T neutron. It is almost

Table III. Fractional Contributions to Nuclear Reaction Rates in the Thorium Fusion-Fission Hybrid Blanket in Specified Energy Ranges

Energy Range (MeV)	Th(n,2n)	Th(n,3n)	Th(n,νf)	Th(n,γ)	^{6}Li(n,α)	^{7}Li(n,n'α)	^{233}U(n,νf)$^{(a)}$
13.5 - 14.9	90.1	98.4	78.6	11.7	0.0	40.7	4.6
2.5 - 13.5	9.9	1.6	12.6	2.5	0.2	59.3	4.6
0.41 - 2.5	—	—	8.8	18.9	2.4	—	29.5
3.4×10^{-3} - 0.41	—	—	0.0	57.5	53.4	—	57.0
0.35 - 3.4×10^{-3}	—	—	—	8.0	26.5	—	3.8
Thermal - 0.35×10^{-3}	—	—	—	1.4	17.5	—	0.5

^{a}At the end of life, ~3% ^{233}U in the thorium.

unchanged throughout the blanket lifetime. The amount of multiplied neutrons due to fissioning is a function of accumulated ^{233}U concentration in the blanket due to the fissioning of ^{233}U. At the beginning of life it is only 0.26 per D-T neutron, increasing to about 0.70 at the end of life. The overall number of available neutrons are thus about 1.80 and 2.24 per D-T neutron at the beginning and end of life, respectively.

The contributions of the various partial nuclear cross sections in each specified energy range are presented in Table III. From this table we see that the most important Th(n,2n), Th(n,3n) and Th(n,νf) reactions are in the high energy range, particularly around the D-T neutron energy, i.e., 13.5 - 15 MeV. The energy below 13.5 MeV also contributes about 10 and 21% to the Th(n,2n) and Th(n,νf) reactions, respectively. The tritium production from ^{7}Li(n,n'α) reactions also favors the high energy ranges as can be seen from Table III. However, more than 50% of the ^{233}U production from ^{232}Th(n,γ) reactions and tritium production from ^{6}Li(n,α) reactions occur in the energy range 3.4 - 410 keV. In the range 0.4 - 2.5 MeV, the ^{233}U production rate is about 19% of the total. About 27% of the tritium production from ^{6}Li(n,α) reactions is from the energy range of 0.35 - 3.4 keV. When the ^{233}U concentration reaches 3%, ^{233}U fissioning occurs mostly in the intermediate energy range, namely about 57% in the range 3.4 - 410 keV and about 30% in the range 0.4 - 2.5 MeV. Table III also reveals that the source neutron energy group, 13.5—15 MeV produces about 12% of the total ^{233}U.

Cross Section Uncertainties

As explained in the previous sections, this thorium fusion-fission hybrid blanket employs thorium in metal form. The blanket nucleonic performance is highly dependent on the status of the thorium nuclear cross section uncertainties. In order to provide information for evaluating the importance of sensitivity to partial cross section uncertainty, the status of the thorium nuclear cross sections, which include (n,2n), (n,3n), (n,γ), (n,νf), (n,elastic) and (n,inelastic), are reviewed in this section.[14] Based on this review, the results of this sensitivity study can be evaluated to offer recommendations for further improvement in cross section data. Also included in this section are the status of the ^{233}U(n,νf) cross section, and those of the constituents of iron- and nickel-based structural alloys, namely Cr, Ni and Fe. The impact of the tritium producing cross sections, ^{6}Li(n,α) and ^{7}Li(n,n'α), are also discussed.

Neutron Multiplication Reactions

The principal neutron multiplication reactions in a hybrid fusion-fission blanket using thorium appear to be the Th(n,νf), Th(n,2n) and Th(n,3n) reactions, and after some blanket exposure, the ^{233}U(n,νf) reaction.

Th(n,νf). The number of prompt neutrons per fission event ($\bar{\nu}_p$) in ^{232}Th appears to be known to about ±1% and is not likely to be a significant source of uncertainty. The Th(n,νf) cross section appears to be known to about ±5% above 1 MeV. Below 1 MeV, the Th(n,νf) cross section is highly uncertain but very small. The ENDF/B-IV Th(n,νf) cross sections are 10 to 15% smaller than recent differential cross section measurements. A larger ^{232}Th(n,νf) cross section will be used in the ENDF/B-V data set for ^{232}Th. The ^{232}Th prompt fission neutron energy spectrum appears to be representable with a Maxwellian fission neutron temperature of 1.21 ± 0.05 MeV.

Th(n,2n) and Th(n,3n). The Th(n,2n) cross sections appear to be known to about ±15%. The ENDF/B-V ^{232}Th(n,2n) cross section will be significantly lower than the ENDF/B-IV data about 8 MeV (about 10% lower in the important 13 to 15 MeV energy range). The ^{232}Th(n,3n) cross section is estimated to be about ±30%. Essentially no direct experimental data exists because ^{230}Th has too long a half life to use the activation method.

^{233}U(n,νf). The ^{233}U(n,νf) cross section is relatively well known and should be uncertain to ±5% or less over the entire energy range of interest with considerably smaller uncertainty in the low thermal range near 0.025 eV. The prompt fission neutron energy spectrum of ^{233}U is also well known and very similar to ^{235}U.

Fissile Production Reaction

The ^{232}Th(n,γ) cross section in the 10 to 1000 keV energy range has been the subject of considerable discussion in recent years. Much of the discussion has been caused by the publication of very low (20 to 25%) Th(n,γ) data by Macklin and Halperin,[15] with very small claimed uncertainties. The uncertainty in the older activation data of Lindner, *et al.*, has recently been drastically reduced by new measurements of the ^{233}Pa decay gamma ray emission probability. It now appears likely that the Macklin and Halperin Th(n,γ) measurement was afflicted with similar (but more severe) problems as occurred in the Moxon and Chaffey ^{238}U(n,γ) measurements using the same technique which were later revised upward. It is significant to note that the Th(n,γ) cross section measured by Moxon and Chaffey[16] using a technique with known problems agreed very well with the Macklin and Halperin data in the 10 to 100 keV energy range where the two experiments overlap.

The uncertainty in the ENDF/B-IV Th(n,γ) cross section in the 3 to 3000 keV energy range is estimated to be ±10% in spite of the much larger differences in the published experimental cross section data. This is because of the excellent agreement between calculated and integral experiment values of $^{232}\sigma_c/^{239}\sigma_f$ obtained in the fast breeder fission reactor programs in both the U.S.[17] and Switzerland.[18] The uncertainty in the evaluated (n,γ) reaction data for ^{232}Th appears to be similar to or maybe even slightly less than for ^{238}U in this energy range.

The uncertainty in the Th(n,γ) cross sections at energies above about 3 MeV increase rapidly to ±20% or more. The Th(n,γ) reaction is small above 3 MeV so that hybrid fusion blanket design uncertainties are not much affected by the increased uncertainty.

Other Reactions

The neutron energy spectrum in the thorium portion of the blanket and the number and energy spectrum of the neutrons reaching the lithium region will be influenced by other cross sections such as the Th-elastic and inelastic cross sections as well as (to a lesser extent) by the cross sections of the Inconel used in the first wall and as the thorium region cladding and structural support.

Thorium Total Cross Section. The ENDF/B-IV Th total cross section data appears to be 10 to 20% too low particularly below 1 MeV and will be revised upward for the ENDF/B-V library. The ENDF/B-V Th total cross sections are claimed to be known to ±3% over the 0.01 to 14 MeV energy range with about ±5% uncertainty above about 15 MeV. The transmission through the thorium region to the lithium region is directly affected by this uncertainty.

Thorium Elastic and Inelastic Cross Sections. Measured elastic scattering cross sections usually include some contributions from low Q value inelastic scattering which are almost impossible to experimentally separate. From a computational point of view, no significant error is introduced by this fact although published uncertainties for the elastic cross sections are increased by this experimental problem. The Th(n,n) cross section is probably known to about ±10% over the 0.1 to 15 MeV energy range. It should be noted that the ENDF/B-IV and ENDF/B-V evaluations differ significantly with the ENDF/B-V data higher by about 10% below about 80 keV and about 10% lower in the 1 to 4 MeV range. This is because of the onset of significant inelastic competition above about 50 keV. Elastic scattering angular distributions computed from model calculations agree reasonably well with experimental data where available.

Considerable experimental data on the Th(n,n') reaction has been obtained since the ENDF/B-III/IV Th(n,n') evaluations were performed. The claimed uncertainty in the ENDF/B-V evaluated Th(n,n') data is ±10 to 15%. The ENDF/B-V Th(n,n') data will be about 15 to 20% higher than the ENDF/B-IV data in the 1 to 7 MeV energy range with considerable differences in the details of the inelastic scattering angular distributions. The details of the angular distributions are not very significant to blanket design studies except for their impact on the mean energy loss per collision which is important in determining the neutron energy spectrum in the throium region which strongly affects the tritium production in the lithium region by the ^{7}Li(n,n'α)T threshold reaction.

Structural Material Cross Sections. The Cr, Fe and Ni cross sections are known to the same, or in most cases, better accuracy than the thorium cross sections. Since Inconel is only about 7% of the thorium and lithium regions, the uncertainties in these cross sections will not be very significant in the overall system uncertainties and a conservative simplification would be to assume the same uncertainties for Cr, Fe and Ni as for thorium.

^{6}Li(n,α)T and ^{7}Li(n,n'α)T Reactions. The ^{6}Li(n,α)T reaction is a well known reaction that is often used as a secondary standard against which other cross sections are measured. The uncertainty in the ^{6}Li(n,α)T reaction cross sections should be ±5% or less over the energies of interest in hybrid fusion-fission blanket designs. A study performed by Steiner and Tobias[19] showed that the ^{6}Li(n,α) cross section is adequate for tritium breeding calculations within 1%. The ^{7}Li(n,n'α)T reaction is somewhat less important in this type of hybrid blanket design, since more than 90% of the tritium breeding is contributed from the ^{6}Li(n,α)T reaction. In this case, the current evaluation may be adequate in predicting the nucleonic performance within 1 to 2%.[19]

Sensitivity Study

Method of Study

The method of the cross section sensitivity study employed here is based on the linear perturbation theory as described by Bartine, *et al.*[20] The calculations of the sensitivities were performed using the ORNL developed sensitivity analysis code, SWANLAKE.[21] The direct and adjoint flux distributions required to perform the sensitivity calculations were computed using ANISN. The agreement of the Th(n,γ) and ^{6}Li(n,α) reaction rates in the regular and adjoint calculations is excellent within about 1%. The calculations for fission reaction rates are also in good agreement within about 2%. The ^{7}Li(n,n'α) reaction rates differ by about 4%. However due to its relatively small contribution to the overall tritium breeding, ~ 10%, the overall tritium breeding ratios still agree within 1%.

Results and Discussions

The overall sensitivities of the thorium partial cross sections to the nucleonic performance of the thorium fusion-fission hybrid blanket are presented in Tables IV and V for the blanket at the beginning and end of life, respectively. All quantities are given in units of percent per 1% of cross section increase.

At the beginning of life, the ^{233}U production rate is mostly affected by the (n,γ) and (n,νf) cross section uncertainties. It increases by about 0.44 and 0.14% if the (n,γ) and (n,νf) cross sections are raised by 1%, respectively. At the end of life, it becomes less sensitive and drops to 0.28% for Th(n,γ) cross section. The effect due to Th(n,νf) cross section uncertainty is also very small. These results are revealed in Tables IV and V.

Table IV. Sensitivities of Thorium Partial Cross Section Uncertainties to ^{233}U Production, Thorium Fission and Tritium Production Rates in a Thorium Fusion-Fission Hybrid Blanket at the Beginning of Life (Percent per 1% Cross Section Increase)

Cross Section Type	Th(n,γ)	Th(n,f)	^{6}Li(n,α)	^{7}Li(n,n'α)	Tritium Breeding Ratio
(n,n)	0.051	0.002	-0.036	0.127	-0.020
(n,n')	0.055	-0.030	-0.120	0.138	-0.094
(n,2n)	0.077	-0.021	0.028	0.194	0.045
(n,3n)	0.085	-0.010	0.052	0.212	0.068
(n,νf)	0.142	1.008	0.132	-0.127	0.106
(n,γ)	0.443	-0.009	-0.370	-0.015	-0.334

The tritium breeding ratio is sensitive to the Th(n,γ) cross section uncertainty at the beginning of life. It decreases by about 0.33% as the Th(n,γ) cross section is raised by 1%. However at the end of life,

Table V. Sensitivities of Thorium Partial Cross Section Uncertainties to ^{233}U Production, Thorium and ^{233}U Fission and Tritium Production Rates in a Thorium Fusion-Fission Hybrid Blanket at the End of Life [a] (Percent per 1% Cross Section Increase)

Cross Section Type	Th(n,γ)	Th(n,f)	$^{233}U(n,f)$	$^{6}Li(n,\alpha)$	$^{7}Li(n,n'\alpha)$	Tritium Breeding Ratio
(n,n)	0.064	0.003	0.017	0.013	-0.139	-0.011
(n,n')	0.067	-0.003	-0.028	-0.010	-0.727	-0.072
(n,2n)	0.084	-0.019	0.019	-0.022	0.215	-0.001
(n,3n)	0.092	-0.008	0.021	-0.007	0.335	0.022
(n,νf)	0.140	1.005	0.132	0.134	-0.129	0.112
(n,γ)	0.282	-0.015	-0.149	-0.008	-0.028	-0.010

[a] 3% ^{233}U in thorium.

the tritium breeding ratio becomes relatively insensitive to all cross section uncertainties. This can also be observed from Tables IV and V. The thorium fission reaction rate and thus the blanket energy multiplication are very sensitive to the Th(n,f) cross section uncertainty. The fission reaction rate increases by about 1% as the corresponding cross section is raised by 1%, no matter whether the blanket is fresh or irradiated. The $^{233}U(n,f)$ reaction rate, which becomes very important toward the end of life when the ^{233}U concentration increases, is also sensitive to the Th(n,γ) and Th(n,f) cross section uncertainties. It changes by about -0.15 and 0.3%, respectively, as the Th(n,γ) and Th(n,f) cross sections increase by 1%.

If the cross section uncertainties shown in the evaluated files as discussed in the previous section are coupled with the above calculated sensitivities, the adequacy of the currently available thorium nuclear data for hybrid design calculations can be assessed. From the previous section, the Th(n,νf) and $^{233}U(n,\nu f)$ cross sections appear to be known to about ±5%. This means that the blanket energy multiplication will be known only to about ±2.5 and 4% at the beginning and end of life, respectively. However, all the ^{233}U and tritium production rates seems to be within ±1% due to these cross section uncertainties. The Th(n,2n) and Th(n,3n) cross section uncertainties are about ±15 and 30%, respectively. The uncertainties in predicting the ^{233}U and tritium production rates are thus about ±1.2 and 7% and ±2.8 and 2%, respectively, due to the Th(n,2n) and Th(n,3n) cross section uncertainties. The blanket energy multiplication, however, can be predicted within ±0.5%. The Th(n,γ) cross section is known to about ±10% in the 3–3000 keV range. The uncertainties due to this cross section uncertainty in predicting the ^{233}U and tritium production rates and blanket energy multiplication are up to ±4.5, 3.3 and 2%, respectively. The Th(n,n) and Th(n,n') cross sections are known to about ±10 and 10–15%, respectively. However, the hybrid blanket does not appear to be sensitive to these cross section uncertainties.

Concluding Remarks and Recommendations

The sensitivities of the nucleonic performance characteristics of a typical thorium fusion-fission hybrid blanket to the important thorium partial cross section uncertainties were calculated. The conclusions and recommendations of this study are summarized as follows:

1. The ^{233}U production rate is sensitive to the Th(n,γ) cross section uncertainty. In order to obtain a confident ^{233}U production rate within ±1%, the Th(n,γ) cross section must be measured accurately within about ±2% versus the presently available ±10%, particularly in the energy range 3–3000 keV.
2. The thorium fission reaction rate and thus the blanket energy multiplication depend significantly on the accuracy of the Th(n,νf) cross section itself. For the blanket energy multiplication to be within ±1%, the Th(n,νf) cross section must be measured within about ±2% versus the present ±5%, in the high energy range 13.5–15 MeV.
3. The tritium breeding ratio is sensitive to both Th(n,γ) and (n,νf) cross section uncertainties. In order to predict the tritium breeding within ±1%, the Th(n,γ) and (n,νf) cross sections could be accurate within about ±3 and ±10%, respectively.

In general, it appears that the hybrid blanket performance is not highly sensitive to the nuclear data uncertainties. The accuracy with which the important reaction cross sections is presently known appears to be adequate for preliminary design but it is expected that further measurements of Th(n,γ) cross section, particularly in the 3 to 3000 keV range, and of the Th(n,νf) cross section in the 13.5 to 15 MeV range will be needed for accurate detailed design.

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