

NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-123

**A Review of Nuclear Data Needs and their Status
for Fusion Reactor Technology
with Some Suggestions on a Strategy to Satisfy the Requirements**

by

Donald L. Smith and Edward T. Cheng

September 1991

**ARGONNE NATIONAL LABORATORY,
ARGONNE, ILLINOIS 60439, U.S.A.**

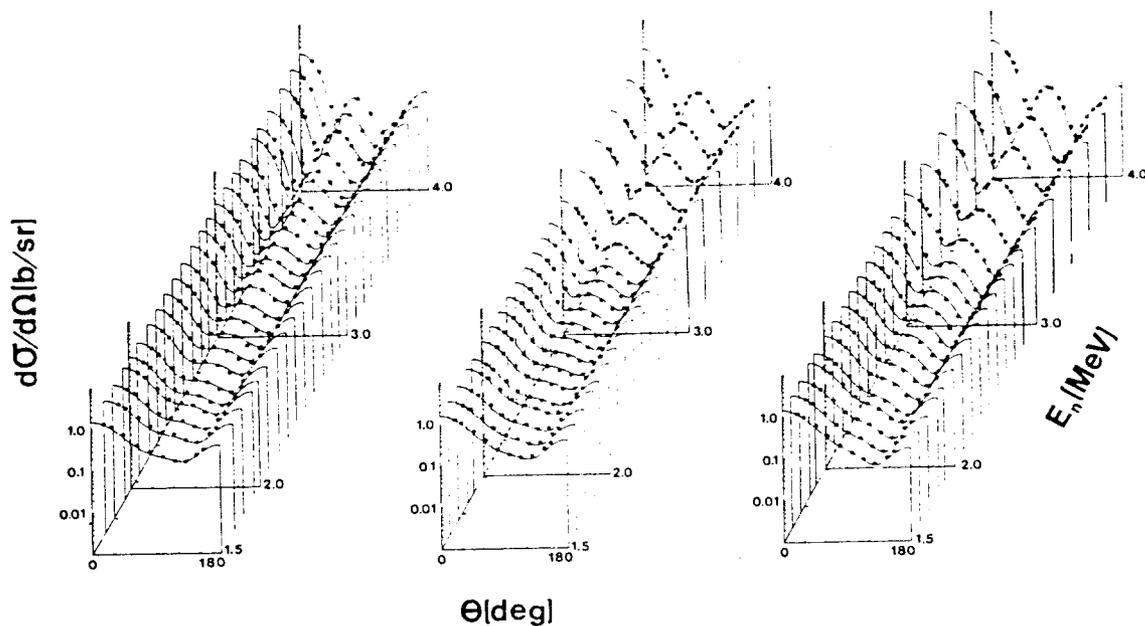
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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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NUCLEAR DATA FOR FUSION. Fusion nuclear data needs. Status review. Cross sections. Radioactive decay properties. Activation processes. Scattering processes. Transmutation processes. Radiation-damage processes. Fuel-cycle processes. Fuel-breeding processes. Neutron-multiplication processes. Kerma. Data measurements. Nuclear-model calculations. Evaluations. A strategy for improving the data base of dosimetry and activation reactions.

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PREFACE

We were invited by the Conference Chairman, Dr. S.M. Qaim, on the advice of his Program Committee, to prepare a review paper on the status of fusion nuclear data for presentation at the International Conference on Nuclear Data for Science and Technology, which was held at Juelich, Germany, on 13-17 May 1991. The paper which was prepared in response to this request appeared as a poster at this conference, and this poster presentation was preceded by an oral introduction [CS91]. In addition, a written version of the paper appears in the formal conference proceedings. The latter, however, is quite abbreviated by the necessary imposition of a severe limitation on the number of pages (a maximum of 6 camera-ready pages per invited contribution). Consequently, it was not possible to include in those few allotted pages the wealth of detailed information and comments which had been gathered during the course of preparing the conference contribution.

The purpose of this report is, therefore, to formally document all of these original notes so that they can serve as a permanent record of the review exercise, for the benefit of those interested readers who wish to know more than could be included in the written conference paper. Beyond that, we offer some suggestions concerning a possible strategy for further improving the nuclear data base associated with those processes which are important for fusion dosimetry and certain other activation concerns. What we recommend here is a well-coordinated effort involving measurements, nuclear modeling, and data evaluation based on the use of well-established statistical analysis procedures for the merging of both objective (experimental) and subjective (theoretical) information. In our view, strong emphasis should be placed on encouraging international cooperative endeavors to aid in achieving these goals in a timely and cost-effective manner. This is particularly appropriate given the contemporary environment of restricted resources, worldwide, for nuclear data development.

The style of this report is quite informal, as we feel is appropriate for an exposition of such a collection of technical notes. Of course, we have edited these original notes somewhat to provide for a logical, orderly presentation of the subject matter, and to insure that the textual portions of the document can be read easily. With these modest provisos, all of our original material from the notes appears intact and unaltered herein, including several tables which were either left out of the conference paper or were condensed and consolidated there for the sake of compactness. Although a few references are included here for general interest, we have made no attempt to systematically credit all of the material which influenced the outcome of this review. This was done, quite honestly, for our own convenience. We hope no authors will be slighted by such omissions.

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ABSTRACT

A review was performed on the needs and status of nuclear data for fusion-reactor technology. Generally, the status of nuclear data for fusion has been improved during the past two decades due to the dedicated effort of the nuclear data developers. However, there are still deficiencies in the nuclear data base, particularly in the areas of activation and neutron scattering cross sections. Activation cross sections were found to be unsatisfactory in 83 of the 153 reactions reviewed. The scattering cross sections for fluorine and boron will need to be improved at energies above 1 MeV. Suggestions concerning a strategy to address the specific fusion nuclear data needs for dosimetry and activation are also provided.

1. INTRODUCTION

E.T. Cheng has reviewed the contemporary nuclear data needs for fusion in a recent paper presented at the 7th ASTM-EURATOM Dosimetry Symposium [Che90a]. He also reported on these data needs at the DOE Fusion Nuclear Data Program Review which was held at Ohio University in 1989 [Che90b]. The scope of the present survey is defined mainly by the needs expressed in his documents. The territory covered by the present review is very large. Consequently, it was out of the question in the present situation for us to undertake a detailed, in-depth survey. From a practical point of view, the resources (time and manpower) to do so simply were not available to us. The last time such a task was pursued in great detail was in the work of O.N. Jarvis (Harwell, U.K.) about one decade ago. The results of this monumental investigation have been published as a formal report [Jar81]. Unfortunately, the content of this earlier report is now quite out of date.

The objective of our present work was to accomplish a relatively modest (by comparison to the work of Jarvis) but nevertheless wide-ranging survey of the status of those nuclear data needs which have been highlighted by the work of Cheng (see above). The emphasis here has been on reactions induced by neutrons and, in some instances, by light ions. Attention was given to both cross sections and relevant decay data. We made no effort to examine photon interaction cross sections or neutron-induced gamma-ray production data, although both are undeniably important for fusion technology. Photon-interaction cross sections are quite well understood from fundamental principles (e.g., see work from NIST by M.J. Berger [Ber+90]). Detailed procedures for calculating these cross sections have been reported in the literature. Furthermore, useful compilations of recommended photon-interaction cross sections have been published. In short, this does not seem to pose much concern for fusion applications. As for neutron-induced gamma-ray production cross sections, that is another matter. While procedures do exist for estimating the relevant parameters, based mostly on energy-balance considerations, relatively fewer experimental data are available for gamma-ray production than are to be found for other classes of neutron reaction cross sections. Since photon production is an important issue in fusion, a lot of work will need to be done to sort out this problem. However, we chose not to deal with this issue in the present investigation. Finally, we decided to avoid undertaking an explicit review of the contemporary data base for radioactive decay parameters, although this is an important issue which cannot be divorced from cross-section considerations for fusion. Instead, we opted for making a few comments on critical decay data issues that impact directly on the determination of cross sections, since we could not avoid touching upon this issue in tackling our stated goal. As is well known, there is an on-going, multi-national evaluation effort in this area (the "A-Chain" Project) which labors to examine all the decay data on a continuous, rotational basis by mass number (with a cycle time of

about 6-8 years). Also, the International Atomic Energy Agency (IAEA) maintains an effort in this area under the auspices of the Nuclear Data Section [Lor86].

The present review is based on our examination of several standard reference works which we felt would provide a good sampling of the status of those nuclear data endeavors relevant to fusion. The interpretation of this information is based mainly on our personal experience, so we bear full responsibility for the conclusions that we put forth in this work. Among the major reference sources which we considered in this investigation are the following:

- Nuclear wallet cards [Tul90]. This document provides information on target and reaction product half lives and decay properties.
- NCRP Radioactivity Measurements Handbook [Man+84]. This book contains decay information (revised to 1984) for many of the more commonly encountered activities in radiation measurements.
- Table of the Isotopes [Led+78]. This work includes general information on a wide range of reaction products, etc. Although the information is rather dated (1978), it is still a very convenient reference for obtaining detailed, decay information on certain of the more exotic radio-isotopes.
- Neutron Cross Sections, Volume II - Curves (hereafter referred to as the Book of Curves) [MDR88]. As the title indicates, this work consists of plots of experimental neutron cross section data, as available at the four international data centers (EXFOR System). ENDF/B curves are plotted when available. Otherwise, eye guides to the data are sometimes provided.
- CINDA [CIN90]. This document appears in several volumes in printed form, and is also available on computer files which can be retrieved from the international data centers. It provides references to the available neutron cross section information over the time interval 1935-90.
- Proceedings of the last three meetings of the DOE Fusion Nuclear Data Program, held at Oak Ridge National Laboratory, Argonne National Laboratory and Ohio University, respectively [HL83,SK86,Gri90].
- Major international nuclear data conference proceedings, i.e., 1979 Knoxville, 1982 Antwerp, 1985 Santa Fe and 1988 Mito [Fow+80,Boe83,You+86,Iga88].
- Three other recent summary reports which were readily available to us proved to be quite useful. These include i) The report on a recent (1990) IAEA-sponsored meeting on long-lived radionuclides

for fusion applications [DaH90], ii) the report on another recent IAEA-sponsored meeting dealing with the FENDL library of cross section data for fusion [PM90], and iii) the proceedings of an NEA-sponsored meeting on neutron activation cross sections for fission and fusion energy applications [WV89].

As mentioned above, we do not claim that our review is as thorough or carefully documented as the work by Jarvis in 1980-1981 [Jar81]. Nevertheless, our present study has the advantage that it is current. We believe that the insight it provides should be adequate to identify the significant strong points and weak points of the contemporary fusion nuclear data base. This, of course, is consistent with our limited objectives for this work. It is well known that there are significant weaknesses in contemporary knowledge of nuclear cross sections for fusion. Beyond that, what is needed is for those specific areas where the deficiencies are most pronounced to be identified so that the limited resources which are available for remedying the situation can be focused effectively to address these needs.

Before addressing specific technical matters, we believe that it is worthwhile examining some of the reasons why the fusion community finds itself in the present predicament, with so many nuclear-data needs apparently unsatisfied. One of the reasons is a purely technical one. The data needs for fusion are, by their very nature, much more extensive than those for fission. This happens because the technology deals with higher neutron energies and, consequently, there are generally more open reaction channels to be considered for each elemental material and isotope. Another technical reason is that fusion technology remains relatively undeveloped by comparison with fission technology. It still has not been clearly established which are the best choices for materials to use in building a fusion reactor. A number of suggested engineering-design options will have to be carefully studied, and the best ones retained as viable possibilities for the foreseeable future. It would be a mistake to pick a particular design approach, to the exclusion of all others, until all of the safety, environmental and economical issues have been thoroughly explored and have withstood the test of time. In order to provide a suitable framework for exploring these various options, nuclear data must be available for a wide range of potential materials that might be used in conceptual fusion-reactor designs.

However, there is another reason why the present status of nuclear data for fusion leaves much to be desired. It is a procedural matter rather than a technical one. We believe it merits an honest discussion. Fusion-nuclear-data research has never received either the emphasis or the allocation of resources from fusion technology programs comparable to what was devoted to fission nuclear data research during the 1960s and 1970s. Then, extensive support for nuclear data development was provided by various national fission reactor programs (the U.S., Canada and several countries in Europe and

the Orient). Many of the nuclear data research facilities and programs now in existence, and most of the techniques which are used for nuclear data research to this day, were developed under these auspices. The fusion programs benefited considerably from this work. Were it not for these earlier programs, the status of nuclear data for fusion would be even poorer than it is now. It is entirely understandable why the fusion community has not given nuclear data (and nuclear issues in general) the emphasis that is merited, in contrast to the experience associated with the development of fission. The principles of fission-energy production were proven long ago (December 1942) by the now-famous demonstration of controlled fission under the West Stands of Stagg Field, University of Chicago. Most of the developmental work in fission technology that has transpired during the 50 years hence has been based on this early work. There were no surprises of major proportions. In fact, large fissile-material production reactors were in operation very shortly after the first proof of principle. In fusion, the situation is vastly different. The crucial proof of principle experiments which will determine whether fusion is a viable controlled-energy source have yet to be completed. The technological problems in the non-nuclear areas (essentially in plasma physics) have been without precedence in the history of technology for their difficulty. The community can indeed be forgiven for perhaps slighting the importance of nuclear issues in the face of such an overwhelming challenge in quite a different area. But, the time is approaching when, in all likelihood, the essential proof of principle for this technology will be achieved. Then, the community will have to start placing a much greater emphasis on the nuclear issues, including the development of fundamental nuclear data. This next important step will have to be forthcoming soon if the ultimate goals of fusion-energy development are to be met, i.e., the development of a safe, environmentally-benign and economically-viable energy source for the centuries ahead.

Basic-nuclear-physics studies of potential energy-source reactions were begun rather early (during the 1940s and 1950s) in support of both fission and fusion-weapons-development programs. The quantitative reliability of these data has been refined considerably since then, but few surprises of dramatic proportions have emerged in the basic physics understanding of these nuclear processes. We mentioned above that fusion demands knowledge of nuclear data at somewhat higher energies than for fission, but their overlap is actually surprisingly large. Here is the reason: Although the mean energy of primary fission-source neutrons is about 2 MeV, there is a long high-energy tail to the approximately Maxwellian distribution of the primary fission-source neutrons. On the other hand, although the source energy of fusion neutrons is about 14 MeV for the most promising process, these neutrons are promptly degraded to a lower average energy through scattering in the reactor structures. This is why the fusion community has been able to benefit from the extensive files of neutron activation and scattering data which were produced under the auspices of the fission-energy development programs. We

should be thankful that this synergism was permitted mankind by the whims of Nature. The most significant new nuclear-data needs which fusion has spawned are for neutron-induced long-lived activities and for certain $(n,2n)$ reactions associated neutron multiplication in fusion blankets. Fast-neutron activation has not been as serious a concern in fission technology because the residual activity of the fission products generated in the fuel assemblies is clearly the overwhelming radioactivity problem which that technology must address. Furthermore, neutron-induced activities in the structural components are a lesser concern in fission than they are for fusion because the average neutron energy in fission reactors is, indeed, considerably lower than for fusion reactors.

There are also social and environmental issues to be considered. Fusion has been promoted as a "clean" energy source because the most promising fuel cycles do not involve radioactive isotopes (exclusive of tritium). However, the public image of fusion as a "clean" energy source could be tarnished readily if the production of activities in structural components of fusion reactor assemblies meant that it would be difficult (and costly) to service or decommission these devices and, ultimately, to dispose of the radioactive wastes. This is a legitimate concern, and it has led to the generation of many new requests for activation nuclear data.

In spite of these major concerns, however, there is still no evidence of a serious commitment from fusion energy technology programs to provide a level of financial support for facilities and programs which would be appropriate to meet the documented needs. Again, the reason is quite understandable in view of the comments made above. In the U.S., most of the relevant support for nuclear-data research comes from the basic nuclear physics research branch of DOE, but the level of effort there is too modest in view of the scope of the problem. What the fusion technology community appears to be doing is trying to "get by" in meeting their needs in the nuclear-data area by encouraging (and in some cases coordinating and/or funding) some small-scale research projects which it hopes will be successfully carried out by an assortment of nuclear-data-research groups who generally receive their main support under other auspices. Promotion of these projects, which often are quite international in their organization, and are also relatively limited in their scope, has been embraced as an approach for addressing fusion-related data problems associated with various specific, technical issues which emerge. These specific concerns are in a state of constant flux, corresponding to an environment of ever changing fusion-reactor-design fashions, concepts or emphases. Many of the data requests end up being forgotten, or are otherwise abandoned, before they are adequately solved by the nuclear data community. This state of affairs is greeted with considerable skepticism by the nuclear data community, and many of the requests are not taken seriously. When serious attempts are made by individual research groups to meet certain data needs, which are then ultimately

rejected as no longer relevant, the scientists involved are usually discouraged from pursuing other fusion data problems in the future. In short, the fusion nuclear data effort has lacked coherence and a sense of long-term commitment which are both needed to insure that the broad, fundamental nuclear data issues will ultimately receive the professional attention that they deserve. Also, this "topic-by-topic" or, more aptly, "crisis-by-crisis" approach, with limited objectives, and even more limited allocated resources, has failed to foster a nurturing environment which is essential for the development of a cadre of young, sophisticated and highly-skilled technical personnel who possess a knowledge of the relevant techniques and have convenient access to those facilities which are needed to insure that these problems can be adequately addressed during the next few decades. The present state of affairs has had quite the opposite effect in that it has tended to turn talented people against considering this area of scientific work, in favor of the pursuit of more promising opportunities and working conditions to be found in other fields. The fusion technology community must come to recognize that these crucial human and facility resources require long lead times to develop. Once developed, these capabilities need to be maintained at a healthy level to insure responsiveness to the new, unforeseen problems which are certain to emerge in the future. The needs which are represented in the list of requests which we addressed in preparing this report is not all-inclusive. They will surely change and evolve dramatically over time.

Our main premise in approaching the present survey is that specific, nuclear parameters cannot be presumed to be well known unless there is available a reasonable body of good-quality experimental information which is relevant to the processes in question. Nuclear model calculations, which are often incorporated in data evaluations for fusion, may be useful for "estimating" the parameters in qualitative fashion, but the uncertainties can exceed factors of two quite easily for most of the complex reaction processes in question, unless there is solid guidance from experiments. It is unfortunate, then, that much of the already very-limited support for nuclear data which does come from the fusion programs is allocated to supporting nuclear-model calculations and evaluations while, at the same time, relegating experimental measurements to a more or less subordinate role. The model-calculation approach is understandably appealing to program planners because large quantities of information can be generated in a relatively short time at quite a low cost. Furthermore, certain desirable consistencies in the generated information are assured (energy balance, partial cross sections summing to total cross sections, etc.). But can the individual results be trusted to be correct? Can we base our confidence in the ultimate safety and economic viability of this important future technology on the basis of information derived mainly from investigations of such a subjective (theoretical) nature? Indeed, our experiences to date with the reliability of model calculations which are not substantiated by data should be cause to remain very unconvinced that the data needs for fusion can be adequately satisfied by nuclear modeling alone.

Consequently, those comments on the status of nuclear data which we put forth in this report are based mainly on the existence and perceived status of the experimental data base, not on the availability of nuclear model results or of specific evaluations which are based largely on nuclear models.

The approach which we take in the present investigation is to draw some qualitative conclusions concerning the status of requisite nuclear data for fusion. Usually a subjective judgment is made as to whether a particular situation is "adequate", "marginal" or "inadequate". It must be kept in mind that these judgments are strictly contemporary in nature, and the situation may well change on short notice depending upon the availability of new information or on an increase or decrease in the stringency of a particular data requirement. The intent of our work is to provide those individuals who work on the design and development aspects of fusion energy research with some insight on the status of the nuclear data which they may require for particular applications. This work should also serve to guide nuclear-data producers as to those particular areas where their efforts might be productively devoted to meeting the contemporary needs.

2. HIGH-PRIORITY NEUTRON DOSIMETRY PROCESSES

A list of the nuclear processes which are suggested for use in fusion dosimetry applications has been prepared by Cheng [Che90a,Che90b]. It appears in Table 1. The individual factors which must be considered in analyzing the status of data for these processes are discussed below:

Half Lives:

When the reaction product is unstable, then knowledge of the half life is a very important issue. It is of particular concern for the relatively short half lives associated with those reactions used in fusion diagnostics applications. These measurements can often span a number of half lives, thereby leading to an amplification of the decay activity uncertainty through the influences of the exponential decay law. The establishment of required accuracies is therefore quite subjective. For example, if the half life is known to 0.2% accuracy but knowledge of the activity is needed after 5 half lives, then its uncertainty will be nearly 1%. It is not unreasonable to require knowledge of the activity of a specimen to 1% or better, so we are led to the conclusion that a half-life uncertainty of 0.2% is unacceptable in this case. The half-life status for each of the pertinent reaction products is reviewed here using the Nuclear Wallet Cards [Tul90].

Reaction No. 1: $O-16(n,\alpha)C-13$

C-13 is stable. This is not a relevant issue.

Reaction No. 2: $Mg-24(n,p)Na-24$

The half life = 14.9590 h ($\pm 0.008\%$) which is very well known. This is not an issue for practical purposes.

Reaction No. 3: $Al-27(n,p)Mg-27$

The half life = 9.462 m ($\pm 0.1\%$) which is quite well known. This is probably not an issue for most practical purposes.

Reaction No. 4: $Al-27(n,\alpha)Na-24$.

The situation is the same as for Reaction No. 2.

Reaction No. 5: $Si-28(n,p)Al-28$

The half life = 2.2414 m ($\pm 0.05\%$) which is quite well known. This is not an issue for practical purposes.

Reaction No. 6: $P-31(n,p)Si-31$

The half life = 157.3 m ($\pm 0.2\%$). This uncertainty could be a problem for some applications. The situation needs improvement.

Reaction No. 7: $Cl-35(n,2n)Cl-34m$

The half life = 32.00 m ($\pm 0.1\%$) which is reasonably well known. This is probably not an issue for most practical purposes.

- Reaction No. 8: K-39(n,2n)K-38
The half life = 7.636 m (\pm 0.2%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 9: Ti-47(n,p)Sc-47
The half life = 3.345 d (\pm 0.09%) which is quite well known. This is not an issue for practical purposes.
- Reaction No. 10: Ti-48(n,p)Sc-48
The half life = 43.7 h (\pm 0.2%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 11: Fe-56(n,p)Mn-56
The half life = 2.5785 h (\pm 0.008%) which is very well known. This is not an issue for practical purposes.
- Reaction No. 12: Ni-58(n,2n)Ni-57
The half life = 35.65 h (\pm 0.1%) which is quite well known. This is not an issue for practical purposes.
- Reaction No. 13: Co-59(n,alpha)Mn-56.
The situation is the same as for Reaction No. 11.
- Reaction No. 14: Cu-63(n,gamma)Cu-64
The half life = 12.701 h (\pm 0.02%) which is very well known. This is not an issue for practical purposes.
- Reaction No. 15: Cu-63(n,2n)Cu-62
The half life = 9.74 m (\pm 0.2%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 16: Zn-64(n,p)Cu-64.
The situation is the same as for Reaction No. 14.
- Reaction No. 17: Zn-64(n,2n)Zn-63.
The half life = 38.50 m (\pm 0.2%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 18: Rb-85(n,2n)Rb-84m
The half life = 20.26 m (\pm 0.2%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 19: Zr-90(n,p)Y-90m
The half life = 3.19 h (\pm 0.3%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 20: Zr-90(n,2n)Zr-89m
The half life = 4.18 h (\pm 0.2%). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 21: Rh-103(n,n')Rh-103m
The half life = 56.12 m (\pm 0.02%) which is very well known. This is not an issue for practical purposes.

- Reaction No. 22: In-115(n,gamma)In-116m
The half life = 54.41 m ($\pm 0.06\%$) which is quite well known. This is not an issue for practical purposes.
- Reaction No. 23: In-115(n,n')In-115m
The half life = 4.486 h ($\pm 0.09\%$) which is quite well known. This is not an issue for practical purposes.
- Reaction No. 24: Au-197(n,gamma)Au-198
The half life = 2.6935 d ($\pm 0.01\%$) which is very well known. This is not an issue for practical purposes.
- Reaction No. 25: Au-197(n,2n)Au-196
The half life = 6.186 d ($\pm 0.2\%$). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 26: Hg-199(n,n')Hg-199m
The half life = 42.6 m ($\pm 0.5\%$). This uncertainty could be a problem for some applications. The situation needs improvement.
- Reaction No. 27: U-235(n,f)
There are a variety of fission products, with assorted half lives. The data requests do not specify which are of interest. Dosimetry often involves direct measurement of fission fragments, in which case half lives of fission products are not relevant. The half life of U-235 can be an issue in sample mass assay. The half life of U-235 = 7.038×10^8 y ($\pm 0.07\%$) which is very well known. This is not an issue for practical sample assay purposes.
- Reaction No. 28: Np-237(n,f)
There are a variety of fission products, with assorted half lives. It was not specified which are of interest. Dosimetry often involves direct measurement of fission fragments, in which case half lives of fission products are not relevant. The half life of Np-237 can be an issue in sample mass assay. The half life of Np-237 = 2.14×10^6 y ($\pm 0.5\%$). This is probably adequately known for most practical sample assay purposes, however some applications might require better accuracy.
- Reaction No. 29: U-238(n,f)
There are a variety of fission products, with assorted half lives. It was not specified which are of interest. Dosimetry often involves direct measurement of fission fragments, in which case half lives of fission products are not relevant. The half life of U-238 = 4.468×10^9 y ($\pm 0.07\%$) which is very well known. This is not an issue for practical sample assay purposes purposes.

The results of this review of half lives appear in Table 2.

Decay Branching Parameters:

Knowledge of the decay-branching factors for radioactive reaction products is very important. It affects the way the production rates are measured and impacts on other technological issues as well. The status of decay-branching information, as reviewed here, is generally based on the NCRP Radioactivity Measurements Handbook [Man+84] and Table of the Isotopes [Led+78]. The former is current to 1984 and the latter to 1978. Some of the deficiencies in knowledge of these parameters may have been resolved as a result of recent work but, since effort in this field has been modest at best during the last decade, these exceptions are unlikely to be very extensive. We decided at the outset of this project that for us to research each such issue in the current literature would demand more extensive resources of time and manpower than were available for the conduct of this survey. Furthermore, we felt that expenditure of the extra effort would not alter the conclusions of this work materially.

Reaction No. 1: $O-16(n,\alpha)C-13$
C-13 is stable. This is not a relevant issue.

Reaction No. 2: $Mg-24(n,p)Na-24$
Decay: Beta [100%]
Gammas: 1.369 MeV [100%]
Others (watch for coincidence summing)
The decay scheme is very well known and thus is adequate for dosimetry applications.

Reaction No. 3: $Al-27(n,p)Mg-27$
Decay: Beta [100%]
Gammas: 0.844 MeV [(71.8 ± 0.4)%]
Others (watch for coincidence summing)
The decay scheme is quite well known and thus is adequate for dosimetry applications.

Reaction No. 4: $Al-27(n,\alpha)Na-24$.
Decay: Beta [100%]
Gammas: 1.369 MeV [100%]
Others (watch for coincidence summing)
The decay scheme is very well known and thus is adequate for dosimetry applications.

Reaction No. 5: $Si-28(n,p)Al-28$
Decay: Beta [100%]
Gammas: 1.779 MeV [100%]
The decay scheme is very well known and thus is adequate for dosimetry applications.

Reaction No. 6: P-31(n,p)Si-31

Decay: Beta [100%]

Gammas: Negligible

The decay scheme is well known. Since the gamma yield is negligible, the usefulness for modern dosimetry applications is questionable.

Reaction No. 7: Cl-35(n,2n)Cl-34m

Decay: Beta [53.4%], EC [46.6%]

Gammas: 2.127 MeV [(42 ± 1)%]

Others (watch for coincidence summing)

The decay scheme needs to be better known. The primary gamma yield is inadequately known for modern dosimetry applications. These comments are based on Table of the Isotopes (1978).

Reaction No. 8: K-39(n,2n)K-38

Decay: EC [100%]

Gammas: 2.168 MeV [(99.80 ± 0.03)%]

Others (watch for coincidence summing)

The decay scheme is very well known and thus is adequate for dosimetry applications.

Reaction No. 9: Ti-47(n,p)Sc-47

Decay: Beta [100%]

Gammas: 0.159 keV [(69.0 ± 0.7)%].

This is based on recent PTB information. The decay scheme is quite well known but knowledge of the gamma yield per decay needs some refinement. The situation is marginally adequate for dosimetry applications.

Reaction No. 10: Ti-48(n,p)Sc-48

Decay: Beta [100%]

Gammas: 0.984 MeV [100%]

Others (watch for coincidence summing)

The decay scheme is quite well known and thus is adequate for dosimetry applications.

Reaction No. 11: Fe-56(n,p)Mn-56

Decay: Beta [100%]

Gammas: 0.847 MeV [(98.8 ± 0.3)%]

Others (watch for coincidence summing)

The decay scheme is quite well known and thus is adequate for dosimetry applications.

Reaction No. 12: Ni-58(n,2n)Ni-57

Decay: Positron [43%], EC [57%]

Gammas: 1.378 MeV [(98.8 ± 0.3)%]

Others (watch for coincidence summing)

The decay scheme is reasonably well known and thus is adequate for most dosimetry applications.

Reaction No. 13: Co-59(n,alpha)Mn-56.

Decay: Beta [100%]

Gammas: 0.847 MeV [(98.8 ± 0.3)%]

Others (watch for coincidence summing)

The decay scheme is quite well known and thus is adequate for dosimetry applications.

Reaction No. 14: Cu-63(n,gamma)Cu-64

Decay: Positron [17.9%], EC [44.8%], Beta [37.3%]

Gammas: 1.346 MeV [(0.472 ± 0.018)%]

The decay scheme is complex and difficult to deal with. Measurement of annihilation radiation is problematic because the exact position of annihilation in the sample or neighboring environment is hard to determine. The 1.346-MeV gamma-ray branch is weak and not too well known. We conclude that the decay process needs to be better known, and methods for using it with good accuracy need to be developed. The situation is only marginally adequate for dosimetry applications.

Reaction No. 15: Cu-63(n,2n)Cu-62

Decay: Positron [97.2%], EC [2.8%]

Gammas: 1.173 MeV [(0.342 ± 0.014)%]

The decay scheme is complex and difficult to deal with. Measurement of annihilation radiation is problematic because the exact position of annihilation in the sample or neighboring environment is hard to determine. The 1.173-MeV gamma-ray branch is weak and not too well known. We conclude that the decay process needs to be much better known, and methods for using it with good accuracy developed. The situation is inadequate for dosimetry applications.

Reaction No. 16: Zn-64(n,p)Cu-64.

Decay: Positron [17.9%], EC [44.8%], Beta [37.3%]

Gammas: 1.346 MeV [(0.472 ± 0.018)%]

The decay scheme is complex and difficult to deal with. Measurement of annihilation radiation is problematic because the exact position of annihilation in the sample or neighboring environment is hard to determine. The 1.346-MeV gamma-ray branch is weak and not too well known. We conclude that the decay process needs to be better known, and methods for using it with good accuracy developed. The situation is marginally adequate for dosimetry applications.

Reaction No. 17: Zn-64(n,2n)Zn-63.

Decay: Positron [92.9%], EC [7.1%],

Gammas: 0.670 MeV [(8.4 ± 0.4)%]

Others (watch for coincidence summing)

The decay scheme is complex and difficult to deal with. Measurement of annihilation radiation is problematic because the

exact position of annihilation in the sample or neighboring environment is hard to determine. The 0.670-MeV gamma-ray branch is not too weak, but it is still poorly known. We conclude that the decay process needs to be much better known, and methods for using it with good accuracy developed. The situation is inadequate for dosimetry applications.

Reaction No. 18: Rb-85(n,2n)Rb-84m

Decay: IT [100%]

Gammas: 0.248 MeV [(64.5 ± 0.2)%]

Others (watch for coincidence summing)

The decay scheme is reasonably well known and thus is probably adequate for dosimetry applications.

Reaction No. 19: Zr-90(n,p)Y-90m

Decay: IT [$> 99\%$], Beta [Very small]

Gammas: 0.480 MeV [(91 ± 4)%]

Others (watch for coincidence summing)

This decay scheme is poorly known and thus is inadequate for dosimetry applications.

Reaction No. 20: Zr-90(n,2n)Zr-89m

Decay: Beta [1.5%], EC [4.7%], IT [93.8%]

Gammas: 0.588 MeV [(89.5 ± 0.5)%]

The decay scheme is fairly well known and thus is probably adequate for dosimetry applications.

Reaction No. 21: Rh-103(n,n')Rh-103m

Decay: IT [100%]

Gammas: Negligible

The activity measurements must be based on detection of X-rays associated with internal conversion. The uncertainties in the yields of K-alpha and K-beta X-rays are several percent. We consider this to be inadequate for dosimetry applications.

Reaction No. 22: In-115(n,gamma)In-116m

Decay: Beta [100%]

Gammas: 1.294 MeV [(84.4 ± 1.8)%]

Others (watch for coincidence summing)

The decay scheme is very complicated and its quantitative knowledge is of marginal accuracy. Thus the status is marginal for dosimetry applications.

Reaction No. 23: In-115(n,n')In-115m

Decay: IT [95.0%], Beta [5.0%]

Gammas: 0.336 MeV [(45.8 ± 0.5)%]

The decay scheme is reasonably well known and is thus considered as adequate for dosimetry applications.

Reaction No. 24: Au-197(n,gamma)Au-198

Decay: Beta [100%]

Gammas: 0.411 MeV [(95.59 ± 0.13)%]

Others (watch for coincidence summing)

The decay scheme is very well known and thus is adequate for dosimetry applications. This reaction is frequently used in fission reactor physics investigations.

Reaction No. 25: Au-197(n,2n)Au-196

Decay: EC [93.0%], Beta [7.0%], Positron [Negligible]

Gammas: 0.356 MeV [(87.6 ± 0.1)%]

Others (watch for coincidence summing)

The decay scheme is quite well known and thus is adequate for dosimetry applications.

Reaction No. 26: Hg-199(n,n')Hg-199m

Decay: IT [100%]

Gammas: 0.158 MeV [(52.3 ± 0.5)%]

Others (watch for coincidence summing)

The decay scheme is fairly well known and thus is probably adequate for dosimetry applications.

Reaction No. 27: U-235(n,f)

There are a variety of fission products. No comment can be made on the decay properties for dosimetry without knowing which species are being considered. Dosimetry often involves direct measurement of U-235 fission fragments, in which case the decay schemes of the fission products are not relevant.

Reaction No. 28: Np-237(n,f)

There are a variety of fission products. No comment can be made on the decay properties for dosimetry without knowing which species are being considered. Dosimetry often involves direct measurement of Np-237 fission fragments, in which case the decay schemes of the fission products are not relevant.

Reaction No. 29: U-238(n,f)

There are a variety of fission products. No comment can be made on the decay properties for dosimetry without knowing which species are being considered. Dosimetry often involves direct measurement of fission fragments, in which case the decay schemes of the fission products are not relevant.

The results of this review of decay properties appear in Table 3.

Reaction Cross Sections:

Knowledge of the differential neutron reaction cross sections for the dosimetry reactions is needed in order to apply the conventional methods. These cross sections are surveyed here mainly with the aid of

CINDA [CIN90] and Neutron Cross Sections, Vol. II - Curves [MDR88]. These documents provide a reasonable overview of the status of available experimental data for the dosimetry reactions.

One of the main problems associated with reviewing these cross sections is that the requirements, in terms of neutron energy range, are not well established in the request lists. The primary neutrons from the D-T fusion process (which is the most important one for power production) are approximately 14 MeV, but there is also concern in dosimetry for measuring the energy-degraded neutrons which are abundant beyond the first wall of the fusion plasma chamber. In general, the interest here is for fast neutrons rather than in the resonance or thermal regions.

Reaction No. 1: $^{16}\text{O}(n,\alpha)^{13}\text{C}$

There is an extensive experimental data base for this reaction reported in the literature, according to CINDA. These are also plotted in the Book of Curves. Many of the data correspond to energies below 7 MeV, but there is considerable information at 14 MeV as well as scattered points elsewhere up to 20 MeV. The reaction was recently evaluated for ENDF/B-VI. The low energy data show considerable structure (up to several MeV). At higher energies, where there is less structure, the data are somewhat sparse. It is hard to comment on the adequacy of these data without knowing exactly what the ultimate application will be. Consequently, the situation should probably be considered as marginal for dosimetry applications.

Reaction No. 2: $^{24}\text{Mg}(n,p)^{24}\text{Na}$

There are extensive data up to 20 MeV, most of it quite consistent. Recent results from several laboratories agree well. The cross section has also been evaluated lately at IRK-Vienna. We consider the status as adequate for dosimetry purposes.

Reaction No. 3: $^{27}\text{Al}(n,p)^{27}\text{Mg}$

This cross section exhibits some structure in the few-MeV energy range. However, there are extensive data for that region and they are reasonably consistent. The region around 14 MeV remains a problem. A recent measurement at Argonne should be quite reliable, but attempts to evaluate the body of largely discrepant data near 14 MeV have led to rather large errors. There are apparently very few data between 10 and 14 MeV. We believe the situation should be treated as marginal for dosimetry purposes.

Reaction No. 4: $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$

This is considered to be one of the best known of the dosimetry reactions, especially around 14 MeV where it can be treated as a standard. Recent results at other energies below 14 MeV are reasonably consistent with the earlier body of work so that the cross section is well known there as well. In fact, it is quite

well known up to 20 MeV too. We consider this as adequate for dosimetry applications.

Reaction No. 5: Si-28(n,p)Al-28

There are extensive data below 8 MeV, but the presence of structure leads to a considerable level of uncertainty. There are also extensive data from 12-18 MeV, particularly around 14 MeV, but they scatter quite noticeably. An attempt was made previously to evaluate the data at around 14 MeV, but the existence of considerable inconsistency in these results guarantees that the cross section is not very well known there. There are essentially no data from 8 to 12 MeV. So, the existing data base leads us to the conclusion that our knowledge of this cross section for dosimetry purposes is marginal at best and possibly inadequate.

Reaction No. 6: P-31(n,p)Si-31

There are extensive data below 8 MeV, but the presence of structure leads to considerable uncertainty. There are also extensive data from 12-18 MeV, particularly around 14 MeV, but they scatter quite a bit. There are practically no data from 10-12 MeV. This reaction suffers from the presence of structure in the MeV range, and from the fact that Si-31 is difficult to measure because it is only beta active (no gamma rays). S-31 was not re-evaluated for ENDF/B-VI, so the existing evaluation is at least ten years old. It is not clear why this reaction is retained by the fusion community as a potential dosimeter when there are better choices. If it is to be retained, the data base would indicate that it be considered as marginal to inadequate.

Reaction No. 7: Cl-35(n,2n)Cl-34m

There are extensive data around 14 MeV, but they scatter greatly. No measurements have been made to define the cross section in the threshold region below 14 MeV. One data set at higher energies (up to 22 MeV) exhibits a very odd shape and should be treated as suspect. Chlorine has not been re-evaluated for ENDF for many years, so the basis for this evaluation has to be antiquated. Clearly, knowledge of this cross section must be considered as inadequate for serious dosimetry work.

Reaction No. 8: K-39(n,2n)K-38

The shape of this cross section is pretty well defined by experimental data from threshold to 14 MeV. Around 14 MeV there are several data sets with no worse scatter than typical for this sort of reaction, and possibly somewhat better. Elemental K has not been re-evaluated for ENDF/B-VI (K-39 is the dominant isotope). Therefore, knowledge of this cross section is marginal if we are seeking precise dosimetry results, but it might be adequate for qualitative dosimetry applications in fusion.

Reaction No. 9: Ti-47(n,p)Sc-47

This reaction has been studied extensively below 10 MeV and is now quite well known near threshold due to work at Argonne and PTB. The situation is much worse at higher energies, including the region around 14 MeV, because there exists a lot of confusion concerning whether the yield for this reaction was measured or that for Ti(n,x)Sc-47 was measured. This issue must be resolved before this reaction can be considered useful for dosimetry work at the upper end of the fusion energy range (> 10 MeV). Therefore, depending upon the application, we should treat the knowledge of this as reaction as marginal/inadequate to adequate.

Reaction No. 10: Ti-48(n,p)Sc-48

The data base for this reaction is extensive, and it covers essentially all energies from threshold to 20 MeV. The data are sparse in the 10-12 MeV range, but the cross section does not exhibit any structure in that region so it isn't a serious problem. Around 14 MeV there is scatter, but the data have been evaluated with reasonable results. Therefore, we shall consider this reaction to be adequate for dosimetry applications.

Reaction No. 11: Fe-56(n,p)Mn-56

There exists an extensive data base for this reaction from threshold to over 20 MeV (except for the usual sparseness in the 10-12 MeV range). The better quality measurements are reasonably consistent. Around 14 MeV, the data have been evaluated relative to well-substantiated standards and they are found to be quite consistent. Finally, the data have been re-evaluated for ENDF/B-VI. Therefore, we shall consider our knowledge of this reaction as adequate for fusion dosimetry applications.

Reaction No. 12: Ni-58(n,2n)Ni-57

There are extensive data for this reaction up to 20 MeV, but serious discrepancies lead to significant uncertainties in the knowledge of this cross section above 15 MeV. However, this region is not a particular concern for fusion dosimetry. Furthermore, this reaction has been evaluated recently by several groups. Most recently, it has been included in a re-evaluation for ENDF/B-VI. Therefore, we shall consider it to be adequately known for fusion dosimetry purposes.

Reaction No. 13: Co-59(n,alpha)Mn-56.

An extensive data base exists for this reaction from threshold to well over 20 MeV. Most of these data are consistent. Furthermore, it was recently re-evaluated for ENDF/B-VI by Argonne. We shall consider this reaction to be adequately known for fusion dosimetry.

Reaction No. 14: Cu-63(n,gamma)Cu-64

Some data exist for this reaction below 4 MeV and there is information available at 14 MeV. However, it cannot be said that the cross section is sufficiently well known for dosimetry applications. There is a question as to the general utility of this reaction for dosimetry. It is certainly not useful for higher energies, and there are superior low-energy dosimeters. Therefore, it is suggested that the need for this reaction for fusion dosimetry be re-examined by the fusion community.

Reaction No. 15: Cu-63(n,2n)Cu-62

There are extensive data available for this reaction. They define the cross section from threshold to over 20 MeV. The information around 14 MeV is reasonably consistent. Furthermore, Cu-63 has been re-evaluated for ENDF/B-VI. Therefore, we shall consider this reaction to be adequately known for fusion dosimetry applications.

Reaction No. 16: Zn-64(n,p)Cu-64

There are extensive data for this reaction from threshold to 20 MeV. Unfortunately, there is a serious discrepancy problem in the 5-10 MeV range. The extensive data in the 14-MeV range have been evaluated on several occasions with reasonable consistency observed. Therefore, we have to consider how this reaction is to be used. If the dosimetry is only for 14-MeV neutrons, then it is probably adequate. On the whole, we must treat it as marginally adequate because of the discrepancy problems at other energies.

Reaction No. 17: Zn-64(n,2n)Zn-63

Extensive data are available from threshold to 20 MeV. However, it is apparent that they scatter considerably. This showed up in comparing evaluations in the vicinity of 14 MeV, where significant differences were observed depending on how the data were treated. Consequently, we view this reaction as being adequate to marginal for dosimetry applications. More work is needed to resolve the discrepancies and reduce the scatter.

Reaction No. 18: Rb-85(n,2n)Rb-84m

There are a number of reported data points in the vicinity of 14 MeV, but the existing information is not adequate to define the shape of the cross section toward threshold. Furthermore, the information which is available appears to be very discrepant. We have to treat this reaction as being inadequate for fusion dosimetry.

Reaction No. 19: Zr-90(n,p)Y-90m

Data are reported in CINDA on the Zr-90(n,p) reaction and in the Book of Curves, but it is not quite clear what pertains to the

isomer, what applies to the ground state and what involves both taken together. To sort this out would require a careful survey of the literature. Such an effort is in progress at Argonne for a new evaluation of Zr which will be introduced as a modification to ENDF/B-VI. At the present time, we have to consider our knowledge of this reaction cross section as inadequate for fusion dosimetry applications.

Reaction No. 20: Zr-90(n,2n)Zr-89m

Data are reported on the Zr-90(n,2n) reaction in CINDA and in the Book of Curves, but it is not quite clear what pertains to the isomer, what applies to the ground state and what involves both taken together. In order to sort this out it would be necessary to carefully survey the literature. Such an effort is in progress at Argonne for a new evaluation of Zr which will be introduced as a modification to ENDF/B-VI. At the present time, we have to consider our knowledge of this reaction cross section as inadequate for fusion-dosimetry applications.

Reaction No. 21: Rh-103(n,n')Rh-103m

Extensive data exist for this reaction, but there are some uncertainties in the cross section owing to difficulties in measuring the activity via X-ray counting. This same problem would impact on any attempts to use this reaction for fusion dosimetry, so it should be questioned as to whether it is worth the bother. The cross section has not been re-evaluated for ENDF/B-VI, so the existing evaluated information is probably at least a decade old. On the basis of these considerations, we have to consider this reaction as being marginally adequate for dosimetry, and we should also label it as hard to use.

Reaction No. 22: In-115(n,gamma)In-116m

In spite of the difficulties associated with the decay scheme, this reaction is probably one of the better-known capture-activation reactions for the dosimetry of low-energy neutrons. It has not been re-evaluated for ENDF/B-VI, so the available evaluated information is at least a decade old. In spite of these qualifications, we shall consider this as adequately known for fusion dosimetry, so long as we realize that this recommendation applies mainly for neutrons with energies of a few MeV or lower.

Reaction No. 23: In-115(n,n')In-115m

There is an extensive data base for this reaction, from threshold to 20 MeV. Most of the available information is consistent. It was recently evaluated at Argonne for ENDF/B-VI. Therefore, we shall consider it as adequate for dosimetry applications. However, a warning should be heeded. There is some indication that photo-excitation of the isomer can produce misleading neutron-dosimetry results when measurements are made in a very intense field of relatively high-energy photons (several-MeV

energy). This claim has not been completely substantiated, but one ought to be aware of the possibility when considering this reaction.

Reaction No. 24: Au-197(n,gamma)Au-198

This reaction is one of the primary standards, but only for energies below about 5 MeV. At higher energies, the situation is quite poor. So, use of this reaction as a dosimetry standard should be confined to lower neutron energies. Then, we can treat it as adequate for dosimetry applications.

Reaction No. 25: Au-197(n,2n)Au-196

The reaction cross section from threshold to well over 20 MeV is quite well defined by experimental data. The cross section is reasonably flat around 14 MeV, where a general consistency of the available cross section results indicates that the normalization is adequately known. Therefore, we shall consider this reaction to be acceptably known for fusion dosimetry applications.

Reaction No. 26: Hg-199(n,n')Hg-199m

The data base for this reaction is quite sparse and does not adequately define the cross section for dosimetry applications. Furthermore, there are some serious discrepancies. Therefore, we shall treat this reaction as inadequately known for dosimetry applications.

Reaction No. 27: U-235(n,f)

This is a primary standard. The cross section is very well known from thermal energies to several tens of MeV. However, if the fusion-dosimetry application involves consideration of a particular fission product, then matters are not so certain. There can be energy dependence in the production of particular fission products. Nevertheless, we shall treat this reaction as being adequately known for fusion dosimetry applications.

Reaction No. 28: Np-237(n,f)

The cross section is very well known from threshold energies to about 20 MeV. However, if the fusion-dosimetry application involves consideration of a particular fission product, then matters are not so certain. There can be energy dependence in the production of particular fission products. Nevertheless, we shall treat this reaction as being adequately known for fusion-dosimetry applications.

Reaction No. 29: U-238(n,f)

This is a secondary standard. The cross section is very well known from threshold energies to well over 20 MeV. However, if the fusion-dosimetry application involves consideration of a

particular fission product, then matters are not so certain. There can be energy dependence in the production of particular fission products. Nevertheless, we shall treat this reaction as being adequately known for fusion dosimetry applications.

The results of this survey are summarized in Table 1.

Five additional reaction processes which were not included in the original list have been suggested for fusion-dosimetry applications. We now proceed with a supplemental review of these activation processes, in order to determine their appropriateness for this purpose. In performing this review, we considered the status of the half life and decay properties (both of which are considerably more important for dosimetry than they are for other activation considerations) as well as the accuracy to which the pertinent cross sections are known.

Ni-58(n,p)Co-58:

This reaction is widely used for dosimetry applications in fission reactors. Consequently, it is suggested that it would be valuable for dosimetry applications in fusion. The half life is 70.82 ± 0.03 days. This uncertainty is only 0.04% so the half life is amply known for dosimetry applications. The decay is by EC (85%) and positron emission (15%). There is a dominant 811-keV gamma ray emitted in $(99.4 \pm 0.3)\%$ of all decays. This provides adequate definition of the decay properties for dosimetry applications. However, one needs to be careful to handle the sum-coincidence events which occur in high-efficiency counting arrangements properly. Turning to a consideration of the cross section, we find that there is an extensive data base for this reaction. In fact, it has been the object of a recent intercomparison of activation measurement methods involving ANL, LANL, IRK and PTB [Smi+91]. These measurements yielded agreement within a few percent at most energies. There has been a recent evaluation for ENDF/B-VI by ORNL. Some care is needed in the use of this reaction because Co-58m is also produced by neutron bombardment of Ni. This isomer has a 9-hour half life which could cause confusion in activity counting. It is advisable to let the isomer activity die away for several half lives before employing the (n,p) reaction as a dosimeter. Since Co-58m decays by IT, one ultimately ends up considering the total production of Co-58 (g + m) in this manner.

Nb-93(n,2n)Nb-92m:

The half life is 10.15 ± 0.02 days, i.e. 0.2% accuracy. This may be known adequately for dosimetry applications, unless it is planned to trace the activity through many half lives. The decay occurs mainly by EC and the decay scheme is quite well known. There is a dominant 934-keV gamma ray which is emitted in

(99.2 ± 0.2)% of all decays. This is well enough known for dosimetry. There are extensive data available for this reaction. In fact, it was also the object of a recent intercomparison of activation measurement methods involving ANL, LANL, IRK and PTB [Smi+91]. These measurements yielded agreement within several percent, except very near the reaction threshold where a precise definition of the neutron energy scale is quite difficult to achieve for differential measurements. The reaction was recently evaluated by the IRK group for the International Reactor Dosimetry File [Wag+90]. Consequently, it is a good choice for dosimetry applications.

F-19(n,2n)F-18:

The half life is 109.77 ± 0.05 minutes, i.e., an uncertainty of only 0.05%. This is very adequately known for dosimetry applications. The decay is by EC (3.1%) and positron emission (96.9%). All decays go to the ground state of the daughter O-18. Therefore, the only practical way to detect the activity in dosimetry is by measurement of 511-keV annihilation radiation. This is not very satisfactory because of the distributed nature of such sources (i.e., uncertainty in the position of the point of annihilation of the positrons). This problem is particularly severe since the dosimetry sample would have to be some compound of fluorine (e.g., teflon), and none of these are particularly absorptive for positrons. In any event, teflon also is not a very good material for making dosimeter foils. It cannot withstand high temperature environments such as one might expect in a reactor. There are extensive data for this reaction, but none exist close to threshold. Finally, reference to the Book of Curves indicates that the available data are somewhat discrepant. There was a recent evaluation of F for ENDF/B-VI, but considering all the above, it is recommended that this reaction be excluded from the fusion dosimetry list. It is not adequately known and, in practice, it is too difficult to use effectively.

Ti-46(n,p)Sc-46:

The half life is 83.810 ± 0.010 days, i.e., 0.1% uncertainty. That is very-well known. The decay is by beta emission and there is a 889-keV gamma ray with a 100% branch. Other gamma rays are also present, so there is a potential for sum-coincidence interference. There are some general points to be considered concerning the use of Ti dosimeters. Three (n,p) reactions (on Ti-46,47,48) have been used traditionally in fission reactor dosimetry for many years. Two of these are included in the original fusion-data-requirements list (see above). These reactions are appealing for a couple of reasons: 1) Ti is a durable material which can withstand fairly high temperatures. 2) The three reactions in question have quite distinct thresholds,

cross-section-excitation-function shapes and half lives so they provide complementary dosimetric sensitivities which have proved to be of considerable benefit in fission-reactor investigations. We might inquire as to whether this is also relevant to fusion. In principle, all the features mentioned above still apply and are favorable; however, there is one negative factor. In fusion, one is concerned with a strong yield of neutrons with energies up to 15 MeV. Ti is problematic as a dosimeter material in this region. In fact, Sc-46 is produced by both Ti-46(n,p) and Ti-47(n,n'p). One approach for dealing with this ambiguity is simply to specify Sc-46 production (regardless of the target isotope) as the dosimetry process. Nevertheless, it is evident from reports in the literature that there has been considerable confusion over this issue. In the same vein, the ambiguity of Ti-47(n,p)Sc-47 and Ti-48(n,n'p)Sc-47 produces problems of interpretation. When one looks at the Book of Curves, this issue manifests itself in the observed wide scatter of data points (there are extensive data available for the present reaction as well as for the others mentioned). None of the Ti isotopes were re-evaluated for ENDF/B-VI. In the evaluations for the Version V dosimetry files, it is clear that there existed considerable confusion over interpretation of the experimental data. Many of the reported data sets purport, for example, to correspond to Ti-46(n,p)Sc-46 while, in fact, they were probably Ti(n,X)Sc-46, etc. Thus, the situation is confused from the perspective of using these processes for dosimetry. Unfortunately, until new, well-documented measurements are reported, or until an evaluator can perform the necessary "archaeology" to properly interpret the data from several old experiments, in order to determine exactly what was measured, it will be necessary to treat our knowledge of this cross section as inadequate for dosimetry. The same holds for the other Ti reactions mentioned above, barring Ti-48(n,p) which is not afflicted by these ambiguities.

Mn-55(n,2n)Mn-54:

The half life is 312.12 ± 0.12 days, i.e., 0.04% uncertainty. This is a very high accuracy. The decay occurs via EC with an 835-keV gamma emitted in 100% of the decays. There is no possibility for sum coincidences which is ideal. There are extensive data available between 12 and 20 MeV. Many of these data are quite discrepant. An attempt was made to evaluate the 14-MeV cross section at Argonne [ESL85]. This effort was fairly successful. Nuclear-model calculations, experimental data and systematics together offer the possibility to make a reasonable determination of this cross section. In fact, this reaction process was recently evaluated for ENDF/B-VI. Therefore, it is suggested that knowledge of this cross section for dosimetry applications is marginally adequate. However, one probably ought

not to use it simply because of sample problems. Manganese is very difficult to obtain in pure form. It has undesirable physical properties in the present context. For example, accurate determination of the contaminants present in Mn samples is always problematic. One could avoid this uncertainty by employing oxide samples, but this material usually is found as a powder which does not press well into pellets. Therefore, it is probably advisable to avoid this reaction for dosimetry applications.

3. OTHER NEUTRON ACTIVATION PROCESSES

Cheng [Che90a,Che90b] has provided an extensive list of neutron-activation reactions which are considered to be of interest in fusion applications other than for dosimetry (see Table 4). What is requested here is basically information which is sufficiently well established to enable conceptual designers to decide which materials would be the best ones to use in a fusion reactor. A number of factors must be considered, e.g., radiation damage, decay heat, and radioactive waste disposal. Many of these issues must be analyzed for their impact over short, intermediate and long-term time frames. There obviously has to be a trade off between certain desirable thermal and structural properties of the materials and the radioactivity questions. A close inspection of Cheng's list indicates that the elements represented there fall into the following general categories:

- Structural materials conventional (Al, Fe, Ni, Co, ...)
- Structural materials - high temperature refractory (Zr, Mo, W, Ta, Re, ...)
- Elements present as significant constituents of chemical compounds (F, O, Na, ...)
- Shielding materials (Si, O, ...)
- Neutron multipliers (Be, Pb, Bi ...)
- Impurities (Hf, ...)

How accurately do we need to know the associated cross sections? The answers to this question will vary a great deal depending on the process in question. The fusion community must eventually provide better quantification of its nuclear data needs for the benefit of researchers who must eventually do the work needed to provide this information. For some processes, knowledge of the cross section to within a factor of two may be adequate. In most instances, however, 20% or less uncertainty should probably be considered as a reasonable goal. This is an important point because the accuracy requirements determine the strategies which must be charted to achieve certain goals. If a factor of two is adequate, then nuclear-model calculations might suffice. Of course, there is no guarantee that any particular nuclear-model calculation could satisfy the requirement for this degree of accuracy. In fact, a recent intercomparison of the results from a number of independent calculations of the cross section for $\text{Co-60}(n,p)\text{Fe-60}$ indicates that it probably would not [Cie90]. However,

if a number of independent calculations were made and then averaged, this average could probably be relied on with some confidence to be within a factor of two, or even closer. However, if 20% or better accuracy is sought, it is clear that nuclear-model analyses will rarely satisfy the needs. Measurements, or perhaps a combination of measurements and nuclear-model calculations, are required. Extensive files of model-calculated cross sections have been generated to address specific neutron-cross-section-data needs, particularly in the area of activation. The fusion community must be careful to accept this body of information for what it really is, namely, a collection of rough estimates of cross sections which eventually must be either verified or suitably refined as a consequence of good-quality, experimental investigations.

Unfortunately, it is the case that many of these reaction cross sections are extremely difficult, if not impossible to measure using contemporary experimental techniques. This situation will not be remedied anytime soon since fundamental limits are being encountered in a number of areas of nuclear experimental methodology. As an example of the amount of effort required to deal with such issues, several laboratories have been collaborating recently, under IAEA sponsorship, in an examination of twelve long-lived activation reactions (6 of these appear on Cheng's list). This project has been in progress for about a three years [DaH90]. Although the investigation is not yet complete, it is quite evident that the work has led to significant improvements in our knowledge of these particular cross sections. Furthermore, this admirable project provides a model for the manner in which the nuclear-data community ought to address these difficult data problems. However, compared to the work which would have to be done to address the whole of Cheng's list, this effort represents a mere "drop in the bucket". The inescapable conclusion is this: If it is really important for the fusion community to know these cross sections to quite-good accuracies for reactor-design applications, then it will be necessary to devote tens or maybe even hundreds of man years of effort to the quest and, of course, to provide funding consistent with this degree of commitment. Support will be required to staff and maintain experimental facilities for the measurements. Theorists, experimentalists and evaluators will have to work together very closely if the data community hopes to eventually converge to enduring values for the pertinent parameters. Truly unmeasurable quantities will have to be deduced indirectly by improving the reliability of those nuclear models used for calculating such cross sections (mainly through benchmarking the codes against similar yet measurable data). It will be a tedious undertaking. But, we must remember that extensive time (several decades), manpower and corresponding funding have been allocated to the plasma research aspects of fusion! Surely the neutronics concerns can be no more demanding than this area of the technology, nor can they represent any less important an issue over the long term.

In this project we have not examined the activation reactions for "other" applications in as much detail as was devoted to the dosimetry reactions. However, we have addressed all of the same issues, namely, half life, decay properties and cross sections. Specific comments on individual reactions are presented below. Those reactions which are being addressed by the IAEA-sponsored coordinated research program (CRP) on the production of long-lived activation reactions, which was mentioned above [DaH90], are so identified in their respective headings by "[IAEA CRP]".

Ag-109(n,2n)Ag-108m [IAEA CRP]:

The half life for Ag-108m is not well known. This issue has to be addressed before considering the cross section. The decay scheme is probably adequately known for applications (EC + positron decays plus a gamma branch which is reasonably well known). Some Ag(n,2n) data are reported in CINDA, but mostly for the ground state. It should be possible, from systematics, to make a reasonably-reliable calculation of the cross section shape. The only major problem is getting the correct isomer ratio so that it can be normalized. A few good 14-MeV experimental values (independently measured and in reasonable agreement) should settle the issue. The present status is inadequate.

Ag-107(n,gamma)Ag-108m:

The half life and decay comments from Ag-109(n,2n)Ag-108m apply here. Quite a few data have been reported for capture to the ground state of Ag-108, but the information for isomer production is sparse. As with all capture cross sections, it is a difficult problem to address the entire applicable energy range, owing to resonance interferences, etc. Calculations could probably be made with fair reliability for the fast-neutron range, and isomer ratios could be calculated similarly from models. The resonances are quite another matter. Capture measurements by direct detection of the capture gamma rays from Ag-107 samples could identify certain resonances, but it would be difficult to identify which ones are associated with the ground state and which belong to the isomer. This is a challenging problem experimentally, and from the point of view of nuclear modeling as well. The importance of this reaction really depends upon the nature of the fusion spectrum. If it is quite hard, it may not be as important as the (n,2n) reaction on Ag-109. If it is strongly energy degraded (e.g., in the blanket), then capture can be important. The present status is inadequate.

Al-27(n,alpha)Na-24:

This reaction was discussed under priority dosimetry reactions. It is very well known and the situation is certainly acceptable for present purposes.

Al-27(n,p)Mg-27:

Knowledge of the parameters for this reaction is not quite good enough to meet the needs for dosimetry applications but, from the point of view of the more general activation considerations considered here, we can consider it as adequately known.

Al-27(n,2n)Al-26 [IAEA CRP]:

The half life is known to within 4% which is probably adequate in this case. The decay scheme is also adequately known (EC + positron decay with a dominant gamma-ray branch). Measurements are very difficult due to the long half life, and they can be done reliably only at very-intense 14-MeV neutron sources. Some data have been reported for 14 MeV. One experimental value has been reported from a fission-reactor measurement, but it cannot be considered reliable due to uncertainties in the neutron spectrum. Nuclear-model calculations and systematics ought to be sufficient to provide a qualitative understanding of the shape of the excitation function. The available data at 14 MeV then could be used to normalize this shape. An important object of the IAEA CRP project will be to evaluate these 14 MeV data in order to generate a consistent value for use in such a normalization exercise. The present status is inadequate.

Bi-209(n,gamma)Bi-210:

This is a fairly complicated situation. Both the isomer (3,000,000 y) and the ground state (5 d) can be produced by this process. The half lives are adequately known. First, we consider the isomer. It decays by alpha emission and there is a dominant gamma-ray branch. The decay scheme probably is known adequately for fusion-activation applications. Next, we consider the ground state. It decays mainly by beta emission (to 138 d Po-210). Po-210 decays by alpha emission. The half life and decay scheme of Po-210 are also adequately known. So, the important matter is to determine the production cross sections for the isomer and ground state of Bi-210. The isomer ratio probably can be calculated with fair reliability. Total-capture-cross-section measurements can be made by a variety of means. Some data have already been reported in the resonance region below 1 MeV, and a few scattered points are available above 1 MeV. However, these data do not adequately define the cross section. More capture measurements need to be made over the entire energy range of interest for fusion applications (which is not well defined by the request). These measurements will have to be made by direct means rather than by activation. This reaction was recently evaluated at Argonne for ENDF/B-VI. The conclusion was that more data are needed to define the cross section better, especially below 0.1 MeV and from 1 - 5 MeV, since the uncertainties there exceed 25%. The present status is inadequate.

Bi-209(n,2n)Bi-208:

The half life is known adequately for applications. The fact that it is very long complicates the measurements. The decay proceeds mainly by EC. The yield of X-rays is not very well known, but the status could be adequate for fusion applications. There are quite a few data available to define this cross section. The reaction was recently evaluated at Argonne for ENDF/B-VI. Since the uncertainties are less than 10%, it can probably be treated as adequately known.

Bi-209(n,n'alpha)Tl-204(sequential reaction):

It is possible to reach Tl-205, which is stable, via the Bi-209(n,n'alpha)Tl-205. The Tl-205(n,2n)Tl-204 sequential reaction could then produce Tl-204. The former reaction was evaluated for ENDF/B-VI by Argonne. The conclusion was that no data were available and, therefore, nuclear-model calculations had to be used to estimate the cross section. The uncertainties are large (more than a factor of two). A few data are available for the Tl-205(n,2n) cross section. These results, plus nuclear-model calculations guided by systematics, ought to provide sufficient information to determine this cross section adequately for fusion applications. However, there appears to be no ENDF evaluation for Tl-205. All told, the present status is inadequate.

Ca-44(n,gamma)Ca-45:

The half life is adequately known for fusion applications. Ca-45 is a beta emitter with negligible gamma-ray yield. The cross section is very difficult to measure. Furthermore, the isotopic abundance of the target Ca-44 is low. ENDF/B-V provides an elemental evaluation for calcium, with no available revision for ENDF/B-VI. There exist very few data on this reaction. The available values are either for the thermal point or for the few-keV region. Thus, the data base is inadequate to define the cross section. In our opinion, it will be impossible to satisfy this request without using an enriched sample, direct-neutron-detection methods and an intense white-source spectrum. The current status is inadequate.

Ca-42(n,alpha)Ar-39:

The half life is adequately known. Ar-39 decays by beta emission without emitting gamma rays. The isotopic abundance of Ca-42 is low. One measurement has been attempted using a fission reactor spectrum, but the data are unreliable. This is an extremely difficult if not impossible measurement to make due to the long half life and unfavorable decay properties. It will most likely be necessary to rely on nuclear modeling, which at present is probably not sufficiently reliable to estimate this cross section to any better than a factor of two accuracy. Therefore, the status is inadequate.

Ca-43(n,n'alpha)Ar-39:

The half life is adequately known. Ar-39 decays by beta emission without gamma rays. The isotopic abundance of Ca-43 is low. No data have been reported. This is an extremely difficult if not an impossible measurement to make due to a long half life and unfavorable decay properties. It will be necessary to rely on nuclear modeling, which at present is probably not sufficiently reliable to estimate this cross section to any better than a factor of two (and possibly even to an order of magnitude) accuracy. The status is inadequate.

Ca-40(n,2p)Ar-39:

The half life is adequately known. Ar-39 decays by beta emission without gamma rays. This is an extremely difficult if not impossible measurement to make due to long half life and unfavorable decay properties. It will be necessary to rely on nuclear modeling, which at present is probably not sufficiently reliable to estimate this cross section to any better than a factor of two (and possibly even to an order of magnitude) accuracy. The cross section is expected to be quite small. The status is clearly inadequate.

Co-59(n,gamma)Co-60:

The half life and decay properties are very well known. There are some data for this reaction but they are rather discrepant. It was evaluated at Argonne for ENDF/B-VI, and it was thereby concluded that the uncertainty in the cross section is probably in excess of 20% for most of the applicable energy range. Some direct capture measurements are required to improve this accuracy. The status is inadequate.

Co-59(n,2n)Co-58:

The half life and decay scheme are very well known. There are extensive data for this reaction. Quite a few of these points can be considered as discrepant. A careful evaluation was performed at Argonne for ENDF/B-VI, based on recent improvements in the knowledge of the cross section at 14 MeV and systematic considerations. As a result, the cross section can be considered to be known to about 10% or better over a fairly wide range of neutron energies. We consider the status as adequate for fusion applications.

Cr-50(n,gamma)Cr-51:

The half life of Cr-51 is well known. The decay scheme is also fairly well known. There is a gamma-ray line with a reasonable branching factor that is known to about 3%. This is probably adequate for present purposes. The abundance of Cr-50 is fairly low. There are data for this reaction but they are quite discrepant. Cr-50 was recently evaluated by ORNL for ENDF/B-VI.

This isotopic evaluation is based largely on nuclear-model calculations, but comparisons were also made with experimental data. The conclusion is that this cross section is not adequately known for fusion applications because of the discrepancies. An isotopic sample should be prepared and direct measurements made of the capture cross section using white-source techniques. We shall treat the status as inadequate.

Cr-52(n,2n)Cr-51:

The half life of Cr-51 is well known. The decay scheme is also fairly well known. There is a gamma-ray line with a reasonable branching factor that is known to about 3%. This is probably adequate for present purposes. There are extensive data available for this reaction, some of it rather discrepant. Estimates of (n,2n) reaction cross sections which are fairly reliable can be made from systematics. A detailed evaluation of 14-MeV data was made at Argonne in 1985. Also, Cr-50 was recently evaluated by ORNL for ENDF/B-VI. This isotopic evaluation is largely based on nuclear-model calculations, but comparisons were also made with experimental data. We shall assume that this cross section is adequately known for fusion applications.

Cu-63(n,p)Ni-63 [IAEA CRP]:

The half life is probably well enough known for fusion applications. The decay of Ni-63 proceeds entirely by beta emission, but there are no gammas. This point, plus the long half life, make conventional activity measurements difficult to carry out. There are a few reported measurements around 14 MeV, and a number of nuclear-model studies are available. In general, the existing data do not define the cross section very well. ORNL recently evaluated this reaction for ENDF/B-VI. The results are based mainly on nuclear model analyses. As a rule, (n,p) reactions are difficult to estimate from systematics arguments and nuclear-model calculations. We have to assume that the status is inadequate.

Cu-65(n,t)Ni-63:

The half life is probably well enough known for fusion applications. The decay of Ni-63 proceeds entirely by beta emission and there are no gammas. This, plus the long half life, make conventional activity measurements difficult. In fact, there are no reported measurements in the literature. ORNL recently evaluated this reaction for ENDF/B-VI. Their results are based entirely on nuclear-model analyses. As a rule, (n,t) reactions are small and difficult to estimate from systematics or model calculations. Therefore, the status is inadequate.

Cu-63(n,gamma)Cu-64:

The half lives and decay properties are adequately known for fusion applications. There are several reported data sets. The

resonances are not well defined but the energy-averaged behavior seems to be fairly well known. ORNL recently evaluated this reaction for ENDF/B-VI. Their results are based largely on nuclear-model calculations, but they were guided by experimental data. We will assume that this cross section is adequately known for fusion applications, but we have to keep in mind the usual words of caution concerning capture reactions, namely, that much depends upon the neutron spectrum and how sensitive the overall reaction response is to the resonance details. These are not well known.

Cu-65(n,2n)Cu-64:

The half lives and decay properties are adequately known for fusion applications. There are many reported data sets. These seem to define the cross section reasonably well. ORNL recently evaluated this reaction for ENDF/B-VI. Their results are based largely on nuclear-model calculations, but they have been guided by experimental data. We will assume that this cross section is adequately known for fusion applications.

Cu-65(n,gamma)Cu-66:

The half life is adequately known. The decay is by beta emission and there is a significant gamma-ray branch. However, the latter is not very well known and this compounds the measurement difficulties. There are some experimental data available for this reaction, but they are not in quite as good a shape as for Cu-63. ORNL recently evaluated this reaction for ENDF/B-VI. Their results are largely based on nuclear-model calculations, but they have been guided by experimental data. We will assume that this reaction is known marginally from the fusion point of view. Depending upon its importance in particular applications, some improvements are probably warranted.

Cu-63(n,alpha)Co-60:

The half life and decay properties are well known. This reaction has been studied extensively and has also been evaluated. It can be considered as well-known from the point of view of fusion applications.

Cu-63(n,2n)Cu-62:

The half life is known adequately for fusion-activation purposes. The decay properties are fairly complex (as discussed above for dosimetry) and there is no dominant gamma ray. This compounds the cross section measurement issue. Nevertheless, there are extensive data available, and they do seem to be reasonably consistent. These results define the cross section from threshold to over 20 MeV. With guidance from nuclear model calculations and systematics, it can be concluded that the cross section is probably known reasonably well. ORNL recently evaluated this

reaction for ENDF/B-VI. These results are based largely on nuclear-model calculations, but they have been guided by experimental data. We will assume that this reaction is known adequately from the fusion point of view.

Cu-65(n,p)Ni-65:

The half life is well known and the decay is by beta emission. While there is a significant gamma-ray branch, the branching ratio is not too well known. There are extensive data at 14 MeV, but the inconsistencies lead to a rather large uncertainty for the evaluated results at that energy. From threshold to 10 MeV, there is only one reported data set. ORNL recently evaluated this reaction for ENDF/B-VI. Their results are based largely on nuclear-model calculations, but they have been guided by experimental data. It is our judgment that knowledge of this cross section is marginal for fusion applications. It could be readily improved by some new measurements at 14 MeV and from threshold to 10 MeV. Meanwhile, the status remains marginal.

F-19(n,2n)F-18:

The half life is well known and the decay proceeds by positron emission (mainly) and EC. There are no signature gamma rays other than annihilation. We believe that the decay properties are known adequately for fusion applications. Also, extensive cross-section data are available. These, combined with systematics and nuclear models, offer the means for adequately defining the cross section for fusion applications. This reaction was evaluated last for ENDF by ORNL in 1980. There have been no significant additions to the data base since then. We will assume that it is known adequately for fusion.

F-19(n,gamma)F-20:

The half life is short, but it is adequately known. The decay is by beta emission, with a 100% gamma branch. Thus, the decay properties are known adequately. There are quite a few data available. These provide some indication of both the resonance structure and the energy-averaged fast-neutron cross section. The production of activities can be quite sensitive to resonance details for low-energy neutrons, so it is difficult to say if the cross section is known well enough at this time for the intended applications. It all depends on the nature of the spectrum. We should probably treat this as marginal pending further study of the situation.

Fe-56(n,2n)Fe-55:

The half life is known adequately and the decay is by EC. X-rays must be observed to detect the decays. Our knowledge of X-ray yields per decay is not very good (according to the NCRP Radiation Measurements Handbook). The process is difficult to

measure. Regardless, there are some data available, and it is surprising how consistent they are around 14 MeV. This point, combined with systematics arguments and nuclear-model calculations leads one to believe that the cross section can be reasonably determined using the available information and techniques. The reaction was recently evaluated by ORNL for ENDF/B-VI. This evaluation is based largely on nuclear-model calculations but these were substantiated by comparison with experimental data. We shall assume that this cross section is known adequately for fusion applications.

Fe-54(n,p)Mn-54:

The half life and decay properties are very well known. The cross section is a dosimetry standard. Therefore, we suggest that it is known adequately for fusion applications.

Fe-56(n,p)Mn-56:

The half life and decay properties are very well known. The cross section is a primary dosimetry standard. Thus it is known adequately for fusion applications.

Fe-58(n,gamma)Co-60(sequential reaction):

We assume that the process under consideration is as follows: Fe-58 captures a neutron to form Fe-59. Fe-59 captures a neutron to form Fe-60. Fe-60 decays to Co-60. Fe-58 is a relatively rare isotope, so that already reduces the possible impact of this process. Let's look at the half lives. Fe-59 has a 44.51 d half life (well known) so this reaction product remains long enough in the reactor to absorb neutrons. Fe-60 has a very long half life (300,000 y), but it is very poorly known. So, the inventory of Fe-60 builds up steadily with the operation of a fusion reactor. Once the decay to Co-60 occurs, Co-60 decays with approximately a 5.271 y half life. Now, consider the decay schemes. The decay scheme for Fe-59 is reasonably well-known. Fe-60 is a beta emitter, but not much else is known about the decay process. Co-60 decay is a well-known process. This brings us to the cross section. There are some scattered data for the Fe-58(n,gamma) process, but they do not define the capture cross section clearly. This reaction was evaluated by ORNL for ENDF/B-VI, but this is largely a model calculation (with some comparisons with data). The formation of Fe-60 from neutron capture by Fe-59 is unmeasurable by contemporary techniques. Therefore, the cross section must be estimated from nuclear model calculations. The uncertainties will be large (more than a factor of two and possibly an order of magnitude). There is no easy way to determine the resonance contributions. Consequently, this is the weak link in understanding the whole process. We must assume that our knowledge of this situation is woefully inadequate for fusion applications, and it is not likely to improve anytime in the near future.

Fe-54(n,n'p)Mn-53:

Mn-53 has a very long half life (3,600,000 years) and it is not well known. The uncertainty exceeds 10%, which is unacceptable. This is not the only serious problem. It is known that the decay proceeds by EC and there are no gamma rays. Consequently, measurements of this activity are nearly impossible. There are some experimental data, but these are based on direct detection techniques which are notorious for missing much of the cross section strength due to instrumental biasing against low-energy emitted particles. Therefore, these data do not provide very reliable guidance on the cross-section magnitude. We must rely on nuclear models. The reaction has been evaluated by ORNL for ENDF/B-VI. These results are from model calculations, with the attendant uncertainties. It is clear that this process is not adequately known. Even though Fe-54 is a minor isotope, the effect could be quite large in the massive inventories of Fe that would be found in a fusion reactor. It is not likely that the situation will improve substantially in the near future.

Hf-179(n,2n)Hf-178m2 [IAEA CRP]:

The half life is known to about 3%, which is not as accurate as one might desire but is probably adequate for fusion applications. The decay is by IT with a dominant gamma ray whose branching factor is well known. The decay scheme is, therefore, considered to be adequately known. There are some data around 14 MeV for the short-lived isomer m1, but none for m2, the long-lived isomer. This reaction is the object of an IAEA CRP project. Hopefully this effort will produce at least one reliable experimental point around 14 MeV. This information, combined with systematics and nuclear-model calculations would probably be sufficient to provide a reasonable estimate of the cross section for fusion applications. Meanwhile, the status is inadequate.

Hf-178(n,2n)Hf-177m:

The half life for the longer-lived (54 m) isomer in Hf-177 is adequately known. The decay occurs via IT, but the yield of the dominant gamma ray is poorly known. This branching factor needs to be better known to establish the cross section. Remarkably enough, there exists essentially no experimental information on this cross section. Until reliable data can be established, in the vicinity of 14 MeV as a minimal requirement, it will not be possible to define the cross section adequately on the basis of systematics and nuclear-model calculations alone. We treat the status as inadequate.

Hf-177(n,gamma)Hf-178m2:

The half life is known to about 3%, which is not as accurate as one would like, but is probably adequate for fusion applications. The decay is by IT with a dominant gamma ray whose branching is

known well. The decay scheme is, therefore, considered to be known adequately. There exist a few capture cross section values for Hf-177, but it is not evident from the data compilations whether they pertain to the isomer in question. Calculations could be performed to determine the isomer ratios (two isomers and the ground state) with some degree of reliability, but still the envelope of the total capture cross section remains in serious doubt. An isotopically enriched sample of Hf could be used for direct-detection-capture measurements at a white-source facility. There is no record that this experiment has ever been done. Model calculations would give estimates to within perhaps a factor of two for the energy-averaged cross section at higher energies, but they could not delineate the resonance structure which can be a very important consideration in typical degraded fission-neutron spectrum from a reactor. We consider this as inadequately known.

Hf-179(n,gamma)Hf-180m:

The half life is not known adequately (the uncertainty is > 5%). The decay occurs via IT, with a dominant gamma ray having a large and reasonably-well-defined branching factor. Therefore, the decay scheme is not a problem. Some data for this reaction are reported in the literature. They give an indication of the energy-averaged capture cross section, but there is no indication as to whether it is the isomer or the total-capture cross section that is considered (we suspect that it is probably the latter). Consequently, these results would need to be interpreted and appropriate isomer ratios calculated. This could be done, but the overall uncertainty in the final result would lead to an inadequate situation. Also, nothing is known of the resonance properties which could be very important for a degraded spectrum. The measurements and indicated isomer ratio analysis should be performed. We consider the situation as inadequate for the present.

Hf-180(n,gamma)Hf-181:

The half life is adequately known. The decay occurs via beta emission, with a dominant gamma ray having a large but not very well-defined branching factor. Therefore, the decay scheme is somewhat of a problem. Some data for this reaction are reported in the literature. They give an indication of the energy-averaged capture cross section, but no mention is made as to whether it is the isomer or the total capture cross section which is considered (we suspect that it is probably the latter). Consequently, these results would need to be interpreted and appropriate isomer ratios calculated. This could be done, but the overall uncertainty in the final result would lead to an inadequate situation. Also, nothing is known of the resonance properties which could be very important for a degraded spectrum. The measurements and indicated isomer ratio analysis should be performed. We consider the situation as inadequate for the present.

Hg-204(n,2n)Hg-203:

Hg-204 is a minor isotope of elemental Hg. The half life is very well known. The decay occurs by beta emission. There is a dominant gamma ray which is reasonably well known. It seems that the decay properties are not a problem for fusion applications. There are reported data, but the scatter around 14 MeV is considerable and there are no points to define the threshold shape. Nevertheless, systematics and nuclear-model calculations, coupled with the existing data, should lead to a reasonable understanding of this reaction. Hg is not in the ENDF evaluations. We conclude that the status of this reaction is currently inadequate, but the goal of acquiring an adequate understanding appears within reach.

Tl-203(n,gamma)Tl-204:

The half life is well known and the decay is by beta emission (mainly) and EC. Most of the decays are to the ground state of Tl-204, so one must observe X-rays to measure the activity. Since the X-ray yields are not well known, this hampers determination of the cross sections. A fair amount of data have been reported for this reaction, but there is still not enough information to define the energy-averaged shape adequately, not to mention the resonance structure. All the usual comments for capture reactions apply here (see above). This reaction should be studied by direct detection techniques, using enriched samples and intense-white-neutron sources. There is no ENDF file for this reaction. Thus, the status is inadequate.

Hg-198(n,2n)Hg-197,197m:

First, we consider Hg-197. The half life is well known and the decay is by EC. There is a gamma branch, but it is not very well known (more than 5% error). This situation must improve. There are a few data points available at 14 MeV for this reaction. Also, measurements have been made of the isomer ratio. There is no ENDF evaluation for this isotope, and no further indication that these data have been evaluated elsewhere. If the data were consistent, it would be possible in principle to provide a reasonable estimate of the cross section from nuclear models and systematics. For the present, we must consider the situation as inadequate. Next, consider Hg-197m. The half life is adequately known and the decay is by IT and EC. There is a prominent gamma ray with a reasonably-well-known branching factor. There are a few data points available at 14 MeV for this reaction. Also, measurements have been made of the isomer ratio. There is no ENDF evaluation for this isotope, and no further indication that these data have been evaluated elsewhere. If the data were consistent, it would be possible in principle to provide a reasonable estimate of the cross section from nuclear models and systematics. For the present, we must consider this situation as inadequate.

Hg-200(n,2n)Hg-199m:

The half life is known reasonably well, and the decay is by IT. There is a prominent gamma ray with a reasonably-well-known branching factor. The ground state of Hg-199 is stable. There are a few data points available at 14 MeV for this reaction. However, there is no ENDF evaluation for this isotope, and no further indication that these data have been evaluated elsewhere. If the data were consistent, it would be possible in principle to provide a reasonable estimate of the cross section from nuclear models and systematics. For the present, we must consider this situation as inadequate.

Hg-198(n,gamma)Hg-199m:

The half life is adequately known for fusion applications. Hg-199m decays by IT and there is a prominent gamma ray with a reasonably-well-known branching factor. Evidently there are no particular problems with the radioactive properties of Hg-199m. There are a few capture data available for Hg-198; however, information on the isomer excitation fraction is sparse. Estimates could be made of the isomer ratio from model calculations. Since the range of interest is probably below a few MeV (because the capture cross section is very small at higher energies), what is needed is definition of the cross section below about 5 MeV. The only available data appear, from the Book of Curves, to lie below a few-hundred keV. So, we conclude that the data base is inadequate to define the cross section for fusion applications. The measurements should not be too difficult in principle because of the favorable decay properties and reasonable isotopic abundance of Hg-198. This is an experiment that should be given priority by measurers.

Hg-200(n,p)Au-200m:

The half life is not very well known (the uncertainty is about 2.7%). While this is not a serious issue for this reaction, there is no reason why it should not be determined better on general principles. Au-200m decays by beta emission and IT. The relative fractions are not well known, nor is the branching factor for the dominant gamma ray. The decay scheme is clearly a problem here, both from the point of view of cross-section determination and for decay heat considerations. Only one 14-MeV data point has been reported. The data base is certainly inadequate for applications. Nuclear-model calculations could be done, but their reliability within a factor of two or more would be questionable. Thus, the status is inadequate.

Hg-196(n,p)Au-196:

Hg-196 has a very small isotopic abundance. One might question why it is a concern in the first place. The half life is well

enough known and the decay occurs via EC and beta emission. There is a gamma branch which is prominent and reasonably well known. Thus, the radioactive properties of the reaction product are not a particular problem. There are no data available and none are likely to be forthcoming because of the isotopic sample problem. Nuclear model calculations could be done, but their reliability within a factor of two or more would be questionable. Thus, the status is inadequate.

Hg-196(n,n'p)Au-195:

Hg-196 has a very small isotopic abundance. One might question why it is a concern in the first place. The half life is very well known and the decay occurs via EC. There is a gamma branch which is prominent but not very well known. Thus, the radioactive properties of the reaction product are somewhat of a problem. There are no data available and none are likely to be forthcoming because of the isotopic sample problem. Nuclear-model calculations could be done, but their reliability within a factor of two or more would be questionable. Thus, the status is inadequate.

Hg-196(n,alpha)Pt-193:

Hg-196 has a very small isotopic abundance. One might question why it is a concern in the first place. The half life is very poorly known. The decay occurs via EC. There are no gammas. Thus, cross section measurements are essentially impossible. There are no data available and none are likely to be forthcoming because of these fundamental difficulties. Nuclear-model calculations will have to be done, but their reliability within a factor of two or more would be questionable. Thus, the status is inadequate and likely will remain so unless it is shown that this reaction is not a serious concern for fusion.

Mg-24(n,p)Na-24:

The half life and decay properties are very well known. Measurements of the activity are easy to do. This reaction is known to near standard accuracy and was the subject of a recent re-evaluation by the IRK group for a revision of the International Reactor Dosimetry File. We consider it to be adequately known.

Mg-25(n,n'p)Na-24:

The same comments apply for the reaction product as in the preceding reaction. According to the Book of Curves, there are data available in the 13-17 MeV range, but they are not adequate to define the threshold behavior. Also, the data at 14 MeV are very discrepant. The ENDF/B-V evaluation for elemental Mg was not re-evaluated for ENDF/B-VI. We conclude the status is inadequate. More measurements are needed, but without separated isotopes these would be very difficult due to the interference from Mg-24(n,p)Na-24.

Mg-24(n,t)Na-22:

The half life and decay properties are very well known. There has been one reported data point by Qaim (Juelich). Since this involved a high-energy Be(d,n) spectrum, it is difficult to relate this information to a differential cross section. At best, the data could be used to check the results of a model calculation, if the neutron spectrum were well determined (which it is really not). Model calculations for this process are also not very reliable, so we have to assume that this reaction is not very well known. Nevertheless, a factor of two accuracy may be sufficient. We shall adhere to the judgment that the status is inadequate, pending further guidance from the fusion community.

Mg-24(n,n'p+d)Na-22 (via two step reaction):

The two-step reaction in question has to include Na-23(n,2n)Na-22 as the second step in the process. The decay properties of Na-22 are very well known. There are data for the (n,2n) process. The cross-section energy dependence around 14 MeV is quite pronounced, which suggests that the uncertainties will be large. Na was not re-evaluated for ENDF/B-VI. Interest in Na had been driven largely by the fast-reactor program in the past, so the motivation for contemporary work is lacking. It is suggested that knowledge of the cross section for the second step in this process is marginally adequate for fusion applications. Turning to the first step in this process, we note that no data have been reported. The measurement is impossible by activation methods because Na-23 is stable. Direct proton measurements suffer from interference by the (n,p) process, and from the fact that it is difficult to detect low-energy protons or deuterons in such a detector system. Estimates could be made from model calculations, but the calculation of (n,n'p) cross sections is a notoriously unreliable undertaking. The situation is entirely inadequate for fusion applications.

Mg-26(n,gamma)Mg-27:

The half life and decay properties of Mg-27 are well known. There are only a few, scattered data points for this reaction, so this data base is woefully inadequate for fusion applications. The usual comments concerning the potential influence of capture resonances, etc., apply in this case (see above). Measurements should be done by direct methods using intense white source machines. The isotopic abundance of Mg-26 is significant, so an isotopic sample could be used to good advantage. This measurement should be done. Meanwhile, the status is inadequate for fusion applications.

Mn-55(n,gamma)Mn-56:

The half life and decay properties are very well known and there are extensive data available for this reaction. Mn is monoisotopic and this further simplifies matters. Mn was recently evaluated for ENDF/B-VI. With the possible exception of uncertainties associated with the detailed resonance descriptions, it is possible to say with reasonable confidence that this reaction is adequately known for fusion applications.

Mn-55(n,2n)Mn-54:

The half life and decay scheme are well known and there are extensive data available for this reaction. An earlier evaluation of 14-MeV data produced quite consistent results. Consequently, with the use of model calculations, systematics and a 14-MeV normalization point that is reliable, this cross section can be considered as quite well known. It was recently evaluated for ENDF/B-VI. We will treat it as adequate for fusion applications.

Mo-95(n,p)Nb-95:

The half life and decay scheme are both well known and there is a prominent decay gamma ray. There exist data on this reaction in the threshold region and around 14 MeV. Unfortunately, the data at 14 MeV are quite discrepant (more than a factor of 3). No evaluation was made for ENDF/B-VI. There is a problem separating this process from (n,n'p) on Mo-96. An effort should be made to perform some new measurements with isotopic samples at 14 MeV to resolve the question. Once this is done, it is likely that the knowledge of this cross section would be adequate for fusion applications. For the present, the status is marginal to inadequate.

Mo-96(n,n'p+d)Nb-95:

Comments on the half life and decay scheme are the same as for the preceding reaction. There are a couple of reported data points, but this constitutes a very inadequate data base. Matters are further complicated by the presence of an isomer which is also activated. No evaluation was made for ENDF/B-VI. Estimates could be based on nuclear models, but experience indicates that the calculation of (n,n'p) cross sections is an uncertain matter. Measurements are affected by (n,p) on Mo-95. However, for fusion applications one is probably interested only in the production cross section of Nb-95, regardless of which isotope is the target. This ought to be taken into consideration in both the measurements and evaluations. We consider the status as inadequate.

Mo-97(n,t)Nb-95:

Our comments on the half life and decay scheme are the same as those for the preceding reaction. There are no reported data. Nevertheless, an estimate at 14 MeV should be possible on the basis of systematics. Calculation of the excitation function with nuclear models would be possible, but experience indicates that such calculations are relatively unreliable as concerns the shape as well as the normalization. No evaluation was made for ENDF/B-VI. Thus, we consider the status as inadequate.

Mo-98(n,gamma)Tc-99:

Although it was not indicated in the request, a two step process is evident here. Tc-99 is formed by the beta decay of Mo-99. Tc-99 is very long lived. First, we consider the capture reaction to Mo-99. Data have been reported but they are discrepant by factors of more than two, and the resonance structure in the important region below 1 MeV is not defined. We consider this reaction as poorly known. The half life of Mo-99 is well known but the decay scheme is more uncertain. In particular, the gamma-ray branch for the prominent line is very poorly known. This impairs the measurement process. Capture measurements by direct detection would be possible, but these require isotopically-enriched samples. This is possible in principle because Mo-98 is fairly abundant. Such measurements need to be done. Model calculations could provide estimates of the cross section, but they would be no better than the measurements and, most probably even worse in reliability. Also, they would not provide the information on resonance structures which could be derived from white-source measurements. No evaluation was made for ENDF/B-VI. We consider this situation as inadequate.

Mo-98(n,gamma)Tc-99m:

Tc-99 and Tc-99m are both formed from the decay of Mo-99. The relative formation yields can be deduced reasonably well from the decay scheme. In fact, most of the decay strength of Mo-99 populates the isomer directly. However, this isomer decays entirely to the ground state with a 6 h half life. Therefore, the production of Tc-99m dominates the short-term activation properties associated with Mo-98, while the Tc-99 long-lived ground state ($> 2 \times 10^5$ y) dominates the long-term activation behavior. Everything that was stated for the preceding reaction, concerning the formation of Mo-99, applies in this context as well. No evaluation was made for ENDF/B-VI. We consider the status as inadequate.

Mo-100(n,2n)Tc-99:

Here we encounter the same situation as for the preceding reaction, namely, a two-step process with formation of Mo-99 in the first stage followed by its decay to Tc-99m (mainly) and,

ultimately, to Tc-99. Data exist for the (n,2n) cross section, both at 14 MeV and in the threshold region. The data at 14 MeV scatter quite a bit, but no more than is typical for such a situation. Since the cross section is flat in this region, it ought to be possible to sort out this situation through an evaluation. It should be feasible to come up with a reasonable estimate for the cross section based on existing data, systematics and nuclear model calculations. No evaluation was made for ENDF/B-VI. For the present, we consider this situation as inadequate.

Mo-100(n,2n)Tc-99m:

The same comments apply as for the preceding reaction, with regard to the formation of Tc-99m vs. Tc-99. Therefore, we consider this situation as inadequate for the same reasons indicated above. The important technological issue concerns determination of the elemental cross section for Tc-99 and Tc-99m formation from fast neutrons on elemental Mo. For applications there is no need to distinguish the individual isotopic reactions. In any event, it cannot be done experimentally. However, in model calculations it is unavoidable to separate the processes. For the present, we consider this as inadequate.

Tc-99(n,2n)Tc-98:

The concern here is for transmutations of the built-up Tc-99. Tc-99 is mildly radioactive (it has a long half life). Tc-98 also has a very-long half life. A single measurement of this process at 14 MeV has been reported by Qaim. Comparison of these results with systematics of 14-MeV cross sections would provide an indication of the uncertainty of this value. Knowledge of the 14-MeV cross section plus model calculations would lead to a reasonably reliable representation of the excitation function. There is no ENDF/B evaluation for Tc-99. Until these matters are addressed, the status must be considered as inadequate.

Tc-98(n,2n)Tc-97m:

There are very few data of any sort for Tc-98, presumably because no isotopic samples are available. This must be considered as unmeasurable under these circumstances. We must rely on model calculations guided by systematics. It should be possible to do this to within better than a factor of 2, perhaps even to 20-30% accuracy, since (n,2n) reactions are generally more amenable to this approach than are other reactions.

Mo-92(n,alpha)Y-88:

There are a few data points around 14 MeV for the (n,alpha) reaction of Mo-92. These results are quite discrepant. The experimental results include production of both the isomer and the ground state of Zr-89. The half lives of Zr-89 and Zr-89m are

both well known. The decays of Zr-89 and Zr-89m involve an admixture of IT (for the isomer), positron emission and EC. The decay schemes are reasonably well known and there are prominent gamma rays with adequately-known branching factors. The isotopic abundance of Mo-92 is reasonable, so these measurements are feasible. More such measurements should be done. Nuclear-model calculations could also be done, and estimates at 14 MeV could be made from systematics in order to try and resolve the discrepancies. No evaluation was made for ENDF/B-VI. The next step concerns the production of Y-88. The only processes are Zr-89(n,n'p+d)Y-88. Since the target is radioactive, this is an unmeasurable cross section. Nuclear models must be used. We consider the status as inadequate.

Mo-92(n,gamma)Mo-93:

The half life of the ground state is long and poorly known. The decay occurs by EC and it populates mainly the Nb-93m isomer. This is a very difficult activation measurement. There is an isomer of Mo-93 which can also be populated by neutron capture. Estimation of the isomer ratio ought to be possible using model calculations. There exist some data on the capture cross section for Mo-92 but they are sketchy. Also, it is not clear from the Book of Curves whether these reported results correspond to the isomer or the ground state. The isomer decays to the ground state so, either way, the long-term consequence is production of Mo-93. In principle, the best way to do this measurement is by direct detection of capture gamma rays. The existing data do not define the resonance structure, and they give only very uncertain information about the energy-averaged capture cross section. No evaluation was made for ENDF/B-VI. This situation is totally unacceptable.

Mo-94(n,2n)Mo-93:

The same comments apply as for the preceding reaction, concerning Mo-93 and Mo-93m decay. This situation leads to difficult measurement problems. Activation measurements really can be made only for isomer formation. The isomer ratio could be estimated from nuclear models, so as to provide a value for the total Mo-93 production rate. There are some data reported around 14 MeV for formation of the isomer. These data, plus systematics and model calculations (including isomer ratios), ought to yield a cross section estimate to within better than a factor of two. No evaluation was made for ENDF/B-VI. We must consider the status as inadequate pending a careful examination of the available information.

N-14(n,p)C-14:

The decay properties of C-14 are well known. The half life is quite long. Considerable data are available for this reaction. These data are in reasonable agreement from the keV energy region

to nearly 10 MeV, and they define the resonance structure. However, the data are very sparse at higher energies. N-14 was the subject of a recent evaluation for ENDF/B-VI. We shall assume that this reaction is adequately known for fusion applications.

N-14(n,n' α)Be-10:

Although not indicated in the request, this is a multiple-step process. The (n,n' α) reaction on N-14 yields B-11, which is stable. The (n,n'p) process on B-11 then yields B-10. Consider N-14(n,n' α) first. There are no relevant data in the literature. The only possibility would be to use direct detection methods, but it is difficult to get a proper target. Thus, we consider this as essentially unmeasurable. Since it is hard to guide model calculations by systematics in the light nuclei, and since N is above the normal range for R-matrix calculations, model calculations are problematic as well. This step is inadequately known and may well remain so for some time to come. We turn now to B-11(n,n'p). Since Be-10 has a very long half life and produces no gammas, this is difficult to measure. The only possibility is by direct detection of the protons, but then it is hard to distinguish from the (n,p) process. Isotopic B-11 samples would be required, even though B-11 is dominant, to avoid interference from B-10. Boron samples are notoriously difficult to make. So, this is a nearly-unmeasurable process. Model calculations might be possible using R-matrix formalism. Still, the whole situation is quite discouraging, and we have to treat the situation as inadequate.

Na-23(n,2n)Na-22:

The half life and decay properties of Na-22 are very-well known, and there are data available for the (n,2n) process. The cross section energy dependence around 14 MeV and below is very pronounced. This suggests that the uncertainties will be large. Na was not re-evaluated for ENDF/B-VI. Interest in Na had been largely driven by the fast reactor program in the past and the interest has waned. It is suggested that knowledge of the cross section for this process is marginally adequate for fusion applications.

Na-23(n, γ)Na-24:

The half life and decay properties of Na-24 are very-well known, and there are extensive data available for this process, including both energy-averaged and high-resolution white-source results. Work on this process was motivated by the fast-reactor program in recent years but interest has waned. Na was not re-evaluated for ENDF/B-VI. However, it is likely that knowledge of this process is adequate for fusion applications, since it is probably adequate for fission reactor technology and that technology is much better developed.

Nb-93(n,2n)Nb-92 and Nb92m:

The half life and decay properties for Nb-92m are well established. There is a prominent gamma ray with a well-known branching factor. For Nb-92, the half life is poorly known as are the decay details. An evaluation for ENDF/B-VI was made at Argonne for the total (n,2n) cross section. There are considerable data available from direct-detection experiments, so it is reasonably well known. There are even more extensive data available specifically for the isomer reaction, and these are relatively consistent. Thus, both processes can be estimated quite well. We shall consider these reactions to be adequately known for fusion applications.

Nb-93(n,gamma)Nb-94:

Nb-94 is long lived and the half life is poorly known. The decay properties of Nb-94 are reasonably well known and there is a prominent gamma ray. Nb-94m is also formed in the capture process. This isomer decays by IT with only a weak gamma-ray yield due to strong internal conversion. The main concern for long-term waste disposal is the total production of Nb-94. This can be measured by direct-detection means, and there is an extensive data base available. An evaluation has been made for ENDF/B-VI at Argonne. It was concluded that the available experimental data are reasonably consistent. Thus, this process is adequately known, including the resonance structure.

Nb-93(n,n')Nb-93m:

The half life and decay properties are now quite well known as a result of extensive work during the last decade. Also, the cross section is currently fairly well established, and may actually be adequate for dosimetry applications. The process was recently evaluated at Argonne for ENDF/B-VI. We shall consider this to be adequately known for fusion.

Nb-93(n,n'alpha)Y-88:

This is a two-step process. First, Y-89 is formed by (n,n'alpha). Then, Y-88 is formed by Y-89(n,2n). Y-89 is the single, stable isotope of elemental Y. Both of these processes have been evaluated recently at Argonne for ENDF/B-VI. First, we consider (n,n'alpha). There are few data available. Measurements would necessarily involve He production or other direct detection methods, but the (n,alpha) process interferes. The cross section must therefore be calculated, but the reliability of such calculations for shape is not good, even when data are available at 14 MeV to establish the normalization. We must assume this first-step process to be rather poorly known. Next, we consider the (n,2n) process. The decay of Y-88 is mainly by EC. The half life and decay properties are well established and there is a

prominent gamma ray with a well-known branching factor. There are extensive and relatively-consistent data available. This reaction was evaluated for ENDF/B-VI at Argonne. The conclusion is that the cross section is reasonably well known. We consider the status as adequate for fusion.

Ni-58(n,p)Co-58:

The half life and decay properties are well known and there is a gamma-ray branch that is prominent and well established. There are extensive data available for this reaction. Knowledge of its cross section is approaching standard quality. Consequently, we can assume that this process is adequately known for fusion activation applications.

Ni-60(n,t)Co-58:

The half life and decay properties are well known and there is a gamma-ray branch that is prominent and well established. Ni-60 is less abundant than Ni-58. Furthermore, this cross section is much smaller than the (n,p) cross section. Therefore, as a producer of Co-58, this reaction is a very minor factor. Only one data point has been reported for this reaction, by Qaim (Juelich). This measurement was made in a broad neutron spectrum so that interpretation of the results is dubious. It is suggested that a model calculation be made and compared against this result. Still, this would provide only a rough estimate of the cross section because model calculations are not particularly reliable for determining either the shape or normalization of (n,t) cross sections. Since the impact of this process is small relative to Ni-58(n,p), perhaps that will be adequate. For the present, we will label the status as inadequate.

Ni-58(n,n'p)Co-57:

The half life is very well known. Decay occurs by EC and there is a prominent gamma ray with a well-established branching factor. Unfortunately, the energy of the gamma is rather low and this leads to absorption problems which make measurements somewhat difficult. There appear to be quite a few data available around 14 MeV, according to CINDA. For some strange reason none of these points are plotted in the Book of Curves, so it is hard to make a casual judgment of the status of the data. Since there appear to be no other energies represented, it would be necessary to evaluate these 14-MeV data and perform model calculations to estimate the shape of the excitation function. The record of success in this sort of calculation is rather poor. The reaction has been evaluated for ENDF/B-VI, but under the circumstances it seems that this reaction should be considered as only marginally well known.

Ni-58(n,2n)Co-57:

This is viewed as a two step process. The (n,2n) reaction takes us to Ni-57. There are extensive data for this reaction, and it has been evaluated for ENDF/B-VI by ORNL, and independently by the IRK group for the International Reactor Dosimetry File. We can consider this process as very well known. The next step is EC and positron emission decay of Ni-57 to Co-57 with a half life of 36 hours. There is no problem interpreting this process, and Ni-57 probably does not exist for long enough in the fusion reactor to be burned up by another two-step process. Therefore, we consider this process as adequately known.

Ni-60(n,p)Co-60:

The half life and decay properties of Co-60 are well known and there are prominent gamma rays with well-known branching factors. Cross section data are available on this reaction; however, the newer data of Vonach and Haight are in strong disagreement with older values from Liskien and Paulsen. There has been a new evaluation of this reaction by ORNL for ENDF/B-VI, but it predated the work of Vonach and Haight. In view of these discrepancies, it is still not possible to say that the cross section is well known, but things are improving. We will label this situation as marginal. It should be known much better because it is our guess that this would be an important contributor to the buildup of long-lived activity in fusion reactor structural components.

Ni-58(n,alpha)Fe-55:

The half life is adequately known. The decay occurs by EC and there are no gamma rays. So, the only activity signature for the measurement is the emission of X-rays. These are difficult to detect except from very thin samples. This is a serious liability for cross section determinations. In spite of that, there are extensive data reported in CINDA. Many of these data are measured in fission spectra or at 14 MeV, but at least one set defines the cross section from threshold to 10 MeV. This reaction has been evaluated by ORNL for ENDF/B-VI. A superficial review such as ours cannot discern just how consistent these data are, or how well the model fits. We will give the matter the benefit of doubt and assume that the process is known marginally well enough for fusion applications. One wonders why we should be concerned with Fe-55 activity. This is a question that only those individuals who are involved with the engineering details of waste disposal could answer.

Ni-58(n,gamma)Ni-59:

Ni-59 has a long half life which is very poorly known. The decay is mainly by EC and there are no gamma rays. Extensive data have been reported. Some of these measurements have been carried out

with separated-isotope samples. There also exist some high-resolution, white source data to define the resonance structure. This process has been evaluated recently for ENDF/B-VI by ORNL. We will give the matter the benefit of doubt and assume that the process is known marginally well enough for fusion applications. One wonders why we should be concerned with Ni-59 activity. This is a question that only those individuals who are involved with the engineering details of waste disposal could answer.

Ni-60(n,2n)Ni-59:

Ni-59 has a long half life, and it is very poorly known. The decay is mainly by EC and there are no gamma rays. There are no reported data for this reaction. The only way to measure the cross section would be by direct neutron detection techniques with an isotopically enriched sample. This has not been done. Still, it should be possible to make a reasonable estimate of the cross section by examining the systematics of 14-MeV cross sections and then performing model calculations to get the shape at other energies. This reaction has been evaluated by ORNL for ENDF/B-VI. On the basis of this, we will assume that knowledge of the cross section is marginal to inadequate for fusion applications. One wonders why we should be concerned with Ni-59 activity. This is a question that only those individuals who are involved with the engineering details of waste disposal could answer.

Ni-62(n,He-3)Fe-60:

The half life is very long and poorly known. Fe-60 decays by beta emission, but otherwise little is known about the decay properties. There are no experimental data. It should be possible to provide an estimate at 14 MeV from systematics. ORNL has provided an evaluation of Ni-62 for ENDF/B-VI based on model calculations. We consider the status as inadequate.

Ni-64(n,n'alpha)Fe-60:

The half life is very long and poorly known. Fe-60 decays by beta emission, but otherwise little is known about the decay properties. There are no experimental data. It should be possible to provide an estimate at 14 MeV from systematics. ORNL has provided an evaluation of Ni-64 for ENDF/B-VI based on nuclear model calculations. The present status is inadequate.

Pb-208(n,gamma)Po-210:

Here we must be concerned with a complicated multistep process consisting of $\text{Pb-208}(n,\gamma)\text{Pb-209} \rightarrow (\text{beta decay}) \rightarrow \text{Bi-209}(n,\gamma)\text{Bi-210m} \rightarrow (\text{beta decay}) \rightarrow \text{Po-210}$. Let us consider the first step. There are quite a few data reported for $\text{Pb-208}(n,\gamma)\text{Pb-209}$. The Book of Curves shows only the high

energy data. Included are a number of values around 14 MeV, and they are quite consistent. According to CINDA, there are also some low-energy values, including results from white-source measurements with direct capture gamma-ray detection. The half life of Pb-209 is well known, but the beta decay produces no gammas. Thus it is hard to measure the activity for this high-Z material. Pb-208 was recently evaluated as part of ENDF/B-VI. We will assume that this step is known with only marginal adequacy. There are data available for Bi-209(n,gamma). An evaluation was performed at ANL, but this only considered the total yield, not specifically the isomer which feeds Po-210. Even at that, the uncertainties are large. The isomer ratio could be calculated and estimates provided of that cross section. We conclude that knowledge of the cross section is very marginal, at best. Considering both processes together, we state that current knowledge of the cross section for Po-210 production is very marginal to inadequate.

Pb-208(n,gamma)Bi-208:

Here we are concerned with a complicated multistep process consisting of $\text{Pb-208}(n,\text{gamma})\text{Pb-209} \rightarrow (\text{beta decay}) \rightarrow \text{Bi-209}(n,2n)\text{Bi-208}$. Let us consider the first step. There are considerable data reported for $\text{Pb-208}(n,\text{gamma})\text{Pb-209}$. The Book of Curves shows only the high-energy data. Included are a number of values around 14 MeV, and they are quite consistent. According to CINDA, there are also some low-energy values, including results from white-source measurements with direct capture gamma-ray detection. The half life of Pb-209 is well known, but the beta decay produces no gammas. Thus, it is hard to measure the activity for this high-Z material. Pb-208 was recently evaluated as part of ENDF/B-VI. We will assume that this step is known with marginal adequacy. There are data available for Bi-209(n,2n). An evaluation was performed at ANL, and it appears that the cross section is fairly well known. These are all direct neutron detection experiments since Bi-208 is very long-lived. We conclude that knowledge of the cross section is marginal, suffering mainly from shortcomings of the first step in the process.

Pb-204(n,2n)Pb-203:

The half life is very well known. There are isomers but they have much shorter half lives and all decay by IT to the ground state. The ground-state decay is by EC, and there is a prominent gamma ray which is reasonably well known. Several data sets have been reported. They appear to define the cross section at 14 MeV with reasonable consistency and also provide a shape to threshold. Systematics and model calculations can give reasonable definition to the (n,2n) cross section. One problem here is that Pb-204 is

such a rare isotope. It has not received evaluation attention by the ENDF effort. Our conclusion is that knowledge of this cross section is probably adequate for fusion applications, but the available information should be subjected to a formal evaluation.

Pb-204(n,t)Tl-202:

The half life and decay properties of Tl-202 are adequately known. From the point of view of measuring the cross section, the radioactivity properties of tritium are more important. There is one measurement of this reaction by Qaim (Juelich), using a broad spectrum Be(d,n) field. This information should be interpreted in concert with nuclear-model calculations. However, such calculations are not very reliable as it concerns both the cross-section shape and normalization. There is no ENDF evaluation for Pb-204. So, we are forced to conclude that knowledge of this cross section is inadequate. But, how important is it to know this information? The cross section is very small and the isotopic abundance of Pb-204 is also small, so it is improbable that this reaction would be of any serious technological concern.

Pb-206(n,alpha)Hg-203:

The half life and decay scheme are both well known. There is a prominent gamma ray with an adequately-known branching factor. According to CINDA, there have been a couple of experimental determinations of this cross section at 14 MeV. Systematic considerations also provide some guidance at 14 MeV. This information, along with model calculations, give us some idea about the cross section, but we must keep in mind that model calculations are not particularly reliable for either shape or normalization determinations of (n,alpha) processes. Pb-206 was re-evaluated for ENDF/B-VI. We shall assume that knowledge of this cross section is either marginal or inadequate, depending upon the accuracy required. We suspect that it is known to within a factor of two.

Pb-207(n,n'alpha)Hg-203:

The half life and decay scheme are well known. There is a prominent gamma ray with an adequately-known branching factor. According to CINDA, there are no experimental determinations of this cross section. Systematics can provide some guidance at 14 MeV. This, along with model calculations, can give some indication of the cross section, but we must keep in mind that model calculations are rather unreliable for either shape or normalization determinations of (n,n'alpha) processes. Pb-207 was re-evaluated for ENDF/B-VI. Therefore, we shall assume that knowledge of this cross section is either marginal or inadequate, depending upon the accuracy required.

Pb-204(n,p)Tl-204:

The half life is adequately known, and other aspects of the decay are also fairly-well established. There is no significant gamma ray yield, so cross section measurements are difficult. Only one fission-reactor activation measurement has been reported. This information is of little use, so it is necessary to resort to nuclear-model calculations, which we know are also not particularly reliable for (n,p) processes. There is no ENDF evaluation for Pb-204. Consequently, we assume that this process is inadequately known. Since Pb-204 has a very small abundance, we wonder how important it is from a technological point of view.

Pb-206(n,t)Tl-204:

The half life is adequately known, and other aspects of the decay are also fairly-well established. There is no significant gamma-ray yield, so cross section measurements are difficult. There are no reported data for this reaction. Thus, it is necessary to resort to nuclear-model calculations, which are not reliable for (n,t) processes. We expect the cross section to be quite small. Some estimates of the 14-MeV cross section probably can be deduced from systematics. Pb-206 has been evaluated for ENDF/B-VI. We will assume that knowledge of this cross section is marginal, at best, but most likely is inadequate.

Re-185(n,gamma)Re-186,186m:

The ground state has a well-known half life and decay scheme, although the one prominent gamma ray has a modest branching factor which is not known well. The isomer has a very long half life which is poorly known. The decay is mainly by IT, but it is not too well known. There are no associated prominent gamma rays. Surprisingly enough, there are extensive data for neutron capture in Re. Direct capture gamma-ray detection methods have produced data, including resonance information, for the total-capture cross section, and there are some data applicable directly to formation of the ground state, which is relatively much shorter lived than the isomer. Furthermore, there has been a recent evaluation of Re-185 for ENDF/B-VI. Given these circumstances, we shall suppose that the cross sections are adequately known for fusion applications.

Re-187(n,2n)Re-186,186m:

The ground state has a well-known half life and decay scheme, although the one prominent gamma ray has a modest branching factor which is not known well. The isomer has a very long half life which is poorly known. The decay is mainly by IT, but it is not too well known. There are no associated prominent gamma rays. Nevertheless, there are a few reported data points around 14 MeV for production of the ground state. This information, coupled

with systematics, nuclear-model calculations and isomer ratio analyses, ought to provide reasonable estimates for both processes. Re-187 has been evaluated for ENDF/B-VI. Given this set of circumstances, we shall suppose that the cross sections are adequately known for fusion applications.

Re-187(n, γ)Re-188,188m:

The ground state has a well-known half life and decay scheme, although the one prominent gamma ray has a modest branching factor which is not known well. More or less the same can be said for the isomer. Surprisingly enough, there are extensive data for neutron capture in Re. Direct capture gamma-ray detection methods have produced data, including resonance information, for the total-capture cross section, and there are some data directly applicable to the formation of the isomer state. Furthermore, there has been a recent evaluation of Re-187 for ENDF/B-VI. Given this set of circumstances, we shall suppose that the cross sections are adequately known for fusion applications.

Re-185(n,2n)Re-184:

The half life for the ground state is adequately known but that for the isomer is very poorly known. The decay properties of Re-184 and Re-184m are probably adequately to marginally known. There are a few scattered data points available, mainly in fission spectra and at 14 MeV. Clearly, these data are inadequate to define the cross section. However, systematics plus nuclear models and isomer ratio analyses provide some additional guidance. Re-185 was evaluated for ENDF/B-V. Consequently, we shall consider our knowledge of this process to be marginal for fusion applications.

Re-187(n,p)W-187:

The half life is quite well known. The decay is by beta emission, but the branching factor for the prominent gamma ray is poorly known. There are a couple of data points reported at 14 MeV. This information, along with nuclear model calculations and systematics, ought to provide some guidance as to the nature of the cross section. However, nuclear-model calculations are not particularly reliable for (n,p) processes. Re-187 was evaluated for ENDF/B-VI. We shall consider this as marginally to inadequately known, depending upon accuracy requirements. More data are needed at lower energies to define the cross section shape better.

Re-187(n, α)Ta-184:

The half life is not as well known as one might wish for fusion purposes. The decay is via beta emission, and the details are fairly-well known, including the branching factor for a prominent gamma ray. A couple of data points have been reported. This information, along with nuclear-model calculations and

systematics, ought to provide some guidance as to the nature of the cross section. However, nuclear-model calculations are not particularly reliable for (n,alpha) processes. Re-187 was evaluated for ENDF/B-VI. We shall consider this as marginally to inadequately known, depending upon accuracy requirements. More data are needed at lower energies to define the cross section shape better.

Re-185(n,alpha)Ta-182:

There are a couple of isomers (both short lived) and the ground state which can be produced in this reaction. We assume that the 114 d ground state is the object of interest. The half life is very-well known. The decay is via beta emission, and this is also fairly-well understood, including the branching factor for a reasonably prominent gamma ray. Only one fission spectrum data point has been reported. This information is not adequate to define the cross section, so reference must be made to nuclear-model calculations and 14-MeV systematics, along with isomer-ratio calculations. However, nuclear-model calculations are not particularly reliable for (n,alpha) processes. Re-185 was evaluated for ENDF/B-VI. We shall consider this as probably inadequately known. More data are needed at lower energies to define the cross section shape better.

Si-28(n,n'p)Na-24,Na-22,Al-26:

Here we are concerned with multistep reactions in which the first step is the (n,n'p) process and subsequent steps lead to production of Na-24, Na-22 and Al-26, respectively. First we consider Si-28(n,n'p). This produces Al-27 which is stable. Only one measurement at 14 MeV has been reported, according to CINDA. It involved the use of nuclear emulsions, which is not a particularly reliable technique. The only recourse, then, is to estimate this cross section through nuclear-model calculations. The process has been evaluated at ORNL recently. Still, we have to assume that even the first stage of this process is not well known. For the subsequent stages, Al-27 is the target. Al was not re-evaluated for ENDF/B-VI, so the existing evaluation is at least a decade old. Al-26 has a short-lived isomer (which decays by positron emission) and a very long-lived ground state. The decay of both are reasonably well understood. The isomer produces no gammas other than 511-keV radiation from positron annihilation. The only reported measurements, however, are for the isomer. It should be possible to calculate the isomer ratio and thereby estimate the ground-state excitation cross section from nuclear models and systematics at 14 MeV. Consequently, we will assume that this process is marginally known. Of course this does not mean that the Al-26 production cross section can be adequately determined, because of the deficiencies in knowledge of the first step as mentioned above. Turning to formation of

Na-24, this is produced by the (n,alpha) reaction on Al-27. This process is very-well known, in fact it is a standard. Still, the uncertainties in the first-step process make it difficult to estimate the production rate for Na-24 from Si-28. Na-22 can be reached only by a sequence of rather complicated multistep processes from Si-28. We shall assume that the combination of these is poorly known and also very improbable!

Si-28(n,alpha)Na-24,Na-22:

Here we are concerned with multistep reactions in which the first step is the (n,alpha) process and subsequent steps lead to production of Na-24 and Na-22. The (n,alpha) reaction leads to Mg-25 which is stable. Consequently, measurements are difficult. In spite of that, quite a few data sets have been reported. These all involve direct detection methods, such as nuclear emulsions, with questionable reliability. This uncertainty is evident from a plot in the Book of Curves. Si has been evaluated by ORNL for ENDF/B-VI, so presumably nuclear-model calculations have been performed. Cross section estimates can be made from systematics, but these are not particularly reliable for light nuclei. All in all, the first stage of this process, production of Mg-25, is probably known only marginally well. Na-24 is produced from Mg-25 by the (n,n'p) reaction. Since Na-24 has a well-known half life and decay scheme, these are not difficult measurements. In fact, there are a number of data points around 14 MeV which ought to provide adequate definition of the cross section. However, since (n,n'p) cross section shapes are difficult to calculate reliably, we must conclude that the Mg-25(n,n'p)Na-24 second-stage cross section is known only marginally well. To get to Na-22 we must follow even more complicated multi-step reaction paths. Consequently, we conclude that the status is inadequate.

Si-28(n,n'alpha)Na-24:

The (n,n'alpha) process leads to Mg-24. This is stable. No data have been reported so, at present, it would be necessary to rely on nuclear-model calculations. These have been done by ORNL for ENDF/B-VI. However, due to the general unreliability of (n,n'alpha) calculations and to a lack of guidance from systematics, this is inadequately known. The second step involves Mg-24(n,p)Na-24 which is quite well known.

Ta-181(n,gamma)Ta-182:

Ta-181 is the dominant stable isotope of Ta. This reaction excites the ground state and two shorter-lived isomers. The half lives and decay properties of these isomeric states are reasonably well known. Since the isomers decay to the ground state, one ends up with stable Ta-182 in each case. Thus, the direct capture gamma-ray measurement approach is appealing. There are extensive data on this process, including high-resolution

white-source results. These measurements deal with the total yield of Ta-182 (g + m). Ta was not re-evaluated for ENDF/B-VI. Nevertheless, we conclude that this process is probably known adequately for fusion applications. This process evidently is a concern only for the short-lived activity since the end reaction product is stable.

Ta-180(n,t)Hf-178m2:

Ta-180 has a very small isotopic abundance and the (n,t) cross section will also be very small. This leads us to question whether this process is really technologically important. Hf-178m2 has a 31 y half life which is not as well known as it should be. The decay is by IT and there is a prominent gamma ray with a branching factor that is reasonably well established. There are no data for this reaction. An estimate of the total 14-MeV (n,t) cross section could be made from systematics, and the partial (m2) isomer fraction could also be calculated. On the whole, any contemporary estimate of this cross section would be highly speculative. We consider it as inadequately known.

T-48(n,alpha)Ca-45:

The half life is adequately known. The decay is by beta emission and there are no known gamma rays. Thus, measurements of the cross section are difficult. There are a few fission reactor and 14-MeV measurements reported. The latter differ by factors of two. Systematics at 14 MeV ought to provide some guidance on the cross section. Nuclear-model calculations have been performed, but these are not particularly reliable. It is suggested that the cross section is probably known to within a factor of two at 14 MeV, but it is probably more uncertain at lower energies. Ti has not been re-evaluated for ENDF since version V. We treat it as inadequate.

Ti-48(n,p)Sc-48:

The half life is well known as is the decay scheme. There is a prominent gamma ray present in 100% of the decays. Furthermore, there are extensive data for this reaction and they are reasonably consistent. They address the whole range from threshold to 20 MeV. This process was not re-evaluated for ENDF/B-VI, but we can still consider it as adequately known for fusion applications.

Ti-46(n,p)Sc-46, Ti-47(n,n'p)Sc-46:

It is only fair to consider these together, because it is the production of Sc-46 that is of interest here. Elemental Ti is usually used for the cross section measurements and will be present in fusion reactors, not separated isotopes. The half life

of Sc-46 is well known. The decay process is also well known and there are prominent gamma rays with 100% branching factors. Below about 11 MeV, Ti-46(n,p) is the only open channel. There are extensive data and the process is quite well known. At 14 MeV, the Ti(n,X) production cross section for Sc-46 has been carefully evaluated. Although matters are less certain between 11 and 14 MeV, this region can be interpolated by models. Although Ti was not re-evaluated for ENDF/B-VI, it is apparent that these processes are adequately understood for fusion applications.

Ti-46(n,n'alpha)Ca-41,Ar-39:

The half lives are known adequately. However, the (n,n'alpha) process brings us to Ca-42 which is a stable but quite-rare isotope of Ca. Therefore, we are concerned with multi-step processes. There are no experimental data for Ti-46(n,n'alpha), and nuclear-model calculations are unreliable. So, we are already in trouble at this stage. Since other steps are involved in forming Ca-41 and Ar-39, this compounds the problem. Starting with Ca-42, Ca-41 is produced by the (n,2n) reaction. A reasonable estimate of the cross section (to within perhaps 20-30% at 14 MeV) can be had from systematics, and the shape could be calculated to better than a factor of two at lower energies using nuclear models. Turning to Ar-39, this is formed from Ca-42 by the (n,alpha) reaction. There are no data available. The 14-MeV cross section could be estimated from systematics, but nuclear-model calculations are not particularly reliable for addressing the other energies. The conclusion is that neither of the production processes in question are adequately known for fusion applications.

V-51(n,alpha)Sc-48:

The half life and decay properties of Sc-48 are well known. There is a prominent gamma ray. There are extensive data from threshold to 20 MeV and most of the points are consistent. This reaction was recently evaluated at ANL for ENDF/B-VI. Consider it as adequately known.

V-50(n,2n)V-49:

V-50 is very rare in elemental V. The half life is exceedingly long, but is probably adequately known. Decay occurs by EC with no gamma rays. The measurements would be very difficult and there are currently no experimental data available. The cross section could be estimated by nuclear models and systematics to within perhaps 20-30% at 14 MeV, with poorer accuracy to be expected at lower energies. This may be marginal to adequate for fusion applications, depending upon the requirements. It must be remembered that V-50 is very rare in nature and one questions whether this is really a legitimate technological concern.

V-51(n,n' α)Sc-47:

The half life and decay properties of Sc-47 are adequately known. There are a few data at 14 MeV, and these seem to be in reasonable agreement with model calculations. The uncertainties at other energies are substantial, but the cross section is small (of the order of a few millibarn). The reaction was evaluated for ENDF/B-VI. Consider this as marginal to adequately known for fusion applications.

V-50(n,n' α)Sc-46:

The half life and decay properties of Sc-46 are well known, but there are no cross section data for this reaction. Calculations could be made, but without data the reliability is poor. Since V-50 is scarce and the cross section is probably fairly small, we wonder if this process is really important? We label it as inadequately known.

V-51(n,t)Ca-45:

This is a multi-step process, and a complex one at that. An (n,t) reaction on V-51 produces stable Ti-49. From there, to get to Ca-45 requires (n,n' α) as the second-step process. The half life of Ca-45 is adequately known, but the decay produces no gammas. Now, consider the (n,t) process on V-51. This was evaluated at Argonne for ENDF/B-VI. There are only fragmentary data available and they are inconsistent. Therefore, that evaluation was based on nuclear-model calculations. An estimate could be made from systematics at 14 MeV. The cross section is probably less than 1 millibarn in that energy range. In any event, the cross section for this first stage is inadequately known. Now, consider the second stage. Ti-49 is not very abundant to make samples and there are no (n,n' α) data available. Nuclear-model calculations are not very reliable. So, this process is not known adequately either. We treat the entire sequence as inadequately known.

Sc-45(n,n' α)Ar-39:

The half life of Ar-39 is adequately known. However, this is a multistep process. The (n,n' α) reaction on Sc-45 produces K-41 which is stable. There are no data available for this reaction. Model calculations would not be particularly reliable without data, so we are already in trouble at this stage. To get to Ar-39 requires an (n,t) reaction on the Sc-45 target. There are no data for this process either. Models are not very reliable, but some estimate from 14-MeV systematics might be obtained. The cross section will be very small, and we conclude that the process is inadequately understood.

K-41(n,t)Ar-39:

See the comments for the preceding reaction. The process is not adequately understood.

W-186(n,2n)W-185:

There is an isomer which is excited along with the ground state of W-185, but the isomer half life is short. It decays by IT to the ground state, so we will focus on the g.s. The half life is quite well known and the decay is by beta emission with no gamma rays. This complicates measurements. However, there have been some measurements of this cross section by direct neutron detection techniques. Model calculations along with 14-MeV systematics should also assist in the determination of this cross section. Furthermore, it has been evaluated recently for ENDF/B-VI. We shall assume it is adequately known.

W-184(n,gamma)W-185:

There is an isomer which is excited along with the ground state of W-185, but the isomer half life is short. It decays by IT to the ground state, so we will focus on the g.s. The half life is quite well known. The decay is by beta emission, but there are no gamma rays. This complicates measurements. There are extensive data on this reaction from about 1 keV to 3 MeV, which probably covers the range of major interest for fusion. Furthermore, it has been evaluated recently for ENDF/B-VI. We shall assume it is adequately known.

W-182(n,p)Ta-182:

There are a couple of isomers which are generated along with the ground state. These isomers are both relatively short-lived and decay by IT to the ground state. We will concentrate on the g.s. The half life is very well known. Decay is by beta emission, and there is a relatively-prominent gamma ray whose branching factor is adequately known. There are a couple of 14-MeV values which have been reported as well as some fission-spectrum results. The latter are not very useful, but the 14-MeV results, coupled with systematics, should provide reasonable definition of the 14-MeV cross section. The shape of the (n,p) cross section at other energies is much less certain because of the usual unreliability of such calculations. This reaction has been evaluated for ENDF/B-VI. We shall assume that it is marginally known.

W-183(n,n'p)Ta-182:

There are a couple of isomers and the ground state which are produced by the reaction. The isomers are both relatively short-lived and they decay by IT to the ground state. We will concentrate on the g.s. The half life is very well known. Decay is by beta emission, and there is a relatively prominent gamma ray whose branching factor is adequately known. There is one reported 14-MeV value from Qaim (Juelich). More data are required in order to define the 14-MeV cross section better. Nuclear-model calculations can be performed, but these are not particularly reliable without guidance from data at other energies. Shape

calculations from nuclear models are not trustworthy for these processes. The reaction has been evaluated for ENDF/B-VI, but we must still consider it as marginally to inadequately known.

W-184(n,t)Ta-182:

There are a couple of isomers and the ground state which are generated by the reaction. The isomers are both relatively short-lived and they decay by IT to the ground state. We will concentrate on the g.s. The half life is very well known. Decay is by beta emission and there is a relatively prominent gamma ray whose branching factor is adequately known. Qaim (Juelich) has made a measurement in the broad Be(d,n) spectrum, but it is difficult to interpret these data in the context of the desired differential cross section. At best, this information could be used to test the normalization of a model calculation. The cross section is very small. Some estimate of the 14-MeV value could be obtained from systematics. The reaction has been evaluated for ENDF/B-VI, still we must consider it as inadequately known.

W-182(n,n'alpha)Hf-178m2:

The half life is long and not very well known. The decay is by IT, and is well established. There is a prominent gamma ray with a well-known branch. According to CINDA, there are no reported data for this reaction. It can be calculated by nuclear models, but in the absence of experimental data this is an unreliable approach. An evaluation for this reaction appears in ENDF/B-VI. Still, we must consider it as inadequately known.

W-186(n,n'alpha)Hf-182 [IAEA CRP]:

An isomer is excited as well as the ground state of Hf-182. The g.s. has a very long half life which is poorly known. The decay is by beta emission and there are no gamma rays. Measurement of the cross section would be very difficult. The isomer has a short half life which is adequately known. The decay is by IT and beta emission, which complicates determination of the total Hf-182 production. The decay of the isomer produces a relatively prominent gamma ray which is known with marginal to adequate accuracy. No data have been reported, but this reaction is on the list which the IAEA CRP on long-lived activities is addressing. Hopefully this exercise will provide some insight on the cross section. Meanwhile, we must consider it as inadequately known.

Zn-64(n,gamma)Zn-65:

The half life is very well known. The decay is by positron emission and EC, and it is reasonably well established. There is a prominent gamma ray with an adequately known branching factor. There are reported data for this reaction, but mostly for thermal and fission spectrum neutrons. Some capture gamma-ray studies have been conducted, but actually there are no studies which

address the cross section issue directly. This is surprising because it should not be a particularly difficult measurement to make. There is no ENDF evaluation for Zn. In the absence of such information, we must conclude that the status is inadequate for fusion.

Zr-90(n,2n)Zr-89:

The ground state and an isomer are excited. Both have reasonably short half lives which are well known. Zr-89 decays by EC and positron emission. There is a prominent gamma ray with a well-known branching factor. Zr-89m decays mainly by IT, but there are also EC and positron emission branches. A prominent gamma ray with well-established branching factor is produced. There are extensive data for both the ground state and isomer production. An evaluation of Zr is in progress at ANL for ENDF/B-VI. Consequently, we can assume that this process is adequately known for fusion.

Zr-90(n,t)Y-88:

The half life is very well known. The decay is mainly by EC, and there is a well-known, prominent gamma ray. Only one measurement has been carried out by Qaim (Juelich) at 14 MeV, using tritium detection methods. This data point, along with systematics, gives some indication of the 14-MeV cross section, but the uncertainties at other energies are very large. Nuclear-model calculations are not particularly reliable for such calculations. An evaluation is in preparation for ENDF/B-VI. For present purposes, we shall assume that our knowledge of the cross section is marginal to inadequate for fusion applications.

Zr-94(n,gamma)Zr-95:

The half life is known well. Decay occurs by beta emission and there is a prominent gamma ray with a well-established branching factor. Data have been reported for the region from 1-200 keV, but there are large discrepancies. An evaluation is in progress at ANL for ENDF/B-VI. It appears that knowledge of this cross section is marginal to inadequate, depending upon the specific requirements.

Zr-96(n,2n)Zr-95:

The half life is known well. The decay is by beta emission and there is a prominent gamma ray with a well-known branching factor. Zr-96 is not very abundant. Several measurements have been reported at 14 MeV. This information, along with model calculations and systematics ought to provide a reasonably adequate understanding of the cross section. Zr is being evaluated at ANL for ENDF/B-VI. Consider the knowledge of this process as marginal to adequate.

Zr-92(n,gamma)Zr-93;Nb-94:

Zr-93 decays to Nb-93 with a very long half life that is not very well known. The decay scheme is also not known well. It is not certain as to whether there are any gamma rays, but that is probably irrelevant because the long half life makes Zr-93 very hard to measure in any case. There are a few reactor-spectrum determinations of this cross section and a 30-keV value from ORNL, measured by direct detection of capture gamma rays. This is a totally-inadequate data base upon which to base the capture cross section. Nuclear modeling could give a rough estimate of the energy-averaged cross section, but this is not particularly reliable. Consider the knowledge of Zr-93 formation as inadequate. Turning to Nb-94, it is not clear how this will be formed. The atomic number of Nb is one larger than Zr, so the only way to reach Nb from Zr is through proton absorption or beta decay. There can be no proton absorption in a fusion reactor, so we look at beta decay. Zr-93 does indeed decay to Nb-93, but the half life is so long that the inventory of Nb-93 available for buildup of Nb-94 through capture is not likely to be significant. All other reaction steps leading to production of Nb-94 from Zr-93 would involve several stages, owing to the decay properties of the Zr and Nb isotopes. This seems very unlikely. In any event, we shall assume that the cross sections for these processes are very poorly known.

Zr-94(n,2n)Zr-93;Nb-94:

Zr-93 decays to Nb-93 with a very-long half life that is not very well known. The decay scheme is also not known well and it is not certain as to whether there are any gamma rays. That is probably irrelevant because the long half life makes Zr-93 very hard to measure in any case. There are no reported measurements for this process. An estimate of the 14-MeV cross section could be derived from systematics. This, combined with nuclear-model calculations, would provide an idea as to the cross-section energy dependence. Consider the knowledge of this process as marginal. Turning next to Nb-94, it is not clear how this will be formed. The atomic number of Nb is one larger than Zr, so the only way to reach Nb from Zr is through a proton absorption or beta decay. There will be no proton absorption occurring in a fusion reactor, so we look at beta decay. Zr-93 does indeed decay to Nb-93, but the half life is so long that the inventory of Nb-93 available for buildup of Nb-94 resulting from neutron capture is not likely to be significant. All other reaction steps leading to production of Nb-94 from Zr-93 would involve several stages, owing to the decay properties of the Zr and Nb isotopes. This seems very unlikely. In any event, we shall assume that the cross sections for these subsequent processes are very poorly known.

0-16(n,p)N-16:

The half life is short and well known. The decay scheme is also well established. There is a prominent high-energy gamma ray with a reasonably well-known branching factor. Extensive data have been reported for this reaction and 0-16 has been evaluated for ENDF/B-VI. We consider this to be adequately known.

0-17(n,alpha)C-14:

The decay properties of C-14 are well known. There are a couple of 14-MeV points for this reaction and some fission-reactor data. This sparse data base is insufficient to define the cross section, which no doubt exhibits some broad structures as is typical of this mass region. We consider the situation to be inadequate.

0-18(n,n'alpha)C-14:

The decay properties of C-14 are well known. There are no data available for this reaction. This lack of data makes it impossible to define the cross section, which no doubt exhibits some broad structures as is typical of this mass region. We consider the situation as inadequate.

The results of the preceding analysis are summarized in Table 4.

4. FUEL-CYCLE PROCESSES

The request list generated by Cheng states that there are three energetically viable reactions that are being considered for the fusion fuel cycle. In order of importance and probable implementation, they are: 1) D-T, 2) D-D and 3) D-He-3.

The D-T and D-D reactions were carefully reviewed by Liskien and Paulsen in 1973 [LP73]. This work provided good definition of the cross sections well above threshold, but it is somewhat deficient very near to threshold, in part because these authors did not employ the procedure (which is now standard) of factoring out the astronomical S-factor in their analysis. We did not undertake a review of the D-He-3 reaction, however there was an extensive program of such measurements for most of the potential fuel cycle reactions during the 1980's at Los Alamos (Jarmie, et al.). This work provided information not only for the major reactions but also for some minor ones as well. It also provided solid information on the low-energy region, which was somewhat deficient in earlier times. Furthermore, there have been extensive and quite reliable R-matrix calculations performed for reactions of this type at both Los Alamos (Hale, et al.), at Ohio University (Lane, White, Ressler, et al.) and at Lawrence Livermore National Laboratory (White and Ressler). Livermore has put together a library of charged particle reactions for light nuclei. Given this extensive and well-documented effort, we believe that it is very likely that the knowledge of these cross sections is adequate for most fusion applications.

The situation is summarized in Table 5. We believe the current situation is adequate until demonstrated otherwise.

5. FUEL-BREEDING PROCESSES

It is generally assumed that the D-T process will be the reaction of choice for the design of fusion reactors well into the foreseeable future. Our concern is with tritium (T) production. The other two fuels (deuterium and helium-3) involved in the three contending processes (see Section 4) occur naturally in Nature. There are only two reactions worthy of consideration for the production of tritium: 1) $\text{Li-6}(n,t)\text{He-4}$ and 2) $\text{Li-7}(n,n't)\text{He-4}$. The characteristics of these reactions are totally different, so we shall discuss them separately:

Li-6(n,t)He-4:

This reaction has no threshold. The data base is extensive and below 100 keV this reaction is treated as a primary cross section standard, mainly because of its important role in Li-glass scintillation detectors which are used for precision neutron fluence measurements at low energies. In fact, this reaction appears in conjunction with several other such standards, e.g., $\text{H}(n,n)$, in a joint evaluation of standards for ENDF/B-VI. This evaluation is being accepted by all the countries in the world. It extends from 1×10^{-5} eV to 20 MeV. Above 100 keV, the data base, while still extensive, exhibits more scatter than at lower energies. This happens because there is a large resonance which peaks at about 150 keV, thereby generating energy-scale definition problems which have afflicted some of the measurements over the years. At higher energies, the cross section drops rather substantially with increasing energy (above 5 MeV) and the data appear to be more or less linear with energy on a full-logarithmic scale (both axes). Measurements at these energies are difficult due to experimental perturbations from neutron energy down-scattering effects, etc. This may not be a serious concern since the contribution to tritium production in a fusion reactor from this reaction is not dominated by the higher-energy neutrons. In addition to the measurements, there are results from extensive R-matrix calculations which have been performed for this reaction (see the comment above), most notably at Ohio University by Lane, et al. Finally, there is a new evaluation for Li-6 which has been included in ENDF/B-VI. Consequently, we are inclined to believe that this reaction is adequately known for fusion applications.

Li-7(n,n't)He-4:

This reaction was the subject of intense investigations during the late 1970's and throughout the 1980's. Since the cross section for tritium production from Li-6 is small at higher energies (above 1 MeV), and Li-7 is the dominant isotope in natural Li, it is clear that Li-7 is a very important source of

tritium production for fusion reactors (perhaps the most important one, depending upon the particular reactor design). Furthermore, when this point first came to be realized, it also became apparent that the data base was in poor shape. A flurry of measurements emerged in the late 1970's and well into the 1980's, with the objective being to reduce the uncertainty of tritium production from Li-7 at 14 MeV to about 3%, and providing better definition of the cross section at lower energies as well. Some of these measurements were discrepant, but gradually most of the sources of systematic error were identified and these uncertainties were reduced. By the late 1980's it became possible to claim with a reasonable degree of confidence that the stated objective had been met. The history of this reaction through 1984 is chronicled in an Argonne report [Smi+84]. A more recent evaluation of this process was undertaken at Los Alamos National Laboratory by Young using covariance matrix techniques to better establish the uncertainties. This work has been incorporated into ENDF/B-VI. The only weak point in our understanding of this reaction is in the threshold region (4-6 MeV) where the energy dependence is very sharp, and there have been no appropriate new measurements to better define the cross section there. Such measurements ought to be performed to reduce the uncertainty, but these require a capability to fabricate Li samples and perform tritium beta-decay measurements. Many laboratories who once possessed it have lost the capability, since most of the work was done about a decade ago. Because of these residual uncertainties, and because the production of tritium may depend quite a bit on the threshold behavior of the reaction in certain blanket configurations, it is necessary to give a marginal/adequate assignment to this process in this review.

Table 5 summarizes the situation for tritium production. It is our feeling that the current status is probably adequate, with the exception that some more work in the threshold reaction would be well worthwhile for $\text{Li-7}(n,n't)\text{He-4}$.

6. NEUTRON-MULTIPLICATION PROCESSES

The technological requirement is to maximize the neutron inventory in the fusion blanket (which contains lithium) in order to enhance the tritium production, as discussed above. Therefore, the cross sections for certain (n,2n) reactions, which are the prime candidates for neutron multipliers, are of interest. Also, the energy and angular spectra of secondary neutrons emitted in these reactions is important because these spectra must be folded with the Li cross sections to determine the tritium production. The important possibilities for neutron multiplication reactions are: 1) Be-9(n,2n)Be-8, 2) Pb(n,2n) and 3) Bi-209(n,2n)Bi-208. Of these, Be is the superior material because both Pb and Bi are afflicted with a parasitic problem, namely the production of unwanted long-lived activities. Bi is currently considered to be the least desirable of the three reactions. One point ought to be stressed to the fusion community, namely, that it is necessary to decide for sure (based on the design information now available) as to whether Pb and Bi are still considered as potential candidates for use as neutron-multiplier reactions. If not, then there is no point in expending further effort on these reactions when it is already certain that they are unfavorable and thus rejected. Here are reviews of these reactions:

Be-9(n,2n)Be-8:

The data base for this reaction is quite extensive. Nevertheless, along with Li-7, this process received extensive experimental and evaluational attention during the 1980's. Differential experiments were carried out at Argonne, and integral experiments were conducted at Livermore and in Japan. Some more integral studies in the Be(d,n) neutron field are still in progress at Argonne. EG&G-Idaho (INEL) has been commissioned to review the status of this reaction and to perform additional measurements. Finally, extensive R-matrix calculations were undertaken by the same individuals who studied Li (see above). Faster computers and more sophisticated R-matrix codes which incorporate nuclear shell-effect corrections have improved the reliability of the recent calculations for this mass region. Be has been re-evaluated by the Livermore group for ENDF/B-VI. The measurements have generally focused on cross sections (both differential and integral) rather than on neutron-emission spectra, but neutron-emission spectra have been measured at ANL. Furthermore, the theory provides a good basis for calculating neutron emission once the processes are understood and validated by experimental data. Under these circumstances, we would be inclined to say this reaction is adequately known until it is demonstrated otherwise.

Bi-209(n,2n)Bi-208:

There are data available for this reaction and the two most comprehensive sets of these are in reasonable agreement. Furthermore, (n,2n) processes are among the most convenient to calculate reliably with nuclear models, particularly when guided by some consistent data. This reaction was evaluated by the Argonne group for ENDF/B-VI. It was concluded that the cross section is known to within about 5% around 14 MeV, but to somewhat poorer accuracies right near threshold. Knowledge of the neutron-emission angular distributions and energy spectra are based on model calculations, and they are not so well known. Still, our understanding of this process is probably adequate for fusion applications for the present.

Pb(n,2n):

Pb-206, -207 and -208 are the dominant isotopes of elemental Pb, accounting for nearly 99% of the total. Each of these isotopes has been re-evaluated for ENDF/B-VI. Nuclear-model calculations for (n,2n) processes can be performed with reasonable reliability as mentioned. Furthermore, (n,2n) measurements have been performed in France for each of these nuclei, using separated isotopes. Knowledge of the neutron-emission angular distribution and energy spectra is based on nuclear-model calculations which are somewhat more speculative. Still, our understanding of these processes is assumed to be adequate for fusion applications for the present.

The situation for neutron multiplication reactions is summarized in Table 5. In our opinion, the situation is reasonably adequate for the present.

7. OTHER RELEVANT NUCLEAR PROCESSES

Finally, we need to discuss the other nuclear data requirements for fusion in general terms. In addition to overall neutronics interest, these concerns fall into several categories as indicated below.

Technological issues:

- 1) Radiation damage: This mainly involves consideration of radiation-induced displacements per atom (dpa) but also, to some extent, it incorporates the production of impurities and other nuclear transmutations. Just as important as the accuracy of the cross sections in determining dpa is the reliability of the models used to do so [Smi80]. Some modest effort has been devoted recently to studying this issue, including the development of a technique to calculate dpa for elements, compounds, etc. [Gre90].
- 2) Power (heat) generation: Usually this is referred to as kerma (kinetic energy released in materials). Knowledge of kerma is important in order to understand energy-deposition profiles in a fusion reactor and, thereby, to evaluate the thermal loading on various materials used in its construction. Of particular concern is the first wall/diverter/limiter. The components are situated in closest proximity to the plasma, and they experience a truly punishing thermal and radiation environment (particularly the first wall which is adjacent to the plasma chamber). Overall, the status of kerma calculations is still rather under-developed, and this is attributable to cross section problems as well as to other factors such as kerma modeling techniques.
- 3) Shielding: We are interested mainly in biological shielding, but, also, consideration must be given to the shielding of magnets and other critical components of a fusion reactor.
- 4) Hybrid blanket: Fission/fusion hybrid schemes have been suggested as possible energy sources throughout the long history of fusion-reactor development investigations. None of these schemes appears to be currently in favor. However, for the present considerations, the relevant interest would be in the cross sections of U, Th and Pu. All of these processes are quite well known as a consequence of fission-reactor development programs, so no further comments need be made at this point. Should hybrid concepts return to favor, it is not likely that these cross sections will be a source of major concern.
- 5) Gamma-ray production: Our concern so far has been with neutron reactions, but there is certainly considerable interest in photon production reactions and photon cross sections because photons are partially responsible for propagating energy in a fusion

reactor. As indicated earlier in this report, this technical area is beyond the experience of the authors and therefore is not a part of the present review. We are aware, however, the ENDF/B-VI evaluations strive to maintain energy balance and include photon production in these considerations. Explicit photon production files are available for most comprehensive evaluations, and one can be sure that the total photon energy released is adequately known, at least to the extent that the neutron and particle cross sections are known. We expect that the main problem lies in specifying the energy distribution of these photons. There are fewer experimental data in this area than is the case for neutron reactions with particle emission. Only a few experimental programs have addressed this topic explicitly, among them the fairly extensive program at ORNL over a decade ago (Kinney, Perey, et al.) and, more recently at ORNL, the work of Dickens and Larson. Photon-production cross sections can be calculated from nuclear-model codes, but this requires knowledge of additional parameters (e.g., dipole strengths) not normally employed for particle emission calculations. Judging from the reliability of the model codes in dealing with particle data (as mentioned above on several occasions), we suspect that the situation is likewise very uncertain for photon emission calculations.

Reactions:

For most of the concerns mentioned above, neutron elastic and inelastic scattering plus the $(n,2n)$ reaction are the major contributors to the effects we must deal with. The exception is for light nuclei, where certain (n,CP) reactions are also important ($CP =$ charged-particle). For example, in calculating dpa from Al, neutron elastic and inelastic scattering accounts for 75% of dpa. The $(n,2n)$ is responsible for only a very small fraction of this effect, and CP processes account for the rest. At lower energies, neutron elastic and inelastic scattering account for an even larger fraction. Al has a relatively low Z , so the CP reactions are considerably larger than they would be for many heavier elements. In the following review, we will focus mainly on the status of elastic and inelastic scattering and the $(n,2n)$ reaction. Another point to keep in mind is that extensive total cross section data of reasonably high quality exist for most materials. This provides a check on the "envelope" to which all other processes must sum. Furthermore, it is very important to know the total cross section if one is to fix uniquely the neutron interaction parameters which are required for calculating the various partial reaction processes. Here are some general comments on these major processes:

Neutron elastic scattering:

Measurements have been made at Argonne, as well as at various other laboratories, for many materials of interest to fusion. The data are quite extensive at energies below 10 MeV, but they are

considerably sparser at higher energies. There is a need for comprehensive 14-MeV scattering measurements. Nevertheless, the underlying physical processes associated with elastic scattering are becoming much better known and various models (i.e., optical/statistical model, the dispersive optical model and coupled-channels models) can be used to calculate scattering cross sections quite accurately (i.e., to few-percent accuracies) when there are data to assist in the selection of model parameters. The success is far better than for calculating (n,CP) processes. The main reason is that the interaction parameters for neutrons in a nuclear potential are fairly well known. There are neutrons on both the entrance and exit channels so the models are relatively reliable. However, there are some important transformations which occur in the reaction mechanisms between about 5 to 15 MeV, as the conversion from statistical-compound-nucleus to direct interaction is observed to take place. These transformations are beginning to be understood in quite some detail below 10 MeV, owing to the extensive investigations which have taken place at Argonne, Ohio University, Duke University, etc., but more work is needed up to 14 MeV. The nuclear data community should undertake further work above 10 MeV and also investigate those nuclei where the data are sparse because of sample problems, etc.

Neutron inelastic scattering:

There are extensive data up to 10 MeV and also some values near 14 MeV. The data elsewhere are sketchy. A lot depends upon the detailed nature of the level structures, e.g. the spin/parity values for the levels. Complete information of this nature must be provided when using such nuclear models. This demonstrates the need for close cooperation between the cross section program and the A-Chain effort. In general, knowledge of the inelastic-scattering cross sections to dominant levels or clumps of excited levels is known to within 20-30% for most of the stable elements which tend to be conducive to the fabrication of convenient scattering samples. Nuclear models provide qualitative agreement with data when guided by reasonable parameter choices. Further work is needed above 10 MeV and for certain nuclei where the data are sparse because of sample problems.

(n,2n) process:

We have already discussed the nature of this process in the present report. The situation can be summarized as follows: In those situations where there are some reliable data near 14 MeV, and possibly a few selected values at lower energies, it is possible to calculate the cross section shape using nuclear models and anticipate fairly good reliability down toward threshold. There is no resonance structure and the neutron-penetration factors are known from the systematics of elastic and inelastic scattering.

Specific materials:

From among the plethora of materials that could be considered, Cheng [Che90a,Che90b] has selected those elements which he believes should receive special emphasis over the next few years:

Structural materials: V, Fe, Ni, Cr, Ti, Cu.

High temperature materials: Zr, Si, C.

Constituents of important compounds: F, O.

Shielding materials: B, W, Si, C, O, Fe.

Blanket materials, e.g. neutron multipliers and fuel breeding: Be, Pb, Li.

Specific discussion for each element:

It has been emphasized that we are focusing on elastic and inelastic scattering as well as the (n,2n) reaction in this portion of the review. Of course, there are some exceptions for the lighter nuclei. Since each of these processes is fairly easy to calculate to accuracies which, in several instances, could possibly satisfy the requirements for fusion (when guided by some pertinent data), we offer a few statements here for each element concerning the availability of experimental data and the existence of contemporary evaluations.

Vanadium:

There are data available for this nucleus for each of the processes. Model calculations have been performed and an evaluation for ENDF/B-VI was prepared at Argonne. We consider the status as adequate.

Iron:

There are data available for this nucleus for each of the processes. Model calculations have been performed and an evaluation on the dominant isotopes for ENDF/B-VI was prepared recently. We consider the status as adequate.

Nickel:

There are data available for this nucleus for each of the processes. Model calculations have been performed and an evaluation on each of the major isotopes for ENDF/B-VI was prepared recently. We consider the status as adequate.

Chromium:

There are data available for this nucleus for each of the processes. Model calculations have been performed and an evaluation of the dominant isotopes for ENDF/B-VI was prepared recently. We consider the status as adequate.

Titanium:

There are data available for this nucleus for each of the processes. Model calculations have been performed, and an elemental evaluation for ENDF/B-V was prepared by Argonne. Since this evaluation is over 10 years old, we shall treat our understanding of these data as marginal/adequate pending further review of the situation.

Copper:

There are data available for this nucleus for each of the processes. Model calculations have been performed and an evaluation for ENDF/B-VI has been prepared for each of the stable isotopes. We consider the status as adequate.

Zirconium:

There are data available for this nucleus for each of the processes. Model calculations have been performed and an evaluation is being prepared at Argonne for elemental Zr. We consider the status as adequate.

Silicon:

Data are available for elastic and inelastic scattering, but the data base for $(n,2n)$ is fairly sparse and these data scatter considerably. Si was recently re-evaluated for ENDF/B-VI by ORNL. Consider the status as marginal/adequate. More reliable $(n,2n)$ information is required to improve the situation.

Carbon:

The only major processes of interest are elastic and inelastic scattering. Both are very well known. The $(n,2n)$ process has a very high threshold, so it is not a concern. Here, the (n,α) process could be a concern since the cross section has a low threshold and is sizable. There are some data available, but they are sketchy. We will assume that our knowledge of the important cross sections is adequate, except possibly if it happens that the (n,α) process is a cause for concern in some applications.

Fluorine:

The processes of interest are elastic and inelastic scattering, and the $(n,2n)$, (n,α) and (n,p) reactions. The total cross section is well known, as are the (n,p) and (n,α) processes. The elastic and inelastic scattering are not very well known because of sample difficulties. The $(n,2n)$ reaction is also not very well known. The

data base reflects these problems. A new evaluation has been prepared for ENDF/B-VI, but it is based entirely on nuclear model calculations which, without adequate elastic and inelastic scattering data, are probably not very reliable. Consequently, we will treat the status as marginal/inadequate. An emphasis needs to be placed on developing techniques for performing scattering measurements on elements such as F which are normally found in stable form only in compounds.

Oxygen:

There are data available for elastic and inelastic scattering, and the $(n,2n)$, (n,p) and (n,α) reactions. As indicated for F, the (n,p) and (n,α) processes are significant in some light nuclei. The $(n,2n)$ process is relatively small, but there are data available. The quality of the elastic and inelastic scattering data are marginal, probably for the same reasons (pertaining to availability of stable measurement samples) as is the case for fluorine. $O-16$ is the dominant isotope and the others account for less than 1% of the total. This isotope was recently evaluated for ENDF/B-VI. This evaluation probably was based largely on nuclear modeling. Owing mainly to the uncertain quality of the available elastic and inelastic scattering data, we shall give this element an adequate/marginal status rating.

Boron:

Neutron interactions with boron are dominated by elastic scattering, the (n,α) reaction, and, to some extent, the $(n,n'\alpha)$ reaction. The (n,α) reaction is a primary standard up to a few-hundred keV, but the data become somewhat discrepant at higher energies. At low energies, it plays a role in detector technology for neutron-fluence measurements. An international task force exists to address the matter of the boron (n,α) and $(n,\alpha\text{-}\gamma)$ cross sections. The elastic-scattering information is marginal above 1 MeV. However, there are extensive data for the total cross section at higher energies. All in all, this makes for a rather strange behavior of boron. Actually, this nucleus is in the range where modern R-matrix calculations with shell-model corrections can be performed, and this has been accomplished at LANL and Ohio University. Modeling helps to tie the diverse data together, and it provides information on energy and angular distributions. Boron still presents a somewhat unsettled situation, so there is little choice but to label it as marginal/inadequate at present. Much depends upon the intended application in fusion systems.

Tungsten:

There are extensive data on elastic and inelastic scattering as well as on the $(n,2n)$ reaction for elemental W, as well as for some of the dominant isotopes. All other processes are very small. Nuclear-

model calculations have been performed, and there have been isotopic evaluations completed for all of the important W isotopes. Consequently, we shall assume that these processes are adequately known for fusion.

Beryllium:

A number of comments were made above concerning the (n,2n) process. There are considerable elastic scattering, inelastic scattering and total cross section data for Be as well, much of it from Argonne. There are no other significant processes to be considered. This reaction has been evaluated at LLNL for ENDF/B-VI. Be is amenable to contemporary R-matrix analysis, as mentioned above. Therefore, we will assume it is adequately known.

Lead:

Several comments were made above for the (n,2n) reaction. Experimental data are available for the total cross section, elastic scattering and (n,2n), for both the element and various important isotopes. There are no other processes of any importance in Pb. Nuclear-model calculations have been performed, and the dominant isotopes have been evaluated for ENDF/B-VI. Consequently, we shall assume that the cross sections are adequately known for applications.

Lithium:

Extensive elastic and inelastic scattering data are available, in addition to the tritium production cross sections mentioned above. Both Li-6 and Li-7 have been studied by R-matrix methods at several laboratories. There are new evaluations for both nuclei in ENDF/B-VI. Therefore, we will assume that they are adequately known for fusion applications.

The situation is summarized in Table 6.

8. A STRATEGY FOR IMPROVING THE DATA BASE FOR DOSIMETRY AND OTHER PERTINENT ACTIVATION PROCESSES

In this section, we provide an outline for a coordinated approach to meeting the stated cross section data needs for fusion. The general principles apply to meeting needs in all of the categories discussed above, but the emphasis in this section is on activation reaction data needs, including dosimetry. We would like to emphasize the importance of interlaboratory and international cooperation in this context. No single laboratory, or country for that matter, currently possesses sufficient resources to mount a unilateral effort. It is wise to continue to capitalize on the professional relationships that have been nurtured for several decades on a world-wide basis in addressing the critical nuclear-data needs for fusion.

General comments:

Clearly, it will take a combined effort, involving measurements, development of basic theory, studies of systematics, nuclear-model calculations, statistical information analysis and data evaluations, in order to meet the needs for fusion activation data. The reason is that these needs are so wide ranging in materials, half lives, decay properties and reaction types that no one approach will suffice. In the area of experiments, the need is really for differential information, but good use can be made of integral data in certain situations, particularly when differential measurements are nearly impossible due to poor sensitivity. Efforts have been made in all these areas, but there appears to be a general lack of coordination, i.e., it is an effort which lacks careful planning and a sense of direction. The first attempt at such an approach is represented by the IAEA CRP on Long Lived Activities which has been in progress since 1988 [DaH90]. More needs to be done along such lines.

Categories of data needs:

Three broad classes of data are needed: i) activity-decay half lives, ii) activity-decay mechanisms, with special attention to improving our knowledge of branching factors for prominent X-rays and gamma rays associated with reaction-product decay (since the most accurate contemporary measurement techniques require such quantitative information), iii) reaction cross sections from threshold, if applicable, to 15 MeV (in the case of capture reactions, a few MeV will generally suffice for the upper limit).

Activity half lives ---

The range of needs here is not large. In most instances, the requisite half lives are adequately known. Inadequate knowledge of half lives not only limits the quality of cross-section measurements, it also impacts upon the ability to calculate the time-dependent dose rates associated with operation of a fusion reactor and the behavior of the activity inventory for a variety of products left over after

the reactor is shut down. The effects on servicing or decommissioning a fusion reactor is obvious. There are a number of shortcomings in the data base, even for some half lives of modest time duration, e.g., minutes, hours and days. The biggest problems are associated with the long half lives. The only way these needs will be met are by measurements. The evaluation effort in this area seems ample (A-Chain project). What is needed is new observational input to the system. A single measurement will not suffice, and some sophisticated radiation detection techniques will be required in certain instances to carry out the measurements. Laboratories equipped to perform such measurements ought to be supported to undertake them. Target accuracies of a few percent or better are needed. A lot depends on the intended use. For general activation and waste disposal applications, the needs are not so stringent. For dosimetry applications the accuracy requirements are more stringent, especially when the activity measurements will extend over several half lives of the reaction product.

Decay schemes ---

The needs for decay scheme information are more extensive than those for half-life data. Otherwise, the comments are the same as indicated above for half lives.

Cross sections ---

Cross section data are needed from threshold, if applicable, to 15 MeV. In the case of capture reactions, an upper limit of a few MeV is probably adequate. A comprehensive review of the actual cross section needs is essential before undertaking a coordinated program to meet the needs. This requires a specification of materials, reaction types and target accuracies. The latter will depend largely on the expected system spectral sensitivity to the data. The effort required to satisfy specified accuracy levels increases very rapidly with a decrease in the target percentage accuracies (it is a very non-linear relationship). It would be very imprudent to request 1% accuracy when 5% would be completely adequate, and possibly 10-20% accuracy would answer some key questions. It is a matter of judgment which can be supplied only by fusion-reactor designers. Once the list of reactions and target accuracies has been established, there is a need to divide the list into three basic categories: i) unmeasurable (not practical to provide any data using contemporary facilities and technologies), ii) marginally measurable (some data could be provided at key energies, e.g., 14 MeV, using brute-force techniques), iii) measurable (comprehensive measurements, at a sufficient number of neutron energies to define the excitation function, could be made using contemporary facilities and techniques--usually it is just a matter of time and manpower to do the job). Some facility development effort will surely be required for (ii) and, quite possibly, for (iii) above.

Coordinated procedures to provide the required information:

We focus here on cross sections because, as indicated above, measurements offer the only approach for satisfying half life and

decay scheme data. In the case of cross sections, what is required are specific measurements, investigations of systematics and specific model calculations. Development of basic theories and specific model-parameter studies also will be needed in order to improve the effectiveness of the nuclear-model calculations. Statistical methods ultimately will be required to merge this information in a sound fashion in order to provide the best possible evaluations for the cross sections. The exercise of sound judgment, on a case-by-case basis, will be required so as to come up with a comprehensive plan for satisfying the cross section needs. Basically this decision process will involve determining the right mix of investigative tools, i.e., measurements, theory, systematics studies and model calculations.

Measurements ---

Whenever a specific quantity can be measured without undue difficulty, then this is the method of choice to determine the required information. A single measurement will never suffice. The possibilities for systematic error are just too great. The scope of the required measurements depends greatly on the nature of the process. It is very important that uncertainty estimates be provided for all the measured quantities. The following list gives an indication of the minimal requirements for each reaction type:

(n,n'): Measurements are needed at a few points from threshold to 14 MeV, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

(n,2n): The minimal requirement is a good knowledge of the 14-MeV cross section. But, a few measurements at lower energies is very desirable.

(n,gamma): The minimal requirement is energy-averaged information from about 1 keV to several MeV. In some instances, detailed resonance information may be required.

(n,p): Measurements at a few points from threshold to 14 MeV are needed, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

(n,alpha): Measurements are needed at a few points from threshold to 14 MeV, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

(n,n'p+d): Measurements are needed at a few points from threshold to 14 MeV, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

(n,t): Measurements are needed at a few points from threshold to 14 MeV, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

(n,He-3): Measurements are needed at a few points from threshold to 14 MeV, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

(n,n'alpha): Measurements are needed at a few points from threshold to 14 MeV, especially at inflection points where the onset of a competing process causes a significant change in the trend of the cross section.

Other processes: Most of these are not significant, but they must be considered on a case-by-case basis, and a plan for satisfying the requirements should be developed accordingly.

Studies of systematics ---

These are very important because they can be used to guide model calculations in those instances where processes are essentially unmeasurable. Such studies have been performed, e.g., for (n,2n), (n,p), (n,alpha) and (n,t) processes at 14 MeV. These were facilitated by the existence of a large cross section data base for this energy region.

Nuclear-model calculations ---

Any desired quantity can be calculated if an appropriate computer-code package is available, but the quality of the result hinges on the sophistication of the model codes used and on their parameterizations. Model-code sophistication can be judged by the included Physics. For this reason, continued effort on improving the Physics incorporated in the model codes should be supported. No one should use a model code as a "black box" without understanding the principles upon which it is based, and the limitations which apply to its use. Knowledge of the parameters is another matter. It is now evident that many commonly used nuclear-model parameters vary dramatically from element to element and isotope to isotope, mainly reflecting details of nuclear shell structure. This is why extensive comparisons of model results with data is so important. They serve to confirm the systematics of model parameters, and also to establish the magnitudes of the corresponding variations which are likely to be encountered in going from element to element. This will facilitate the specification of uncertainties associated with those model calculations which cannot be readily guided by data. An enormous amount of work is needed here to exploit the possibilities which this approach offers. Put in simplest terms, the situation is this: If we cannot calculate reliably those things we can measure directly (without fudging), then we can hardly expect to trust our calculations for those quantities we cannot measure at all.

Statistical procedures and evaluations ---

Evaluation entails the sophisticated merging of all available information on a particular physical quantity, i.e., experimental data, model calculations, and values deduced from studies of systematics. Decisions have to be made concerning the scope of any experimental data base that is to be evaluated. For example, it must be established whether the data evaluation should focus on a specific energy range (e.g., in the vicinity of 14 MeV). All information included in an evaluation must be incorporated in a manner which reflects appropriately the confidence one ought to have in that information. Reliable information needs to be weighted much more heavily than speculative information. The confidence we ultimately have in a final cross section evaluation must be quantified by attributing numerical uncertainties to the recommended parameters so that these can then be propagated properly through to the final observables of a fusion reactor system, as required. Without such quantitative specifications of confidence, the evaluation is essentially useless for engineering-development purposes.

9. CONCLUSIONS

There is no doubt in our minds that a great deal of work needs to be done to satisfy the current list of requests for fusion nuclear data, as compiled by Cheng [Che90a,Che90b].

First, let us consider dosimetry reactions. The pertinent information for making a judgment appears in Tables 1-3. Obviously, knowledge of the cross sections cannot be divorced from an understanding of the basic decay information. There are no serious deficiencies in knowledge of the dosimetry reaction decay half lives, but 9 out of 25 could benefit from some improvement if they are to be used effectively over time ranges extending to several half lives. When examining other relevant decay parameters, particularly branching factors, we found that out of 25 reactions reviewed, 14 are adequately known, 5 are marginally known and 5 are inadequately known for dosimetry purposes. Therefore, there are some serious shortcomings in the decay data base. This matter needs attention. Finally, consider the dosimetry reaction cross sections. We found that out of 29 reactions, 15 are adequately known for dosimetry, while 6 are clearly inadequate. Of the remaining ones, 4 are marginal and 4 range from adequate to inadequate depending upon the intended energy range for use of the dosimeter. There are clearly some serious problems here that demand attention.

In the category of activation reactions for other fusion concerns, mainly waste disposal, there are 132 reactions which were considered (see Table 4). Among these, we found that 31 were probably adequately known, 31 were of marginal status (to varying degrees) and 69 were clearly inadequate. This is certainly a very unacceptable state of affairs. Unfortunately, many of the reactions on the list will be very difficult to study experimentally.

It appears that the current situation is reasonably acceptable for the main fuel-cycle reactions, for the neutron multiplication reactions and for tritium fuel breeding, with the possible exception of the $\text{Li-7}(n,n't)\text{He-4}$ reaction near threshold (see Table 5 for a summary of the situation).

The nuclear-data needs for a host of additional requirements and materials are summarized in Table 6. Sixteen elements were examined in the present review. For 11 of these, the situation appears to be reasonably acceptable at present. For the others, it is marginal to varying degrees.

Finally, we must keep in mind that the nuclear-data needs for fusion are constantly changing, with regard to materials, reaction processes and levels of accuracy demanded. We are convinced that, on

the whole, these requirements will become even more extensive with the passing of time as fusion technology focuses more on the nuclear issues in the future. Surely, certain materials and processes will eventually be dropped from the request list, as some of the design options now being considered are abandoned in favor of the final choices for engineering development. However, at that stage, the demands for accuracy will no doubt escalate for those nuclear processes which remain at the forefront of concern for the technology. This was true in the development of fission-reactor technology, so there is no reason to suspect that matters will be any different for fusion.

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Table 1: Status of reaction cross sections for high-priority dosimetry reactions

| <u>Reaction Number</u> | <u>Reaction</u> | <u>Comments on Status</u> |
|------------------------|-------------------------|-----------------------------------|
| 1 | O-16(n, alpha)C-13 | Marginal |
| 2 | Mg-24(n, p)Na-24 | Adequate |
| 3 | Al-27(n, p)Mg-27 | Marginal |
| 4 | Al-27(n, alpha)Na-24 | Adequate |
| 5 | Si-28(n, p)Al-28 | Marginal/inadequate* |
| 6 | P-31(n, p)Si-31 | Marginal/inadequate* |
| 7 | Cl-35(n, 2n)Cl-34m | Inadequate |
| 8 | K-39(n, 2n)K-38 | Adequate |
| 9 | Ti-47(n, p)Sc-47 | Adequate/marginal/inadequate* |
| 10 | Ti-48(n, p)Sc-48 | Adequate |
| 11 | Fe-56(n, p)Mn-56 | Adequate |
| 12 | Ni-58(n, 2n)Ni-57 | Adequate |
| 13 | Co-59(n, alpha)Mn-56 | Adequate |
| 14 | Cu-63(n, gamma)Cu-64 | Inadequate. Questionable utility. |
| 15 | Cu-63(n, 2n)Cu-62 | Adequate |
| 16 | Zn-64(n, p)Cu-64 | Marginal |
| 17 | Zn-64(n, 2n)Zn-63 | Adequate/marginal* |
| 18 | Rb-85(n, 2n)Rb-84m | Inadequate |
| 19 | Zr-90(n, p)Y-90m | Inadequate |
| 20 | Zr-90(n, 2n)Zr-89m | Inadequate |
| 21 | Rh-103(n, n')Rh-103m | Marginal. Hard to use. |
| 22 | In-115(n, gamma)In-116m | Adequate |
| 23 | In-115(n, n')In-115m | Adequate |
| 24 | Au-197(n, gamma)Au-198 | Adequate |
| 25 | Au-197(n, 2n)Au-196 | Adequate |
| 26 | Hg-199(n, n')Hg-199m | Inadequate |
| 27 | U-235(n, f) | Adequate, depending on use. |
| 28 | Np-237(n, f) | Adequate, depending on use. |
| 29 | U-238(n, f) | Adequate, depending on use. |

* Status may vary depending on intended use (i.e., the energy range of interest).

Table 2: Reaction-product-decay half lives for high-priority dosimetry reactions

| <u>Reaction</u> | <u>Half life</u> | <u>Comments on Status</u> |
|------------------------|---------------------------|---------------------------|
| Mg-24(n,p)Na-24 | 14.9590 h (\pm 0.008%) | Very-well known |
| Al-27(n,p)Mg-27 | 9.462 m (\pm 0.1%) | Quite-well known |
| Al-27(n,alpha)Na-24 | 14.9590 h (\pm 0.008%) | Very-well known |
| Si-28(n,p)Al-28 | 2.2414 m (\pm 0.05%) | Quite-well known |
| P-31(n,p)Si-31 | 157.3 m (\pm 0.2%) | Needs improvement |
| Cl-35(n,2n)Cl-34m | 32.00 m (\pm 0.1%) | Reasonably-well known |
| K-39(n,2n)K-38 | 7.636 m (\pm 0.2%) | Needs improvement |
| Ti-47(n,p)Sc-47 | 3.345 d (\pm 0.09%) | Quite-well known |
| Ti-48(n,p)Sc-48 | 43.7 h (\pm 0.2%) | Needs improvement |
| Fe-56(n,p)Mn-56 | 2.5785 h (\pm 0.008%) | Very-well known |
| Ni-58(n,2n)Ni-57 | 35.65 h (\pm 0.1%) | Quite-well known |
| Co-59(n,alpha)Mn-56 | 2.5785 h (\pm 0.008%) | Very-well known |
| Cu-63(n,gamma)Cu-64 | 12.701 h (\pm 0.02%) | Very-well known |
| Cu-63(n,2n)Cu-62 | 9.74 m (\pm 0.2%) | Needs improvement |
| Zn-64(n,p)Cu-64 | 12.701 h (\pm 0.02%) | Very-well known |
| Zn-64(n,2n)Zn-63 | 38.50 m (\pm 0.2%) | Needs improvement |
| Rb-85(n,2n)Rb-84m | 20.26 m (\pm 0.2%) | Needs improvement |
| Zr-90(n,p)Y-90m | 3.19 h (\pm 0.3%) | Needs improvement |
| Zr-90(n,2n)Zr-89m | 4.18 h (\pm 0.2%) | Needs improvement |
| Rh-103(n,n')Rh-103m | 56.12 m (\pm 0.02%) | Very-well known |
| In-115(n,gamma)In-116m | 54.41 m (\pm 0.06%) | Quite-well known |
| In-115(n,n')In-115m | 4.486 h (\pm 0.09%) | Quite-well known |
| Au-197(n,gamma)Au-198 | 2.6935 d (\pm 0.01%) | Very-well known |
| Au-197(n,2n)Au-196 | 6.186 d (\pm 0.2%) | Needs improvement |
| Hg-199(n,n')Hg-199m | 42.6 m (\pm 0.5%) | Needs improvement |
| U-235(n,f) | Various Fission Prod. | Not reviewed |
| Np-237(n,f) | Various Fission Prod. | Not reviewed |
| U-238(n,f) | Various Fission Prod. | Not reviewed |

Table 3: Reaction-product-decay properties for high-priority dosimetry reactions

| <u>Reaction</u> | <u>Decay Processes</u> | <u>Comments on Status</u> |
|-------------------------|---------------------------|---------------------------|
| O-16(n, alpha)C-13 | Stable | Not relevant |
| Mg-24(n, p)Na-24 | Beta, Gamma | Adequate |
| Al-27(n, p)Mg-27 | Beta, Gamma | Adequate |
| Al-27(n, alpha)Na-24 | Beta, Gamma | Adequate |
| Si-28(n, p)Al-28 | Beta, Gamma | Adequate |
| P-31(n, p)Si-31 | Beta | Questionable utility |
| Cl-35(n, 2n)Cl-34m | Beta, EC, Gamma | Inadequate |
| K-39(n, 2n)K-38 | EC, Gamma | Adequate |
| Ti-47(n, p)Sc-47 | Beta, Gamma | Marginally-adequate |
| Ti-48(n, p)Sc-48 | Beta, Gamma | Adequate |
| Fe-56(n, p)Mn-56 | Beta, Gamma | Adequate |
| Ni-58(n, 2n)Ni-57 | Positron, EC, Gamma | Adequate |
| Co-59(n, alpha)Mn-56 | Beta, Gamma | Adequate |
| Cu-63(n, gamma)Cu-64 | Positron, EC, Beta, Gamma | Marginally-adequate |
| Cu-63(n, 2n)Cu-62 | Positron, EC, Gamma | Inadequate |
| Zn-64(n, p)Cu-64 | Positron, EC, Beta, Gamma | Marginally-adequate |
| Zn-64(n, 2n)Zn-63 | Positron, EC, Gamma | Inadequate |
| Rb-85(n, 2n)Rb-84m | IT, Gamma | Adequate |
| Zr-90(n, p)Y-90m | IT, Beta | Inadequate |
| Zr-90(n, 2n)Zr-89m | Beta, EC, IT, Gamma | Adequate |
| Rh-103(n, n')Rh-103m | IT, X-rays | Inadequate |
| In-115(n, gamma)In-116m | Beta, Gamma | Marginally-adequate |
| In-115(n, n')In-115m | IT, Beta, Gamma | Adequate |
| Au-197(n, gamma)Au-198 | Beta, Gamma | Adequate |
| Au-197(n, 2n)Au-196 | EC, Beta, Positron, Gamma | Adequate |
| Hg-199(n, n')Hg-199m | IT, Gamma | Adequate |
| U-235(n, f) | Various Fission Products | Not reviewed |
| Np-237(n, f) | Various Fission Products | Not reviewed |
| U-238(n, f) | Various Fission Products | Not reviewed |

Table 4: Status of nuclear data for fusion activation cross sections

| <u>Reaction</u> | <u>Half life</u> | <u>Decay features</u> | <u>Cross section</u> |
|--------------------------|------------------|-----------------------|-------------------------|
| Ag-109(n,2n)Ag-108m | Inadequate | Adequate | Inadequate |
| Ag-107(n,gamma)Ag-108m | Inadequate | Adequate | Inadequate |
| Al-27(n,alpha)Na-24 | Adequate | Adequate | Adequate |
| Al-27(n,p)Mg-27 | Adequate | Adequate | Adequate |
| Al-27(n,2n)Al-26 | Adequate | Adequate | Inadequate |
| Bi-209(n,gamma)Bi-210 | Adequate | Adequate | Inadequate |
| Bi-209(n,2n)Bi-208 | Adequate | Marginal/adequate | Adequate |
| Bi-209(n,n'alpha)Tl-204* | Adequate | Marginal | Inadequate |
| Ca-44(n,gamma)Ca-45 | Adequate | Marginal | Inadequate |
| Ca-42(n,alpha)Ar-39 | Adequate | Marginal | Inadequate |
| Ca-43(n,n'alpha)Ar-39 | Adequate | Marginal | Inadequate |
| Ca-40(n,2p)Ar-39: | Adequate | Marginal | Inadequate |
| Co-59(n,gamma)Co-60 | Adequate | Adequate | Marginal/ Inadequate |
| Co-59(n,2n)Co-58 | Adequate | Adequate | Adequate |
| Cr-50(n,gamma)Cr-51 | Adequate | Adequate | Inadequate |
| Cr-52(n,2n)Cr-51 | Adequate | Adequate | Adequate |
| Cu-63(n,p)Ni-63 | Adequate | Marginal | Inadequate |
| Cu-65(n,t)Ni-63 | Adequate | Marginal | Inadequate |
| Cu-63(n,gamma)Cu-64 | Adequate | Adequate | Adequate |
| Cu-65(n,2n)Cu-64 | Adequate | Adequate | Adequate |
| Cu-65(n,gamma)Cu-66 | Adequate | Inadequate | Marginal |
| Cu-63(n,alpha)Co-60 | Adequate | Adequate | Adequate |
| Cu-63(n,2n)Cu-62 | Adequate | Marginal | Adequate |
| Cu-65(n,p)Ni-65 | Adequate | Marginal | Marginal |
| F-19(n,2n)F-18 | Adequate | Adequate | Adequate |
| F-19(n,gamma)F-20 | Adequate | Adequate | Marginal |
| Fe-56(n,2n)Fe-55 | Adequate | Marginal | Adequate |
| Fe-54(n,p)Mn-54 | Adequate | Adequate | Adequate |
| Fe-56(n,p)Mn-54: | Adequate | Adequate | Adequate |
| F-58(n,gamma)Co-60* | Inadequate | Marginal | Inadequate |
| Fe-54(n,n'p)Mn-53 | Inadequate | Marginal | Inadequate |
| Hf-179(n,2n)Hf-178m2 | Inadequate | Adequate | Inadequate |
| Hf-178(n,2n)Hf-177m | Adequate | Inadequate | Inadequate |
| Hf-177(n,gamma)Hf-178m2 | Inadequate | Adequate | Inadequate |
| Hf-179(n,gamma)Hf-180m | Inadequate | Adequate | Inadequate |
| Hf-180(n,gamma)Hf-181 | Adequate | Marginal | Inadequate |
| Hg-204(n,2n)Hg-203 | Adequate | Adequate | Inadequate |
| Tl-203(n,gamma)Tl-204 | Adequate | Inadequate | Inadequate |

Table 4: (continued)

| <u>Reaction</u> | <u>Half life</u> | <u>Decay features</u> | <u>Cross section</u> |
|---------------------------|------------------|-----------------------|-------------------------|
| Hg-198 (n,2n) Hg-197,197m | Adequate | Inadequate | Inadequate |
| Hg-200 (n,2n) Hg-199m: | Adequate | Adequate | Inadequate |
| Hg-198 (n,gamma) Hg-199m | Adequate | Adequate | Inadequate |
| Hg-200 (n,p) Au-200m | Inadequate | Inadequate | Inadequate |
| Hg-196 (n,p) Au-196 | Adequate | Adequate | Inadequate |
| Hg-196 (n,n'p) Au-195 | Adequate | Inadequate | Inadequate |
| Hg-196 (n,alpha) Pt-193 | Inadequate | Inadequate | Inadequate |
| Mg-24 (n,p) Na-24 | Adequate | Adequate | Adequate |
| Mg-25 (n,n'p) Na-24 | Adequate | Adequate | Inadequate |
| Mg-24 (n,t) Na-22 | Adequate | Adequate | Inadequate |
| Mg-24 (n,n'p) Na-22* | Adequate | Adequate | Inadequate |
| Mg-26 (n,gamma) Mg-27 | Adequate | Adequate | Inadequate |
| Mn-55 (n,gamma) Mn-56 | Adequate | Adequate | Adequate |
| Mn-55 (n,2n) Mn-54 | Adequate | Adequate | Adequate |
| Mo-95 (n,p) Nb-95 | Adequate | Adequate | Marginal/ Inadequate |
| Mo-96 (n,n'p) Nb-95 | Adequate | Adequate | Inadequate |
| Mo-97 (n,t) Nb-95 | Adequate | Adequate | Inadequate |
| Mo-98 (n,gamma) Tc-99* | Adequate | Inadequate | Inadequate |
| Mo-98 (n,gamma) Tc-99m* | Adequate | Inadequate | Inadequate |
| Mo-200 (n,2n) Tc-99* | Adequate | Inadequate | Inadequate |
| Mo-200 (n,2n) Tc-99m | Adequate | Inadequate | Inadequate |
| Tc-99 (n,2n) Tc-98 | Inadequate | Inadequate | Inadequate |
| Tc-98 (n,2n) Tc-97m | Adequate | Inadequate | Inadequate |
| Mo-92 (n,alpha) Y-88 | Adequate | Adequate | Inadequate |
| Mo-92 (n,gamma) Mo-93 | Inadequate | Inadequate | Inadequate |
| Mo-94 (n,2n) Mo-93 | Inadequate | Inadequate | Inadequate |
| N-14 (n,p) C-14 | Adequate | Adequate | Adequate |
| N-14 (n,n'alpha) Be-10* | Inadequate | Inadequate | Inadequate |
| Na-23 (n,2n) Na-22 | Adequate | Adequate | Marginal |
| Na-23 (n,gamma) Na-24 | Adequate | Adequate | Adequate |
| Nb-93 (n,2n) Nb-92,92m | Inadequate | Inadequate | Adequate |
| Nb-93 (n,gamma) Nb-94 | Inadequate | Adequate | Adequate |
| Nb-93 (n,n') Nb-93m | Adequate | Adequate | Adequate |
| Nb-93 (n,n'alpha) Y-88* | Adequate | Adequate | Adequate |
| Ni-58 (n,p) Co-58 | Adequate | Adequate | Adequate |
| Ni-60 (n,t) Co-58 | Adequate | Adequate | Inadequate |
| Ni-58 (n,n'p) Co-57 | Adequate | Adequate | Marginal |
| Ni-58 (n,2n) Co-57* | Adequate | Adequate | Adequate |
| Ni-60 (n,p) Co-60 | Adequate | Adequate | Marginal |
| Ni-58 (n,alpha) Fe-55 | Adequate | Marginal | Marginal |
| Ni-58 (n,gamma) Ni-59 | Inadequate | Marginal | Marginal/ Inadequate |
| Ni-60 (n,2n) Ni-59 | Inadequate | Marginal | Marginal/ Inadequate |

Table 4: (continued)

| <u>Reaction</u> | <u>Half life</u> | <u>Decay features</u> | <u>Cross section</u> |
|---------------------------------------|------------------|-----------------------|-------------------------|
| Ni-62(n,He-3)Fe-60 | Inadequate | Inadequate | Inadequate |
| Ni-64(n,n'alpha)Fe-60 | Inadequate | Inadequate | Inadequate |
| O-16(n,p)N-16 | Adequate | Adequate | Adequate |
| O-17(n,alpha)C-14 | Adequate | Adequate | Inadequate |
| O-18(n,n'alpha)C-14 | Adequate | Adequate | Inadequate |
| Pb-208(n,gamma)Po-210* | Inadequate | Marginal | Marginal/ Inadequate |
| Pb-208(n,gamma)Bi-208* | Marginal | Marginal | Marginal |
| Pb-204(n,2n)Pb-203 | Adequate | Adequate | Adequate |
| Pb-204(n,t)Tl-202 | Adequate | Adequate | Inadequate |
| Pb-206(n,alpha)Hg-203 | Adequate | Adequate | Marginal/ Inadequate |
| Pb-207(n,n'alpha)Hg-203 | Adequate | Adequate | Marginal/ Inadequate |
| Pb-204(n,p)Tl-204 | Adequate | Adequate | Inadequate |
| Pb-206(n,t)Tl-204 | Adequate | Adequate | Inadequate |
| Re-185(n,gamma)Re-186g,m | Inadequate | Inadequate | Adequate/ Marginal |
| Re-187(n,2n)Re-186g,m | Inadequate | Inadequate | Adequate/ Marginal |
| Re-187(n,gamma)Re-188g,m | Adequate | Inadequate | Adequate/ Marginal |
| Re-185(n,2n)Re-184 | Inadequate | Adequate/Marginal | Marginal |
| Re-187(n,p)W-187 | Adequate | Inadequate | Marginal/ Inadequate |
| Re-187(n,alpha)Ta-184 | Marginal | Adequate | Marginal/ Inadequate |
| Re-185(n,alpha)Ta-182 | Adequate | Adequate | Inadequate |
| Si-28(n,n'p)Na-24*, Na-22*, Al-26* | Adequate | Adequate | Inadequate |
| Si-28(n,alpha)Na-24*, Na-22* | Adequate | Adequate | Inadequate |
| Si-28(n,n'alpha)Na-24* | Adequate | Adequate | Inadequate |
| Ta-181(n,gamma)Ta-182 | Adequate | Adequate | Adequate |
| Ta-180(n,t)Hf-178m2 | Inadequate | Adequate | Inadequate |
| T-48(n,alpha)Ca-45 | Adequate | Marginal | Inadequate |
| Ti-48(n,p)Sc-48 | Adequate | Adequate | Adequate |
| Ti-46(n,p)Sc-46, | Adequate | Adequate | Adequate |
| Ti-47(n,n'p)Sc-46 | | | |
| Ti-46(n,n'alpha)Ca-41, Ar-39* | Adequate | Adequate | Inadequate |
| V-51(n,alpha)Sc-48 | Adequate | Adequate | Adequate |
| V-50(n,2n)V-49 | Adequate | Marginal | Marginal |
| V-51(n,n'alpha)Sc-47 | Adequate | Adequate | Adequate/ Marginal |

Table 4: (continued)

| <u>Reaction</u> | <u>Half life</u> | <u>Decay features</u> | <u>Cross section</u> |
|--------------------------------------|------------------|-----------------------|-------------------------|
| V-50(n,n'alpha)Sc-46 | Adequate | Adequate | Inadequate |
| V-51(n,t)Ca-45 | Adequate | Marginal | Inadequate |
| Sc-45(n,n'alpha)Ar-39* | Adequate | Marginal | Inadequate |
| K-41(n,t)Ar-39 | Adequate | Marginal | Inadequate |
| W-186(n,2n)W-185 | Adequate | Marginal | Adequate |
| W-184(n,gamma)W-185 | Adequate | Marginal | Adequate |
| W-182(n,p)Ta-182 | Adequate | Adequate | Marginal |
| W-183(n,n'p)Ta-182 | Adequate | Adequate | Marginal/ Inadequate |
| W-184(n,t)Ta-182 | Adequate | Adequate | Inadequate |
| W-182(n,n'alpha)Hf-178 _{m2} | Inadequate | Adequate | Inadequate |
| W-186(n,n'alpha)Hf-182 | Inadequate | Marginal | Inadequate |
| Zn-64(n,gamma)Zn-65 | Adequate | Adequate | Inadequate |
| Zr-90(n,2n)Zr-89 | Adequate | Adequate | Adequate |
| Zr-90(n,t)Y-88 | Adequate | Adequate | Marginal/ Inadequate |
| Zr-94(n,gamma)Zr-95 | Adequate | Adequate | Marginal/ Inadequate |
| Zr-96(n,2n)Zr-95 | Adequate | Adequate | Adequate/ Marginal |
| Zr-92(n,gamma)Zr-93, Nb-94* | Inadequate | Inadequate | Inadequate |
| Zr-94(n,2n)Zr-93 Nb-94* | Inadequate | Inadequate | Inadequate |

* Multi-step process leading to the indicated product.

Table 5: Status of reaction cross sections for special applications in fusion technology

| <u>Application</u> | <u>Reaction</u> | <u>Status</u> |
|------------------------|--------------------|-----------------------|
| Fuel cycle | D-T | Adequate |
| | D-D | Adequate |
| | D-He-3 | Adequate |
| Fuel breeding | Li-6(n,t)He-4 | Adequate |
| | Li-7(n,n't)He-4 | Marginal/ adequate |
| Neutron multiplication | Be-9(n,2n)Be-8 | Adequate |
| | Bi-209(n,2n)Bi-208 | Adequate |
| | Pb-206(n,2n)Pb-205 | Adequate |
| | Pb-207(n,2n)Pb-206 | Adequate |
| | Pb-208(n,2n)Pb-207 | Adequate |

Table 6: Status of reaction cross sections for other design and development requirements in fusion technology*

| <u>Material</u> | <u>Reactions</u> | <u>Application</u> | <u>Status</u> |
|-----------------|------------------------------------|------------------------------------|-------------------------|
| Vanadium | $(n,n), (n,n'), (n,2n)$ | Structural | Adequate |
| Iron | $(n,n), (n,n'), (n,2n)$ | Structural, shielding | Adequate |
| Nickel | $(n,n), (n,n'), (n,2n)$ | Structural | Adequate |
| Chromium | $(n,n), (n,n'), (n,2n)$ | Structural | Adequate |
| Titanium | $(n,n), (n,n'), (n,2n)$ | Structural | Marginal/ adequate |
| Copper | $(n,n), (n,n'), (n,2n)$ | Structural | Adequate |
| Zirconium | $(n,n), (n,n'), (n,2n)$ | High temperature | Adequate |
| Silicon | $(n,n), (n,n'), (n,2n)$ | High temperature | Marginal/ adequate |
| Carbon | $(n,n), (n,n'), (n,\alpha)$ | High temperature, Shielding | Adequate |
| Fluorine | $(n,n), (n,n'), (n,p), (n,\alpha)$ | Compound constituent | Marginal/ inadequate |
| Oxygen | $(n,n), (n,n'), (n,p), (n,\alpha)$ | Compound constituent, Shielding | Adequate/ marginal |
| Boron | $(n,n), (n,\alpha), (n,t, \alpha)$ | Shielding | Marginal/ inadequate |
| Tungsten | $(n,n), (n,n'), (n,2n)$ | Shielding | Adequate |
| Beryllium | $(n,n), (n,n'), (n,2n)$ | Neutron multiplier | Adequate |
| Lead | $(n,n), (n,n'), (n,2n)$ | Neutron multiplier | Adequate |
| Lithium | $(n,n), (n,n'), (n,t), (n,n't)$ | Fuel breeding | Adequate |

* The interest in this context is in overall neutronic, radiation damage (dpa), heat generation (kerma), and shielding processes.