STATUS OF CROSS-SECTION DATA FOR GAS PRODUCTION FROM VANADIUM AND ^{26}AL FROM SILICON CARBIDE IN A D-T FUSION REACTOR

Itacil C. Gomes
Technology Development Div.
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439
USA

Donald L. Smith
Technology Development Div.
Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439
USA

Edward T. Cheng
TSI Research, Inc.
225 Stevens Ave.
Solana Beach
CA 92075
USA

ABSTRACT

Current designs of fusion-reactor systems seek to use radiation-resistant, low-activation materials that support long service lifetimes and minimize radioactive-waste problems after decommissioning. Reliable assessment of fusion materials performance requires accurate neutron-reaction cross sections and radioactive-decay constants. The problem areas usually involve cross sections since decay parameters tend to be better known. The present study was motivated by two specific questions: i) Why are the ^{51}V(n,np)^{50}Ti cross section values in the ENDF/B-VI library so large (a gas production issue)? ii) How well known are the cross sections associated with producing 7.4x10^{5} y ^{26}Al in silicon carbide by the process ^{28}Si(n,np+d)^{27}Al(n,2n)^{26}Al (a long-lived radioactivity issue)? The energy range 14-15 MeV of the D-T fusion neutrons is emphasized. Cross-section error bars are needed so that uncertainties in the gas and radioactivity generated over the lifetime of a reactor can be estimated. We address this issue by comparing values obtained from prominent evaluated cross-section libraries. Small differences between independent evaluations indicate that a physical quantity is well known while the opposite signals a problem. Hydrogen from ^{51}V(n,p)^{51}Ti and helium from ^{51}V(n,α)^{48}Sc are also important sources of gas in vanadium, so they too were examined. We conclude that ^{51}V(n,p)^{51}Ti is adequately known but ^{51}V(n,np+d)^{50}Ti is not. The status for helium generation data is quite good. Due to recent experimental work, ^{27}Al(n,2n)^{26}Al seems to be fairly well known. However, the situation for ^{28}Si(n,np+d)^{27}Al remains unsatisfactory.

1. INTRODUCTION

High-performance reactor materials should exhibit low levels of gas production and activation in neutron radiation environments. The production of hydrogen and helium gas in intense radiation fields contributes synergistically with radiation damage to change material properties. The growth of significant inventories of long-lived radioactive species during reactor operation requires burial of affected components in long-term repositories after decommissioning. If large amounts of radioactivity must be so disposed, this adds significantly to the cost of nuclear-energy options. In fusion, 14-15 MeV neutrons from the D-T source predominate in high-fluence regions (*e.g.*, near the reactor first wall or in the blanket). At these energies, many threshold-reaction channels that generate hydrogen and helium gas and radioactivity are open. Materials attractive for fission reactors may be very undesirable for fusion systems. The performance of candidate fusion-reactor materials can be assessed reliably only if accurate cross-section data are available for the important reactions.

Vanadium and silicon carbide are candidate materials for fusion-reactor systems [1]. Two issues involving nuclear data have emerged recently concerning these materials: i) What amounts of hydrogen would be generated by D-T neutrons on vanadium? ii) What levels of ^{26}Al activity, with a half life of (7.4±0.3)x10^{5} y [2], might be produced in silicon carbide within the reactor blanket. ^{51}V(n,p)^{51}Ti and ^{51}V(n,np+d)^{50}Ti are considered to be the principal sources of hydrogen in vanadium. The two-step process ^{28}Si(n,np+d)^{27}Al(n,2n)^{26}Al is mainly responsible for the formation of ^{26}Al in a fusion reactor [3]. Thus, our investigation stresses these particular reactions. However, helium production, mainly from ^{51}V(n,α)^{48}Sc, is also treated since helium is the major concern for gas generation by neutrons in a D-T fusion reactor.

This paper reports on a survey of pertinent neutron cross-section data for these processes. We have made estimates of the data uncertainties based on observing the differences between recommended values from prominent cross-section evaluations found in the literature. This approach assumes that each of these evaluations was based on the best possible use of objective information available to the responsible evaluators. In those situations where extensive, consistent experimental information exists, these

DISCLAIMER

evaluations tend to agree rather well. When the experimental data are sparse, and evaluators resorted to nuclear models, discrepancies between the evaluations are more evident. Then, we have to assume that larger evaluations tend to agree rather well. When the experimental data are sparse, and evaluators resorted to nuclear models, discrepancies between the evaluations are more evident. Then, we have to assume that larger uncertainties persist. General comments on cross-section evaluations and error estimation appear in Section 2. In Section 4, the status of the vanadium neutron cross sections is examined in some detail, and the impact on hydrogen and helium gas production is discussed. Data for reactions that generate ^{26}Al in a fusion reactor are surveyed in Section 5. Finally, the impact of data uncertainties on fusion applications is mentioned in Section 6, along with conclusions drawn from this study.

2. PHYSICAL CONSIDERATIONS

Evaluated cross-section libraries are based on examination of experimental data, on nuclear-model calculations, or on a combination of both. In the present context, we found the following fundamental physical consistency criteria to be very useful in assessing the status of neutron cross-section data for energies < 20 MeV: i) Total = Elastic + Non-elastic; ii) Non-elastic = Inelastic + Sum Reactions; iii) Hydrogen Production = (n,p) + (n,np) + (n,d) + (n,t); iv) Helium Production = (n,α) + (n,nα) + (n,^{3}He).

Each process poses unique measurement challenges. Total cross sections are relatively easy to measure if appropriate samples and intense neutron sources can be obtained. Elastic-scattering cross sections are more difficult to measure, while inelastic scattering cross sections are very hard to determine accurately. Non-elastic cross sections are usually derived from the difference between the total and elastic-scattering cross sections, according to criterion (i). Transmutation-reaction cross-section measurements involve widely differing degrees of difficulty. If the cross sections are very small, they are always very hard to measure because the yields are low. A measurement may be facilitated if the reaction leads to a radioactive product that can be studied easily by the activation method. However, when the product is long-lived, or stable, such measurements are quite formidable. For low-threshold reactions, perturbations from scattered neutrons are problematic, while for high-threshold reactions these secondary neutrons have little experimental influence.

Nuclear-model calculations can guide evaluations in those situations where measurements are very difficult or impossible. Since these calculations tend to yield results that are consistent in the context of criteria (i)-(iv), this approach is most appealing to evaluators. However, consistency is not equivalent to accuracy! The cross-sections obtained from nuclear modeling are often quite sensitive to model assumptions and the physical parameters employed for analysis. Key factors are: i) specific model assumptions (*e.g.*, statistical vs. direct); ii) values of optical-model (OM) parameters for the incident neutron and emitted neutrons and charged particles; iii) accurate level parameters (spins, parities, *etc.*) or level-density representations for the product nuclei; iv) the assumed gamma-emission models and parameters. Uncertainties associated with details of nuclear modeling lead us to the following general conclusions about accuracy: i) Total cross sections usually can be calculated quite reliably (< 5%). ii) Elastic scattering can also be determined with moderate accuracy (5-10%). iii) Large-reaction-channel cross sections can be calculated with reasonable success (10-20%). iv) Small transmutation-reaction cross sections are usually very difficult to determine (20-50+%). The uncertainties shown as (...) represent the lower limits that can be expected from contemporary nuclear modeling practice. Often the situation is much worse. To approach these indicated accuracy limits, one needs to use model parameters that are validated by measured data for the element in question or data for neighboring nuclei with similar structure.

3. INFORMATION SOURCES

Our survey refers to several recent evaluations from the literature. These include the general-purpose libraries ENDF/B-VI (USA) [4], JENDL-3 (Japan) [5], JEF-2 (EC) [6], CENDL-2 (China) [7], and BROND-2 (Russia) [8], and the special purpose libraries ADL-3T (Russia) [9], EAF-3 (EC) [10], ACTL-82 (USA) [11], and FENDL/A-1 and 2 (IAEA) [12]. Mono-energetic cross-section values at 14, 14.5, and 15 MeV were extracted from each source.

4. STATUS OF NEUTRON CROSS-SECTION DATA FOR VANADIUM

Natural vanadium contains 99.750% ^{51}V [13]. Neutron elastic- and inelastic-scattering cross sections govern neutron propagation and energy transfer in vanadium fusion-reactor components. Neutron transmutation-reaction cross sections are responsible for gas and radioactivity production. Although our main concern for in this paper is gas production, in the case of vanadium we give some consideration to other partial cross sections in order to demonstrate how the uncertainties can vary from one reaction channel to another. It is generally desirable to consider all reaction channels simultaneously due to the consistency criteria of Section 2. This is especially true when the main concern is for reaction processes with modest cross sections since their magnitudes can be strongly influenced by competition between the various open reaction channels. For gas production, the main interest is in 14-15 MeV D-T fusion neutrons so our study is restricted to these energies in spite of the fact that lower energies are also important in other contexts. The starting point for our investigation of vanadium was to determine which reaction processes are energetically feasible for neutron energies ≤ 15 MeV. This was done using nuclear-mass information [13] and the well-known Q-equation, namely, Q = ΣR (Reactant masses) - ΣP (Product masses) [14]. This equation was structured in energy units for the present analysis.

The results from our energy-balance calculations appear in Table 1. Those reaction channels for which Q < -15 MeV are of no interest for fusion in the present context so they were not considered. Furthermore, certain reactions that are energetically allowed, but are known *a priori* to have cross sections that are so small that they are of minimal practical consequence for gas production, were also excluded from further consideration. These reactions are (n,^{3}He), (n,2p), and (n,αp). Also, the present survey does not examine angular-distribution effects associated with the particle-emission channels. Table 2 indicates which data are available from the individual evaluated data libraries. Table 3 shows those values compiled from the various sources for a single energy, namely, 14 MeV.

Table 1: ^{51}V reaction Q-values [a]

		Reactant Masses		Sum Reactants	Product Masses							Sum Products	Calculated Q-value
X	RP	^{51}V	n	ΣR	n/2n/3n	p/ 2p	d	t	^{3}He	α	RP	ΣP	Q
γ	^{52}V	-52.198	8.071	-44.127	0	0	0	0	0	0	-51.438	-51.438	7.311
n	^{51}V	-52.198	8.071	-44.127	8.071	0	0	0	0	0	-52.198	-44.127	0
2n	^{50}V	-52.198	8.071	-44.127	16.142	0	0	0	0	0	-49.218	-33.076	-11.051
3n	^{49}V	-52.198	8.071	-44.127	24.213	0	0	0	0	0	-47.956	-23.743	-20.384
p	^{51}Ti	-52.198	8.071	-44.127	0	7.289	0	0	0	0	-49.727	-42.438	-1.689
np	^{50}Ti	-52.198	8.071	-44.127	8.071	7.289	0	0	0	0	-51.426	-36.066	-8.061
2n-p	^{49}Ti	-52.198	8.071	-44.127	16.142	7.289	0	0	0	0	-48.558	-25.127	-19
2p	^{50}Sc	-52.198	8.071	-44.127	0	14.578	0	0	0	0	-44.54	-29.962	-14.165
d	^{50}Ti	-52.198	8.071	-44.127	0	0	13.136	0	0	0	-51.426	-38.29	-5.837
n-d	^{49}Ti	-52.198	8.071	-44.127	8.071	0	13.136	0	0	0	-48.558	-27.351	-16.776
t	^{49}Ti	-52.198	8.071	-44.127	0	0	0	14.95	0	0	-48.558	-33.608	-10.519
nt	^{48}Ti	-52.198	8.071	-44.127	8.071	0	0	14.95	0	0	-48.487	-25.466	-18.661
^{3}He	^{49}Sc	-52.198	8.071	-44.127	0	0	0	0	14.931	0	-46.552	-31.621	-12.506
^{3}He-n	^{48}Sc	-52.198	8.071	-44.127	8.071	0	0	0	14.931	0	-44.493	-21.491	-22.636
α	^{48}Sc	-52.198	8.071	-44.127	0	0	0	0	0	2.425	-44.493	-42.068	-2.059
nα	^{47}Sc	-52.198	8.071	-44.127	8.071	0	0	0	0	2.425	-44.332	-33.836	-10.291
pα	^{47}Ca	-52.198	8.071	-44.127	0	7.289	0	0	0	2.425	-42.34	-32.626	-11.501

[a] The reactions considered are ^{51}V(n,X)RP. Q = Mass(^{51}V+n) - Mass(RP+X). Q = Energy released by reaction process (in MeV). Q < 0 indicates that energy must be introduced for the reaction to proceed. The values found in the columns labeled "Reactant Masses", "Sum Reactants", "Product Masses", and "Sum Products" are expressed in terms of mass excesses based on a mass excess of zero for ^{12}C (*i.e.*, the ^{12}C nuclear mass scale).

Table 2: Vanadium evaluated cross-section libraries used in the present investigation [a]

	ENDF/B-VI	JENDL-3	JEF-2	CENDL-2	ADL-3T	EAF-3	FENDL/A-2
Total	+	+	+	+			
Elastic	+	+	+	+			
Non-elastic			+	+			
Inelastic	+	+	+	+			
(n,γ)	+	+	+	+	+	+	+
(n,2n)	+	+	+	+	+	+	+
(n,p)	+	+	+	+	+	+	+
(n,np)	+	+	+	+	+	+	+
(n,d)	+	+	+	+	+	+	+
(n,2p)	+				+	+	+
(n,t)	+	+	+	+	+	+	+
(n,^{3}He)	+				+	+	+
(n,α)	+	+	+	+	+	+	+
(n,nα)	+	+	+	+	+	+	+
(n,pα)	+						

[a] The availability of vanadium cross-section data for a specific process from the indicated library is flagged by a bullet symbol (+).

Table 3: Cross-section values at 14-MeV from the selected libraries [a]

	ENDF/B-VI	JENDL-3	JEF-2	CENDL-2	EAF-3	FENDL/A-2	ADL-3T	Average	Std Dev	% Std Dev
Total	2355	2350	2320	2350	NA	NA	NA	2344	16.0	0.7
Elastic	1101	1018	1006	1039	NA	NA	NA	1041	42.5	4.1
Non-el (1)	1254	1332	1315	1311	NA	NA	NA	1318	44.7	3.4
Non-el (2)	1254	1332	1315	1311	NA	NA	NA	1318	44.8	3.4
Inelastic	409	622	563	604	NA	NA	NA	571	96.5	16.9
(n,γ)	0.64	0.02201	0.176	0.64	0.6088	0.6084	0.6087	0.3905	0.2960	75.8
(n,2n)	480	604	635	504	460	532	531	541	65.0	12.0
(n,p)	28.6	31.0	36.1	28.1	32.3	30.92	30.38	30.13	3.661	12.2
(n,n-p)	315	54.44	17.9	155.4	56.3	314	68.46	110	100	91.0
(n,d)	5.544	4.5	30.2	3.752	7.26	5.557	3.403	9.194	9.52	104
(n,t)	0.0114	1.0	12.3	0.141	0.6576	0.01253	0.1687	2.044	4.537	222
(n,α)	14.9	15.6	19.4	15.31	13.94	14.89	15.42	15.57	1.791	11.5
(n,n-α)	0.1	0.0003447	0.189	0.0001417	2.5	0.003842	0.003838	0.3995	0.9291	233
Total H	349	90.94	96.5	187.4	96.51	350	102.4	151.3	93.6	61.8
Total He	15.0	15.6	19.59	15.31	16.44	14.89	15.42	15.97	1.712	10.7

[a] Values are given in millibarn. The (n,2p), (n,αp), and (n,^{3}He) contributions are too small to consider. Non-el (1) = Total - Elastic, Non-el (2) = Sum of partial non-elastic cross sections given in the table. In those cases where the Non-elastic cross section is given explicitly in the evaluated libraries, they are copied into Non-El (1) rather than being calculated as indicated above. Small differences may exist between Non-el (1) and Non-el (2).

Uncertainty information is given in Table 4 for all three energies. We can draw the following conclusions:

Adequately known: Total, Elastic, Non-elastic, Inelastic, (n,2n), (n,p), (n,α), and Total He.

Inadequately known: (n,γ), (n,np), (n,d), (n,t), (n,nα) and Total H.

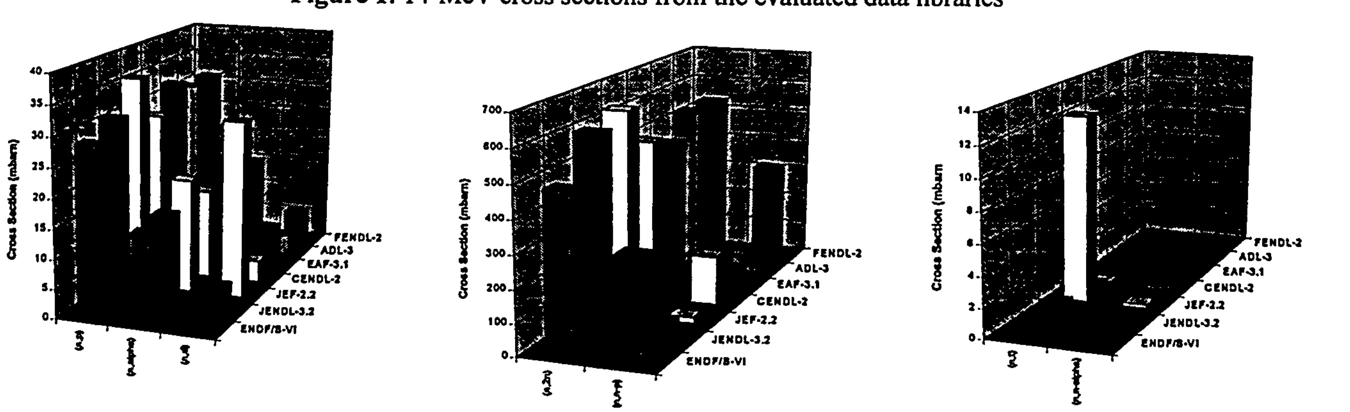
Several 14-MeV vanadium cross sections from these libraries are displayed in Figure 1. Two points emerge from inspecting this figure: First, the discrepancies are very large for the small cross sections. This is also evident in the entries of Tables 3 and 4. Second, there appears to be a negative correlation between the magnitude of the (n,2n) cross section and some of the smaller cross sections. This is most easily seen from an inspection of the (n,np) process. For those data sets with larger (n,2n) cross sections, the (n,np) cross sections are smaller, and vice-versa. This seems to be a consequence of the physical consistency criteria discussed in Section 2.

Table 4: Standard deviations of the average cross sections calculated from values found in the individual libraries [a]

	Total	Elastic	Non-el	Inelastic	(n,γ)	(n,2n)	(n,p)	(n,np)	(n,d)	(n,t)	(n,α)	(n,nα)	Total H	Total He
14 MeV	0.7	4.1	3.4	16.9	75.8	12.0	12.2	91.0	104	222	11.5	233	61.8	10.7
14.5 MeV	0.8	4.0	3.3	17.3	76.8	10.1	12.5	80.9	93.4	217	11.7	230	52.5	12.8
15 MeV	1.0	4.3	3.5	18.4	77.8	9.5	13.1	73.1	84.4	211	11.5	227	45.5	15.5
Status	OK	OK	OK	OK	Problem	OK	OK	Problem	Problem	Problem	OK	Problem	Problem	OK

[a] Values given are standard deviations (in %) associated with averages of corresponding cross sections from the considered libraries. Total H = (n,p) + (n,np) + (n,d) + (n,t). Total He ≈ (n,α) + (n,nα). Non-el is obtained by summing the partial reaction cross sections. Inelastic = Non-elastic - Sum Reactions. The inelastic scattering cross section is often adjusted to force consistency since continuum inelastic scattering is hard to measure directly.

Figure 1: 14-MeV cross sections from the evaluated data libraries



From an examination of documentation for the individual evaluations, and a survey of the available experimental cross-section data mentioned in BNL-325 [15] and CINDA [16], we distilled the following observations:

Total and Elastic Scattering

These cross sections can be calculated using neutron OM parameters for ^{51}V. OM parameters are fairly well known in this mass and energy range. Extensive total and elastic-scattering data exist for neutron energies < 10 MeV. Some data exist up to 20 MeV. They can be used to validate the analyses. The evaluations considered here are based on calculations that were compared to experimental data.

Non-elastic

This cross section is constrained by the consistency criterion (i) in Section 2. Since total and elastic-scattering cross sections are well defined, this suggests that the non-elastic cross section should be reasonably well known too.

Inelastic Scattering

Inelastic scattering to well-resolved discrete levels can generally be measured to 10-20% accuracy. However, continuum-inelastic scattering is notoriously difficult to measure. When constructing evaluated libraries, the continuum inelastic scattering cross section is often adjusted to satisfy criterion (ii) of Section 2 after choices are made for all of the reaction-channel cross sections. For vanadium, the uncertainty is apparently < 20%, based on variations between the evaluated libraries.

(n,2n)

^{50}V is stable, so it is difficult to measure this cross section. The paucity of experimental data and the extent of the discrepancies observed limit the attainable accuracy. Yet, the various evaluations do seem to agree reasonably well. This might occur because these cross sections all originate from nuclear-model calculations that possibly used similar techniques and parameters. More likely - since the (n,2n) cross sections are relatively large - they tend to be constrained by the criteria of Section 2. Because the existing experimental data are too unreliable to provide validation of the nuclear-model results, we suspect that the uncertainties in this cross section are a bit larger than implied by the error values that appear in Tables 3 and 4.

(n,p)

This cross section can be measured with reasonable accuracy by the activation method, and there are abundant data of good quality to be found in the literature. While the existing evaluations are often based on nuclear-model calculations, the evaluators have clearly paid attention to the available experimental data. This explains why the cross sections (though not particularly large) appear to be moderately well known. This reaction is an important contributor to hydrogen production in vanadium so it is therefore important to consider it for the present purpose.

(n,np)

Measurements cannot be made by the activation method so there are few experimental data available to guide the evaluations. They are all based on nuclear models. The large differences between results from the various evaluations are obvious from Figure 1. The ENDF/B-VI results (and hence FENDL/A-2 which adopted them) seem to be anonymously large. This fact originally drew the attention of the fusion community to the problem. Most of the other evaluations yield values that are distinctly lower than ENDF/B-VI (by about a factor of 2-3). This discrepancy is a critical issue for the fusion community because of the considerable impact on gas production in vanadium. Two relatively old experimental data sets based on directly observing the emitted protons [(n,p) + (n,np)], also suggest that the cross section should be much lower than predicted by ENDF/V-VI [17,18]. Thus, we suspect that the (n,np) cross section ought to be smaller near 14 MeV than the ENDF/B-VI value (perhaps ≈ 100 millibarn). New vanadium proton-emission and/or integral hydrogen-production measurements for D-T fusion neutrons are needed to resolve this issue.

(n,α)

The same comments made for (n,p) apply here. It appears that this cross section is reasonably well known.

(n,d), (n,t), (n,nα)

These are small cross sections so the contribution to gas production is modest. There are few experimental data. Results obtained from nuclear-model calculations are very sensitive to the selected parameters and to competition from the stronger reaction channels. Therefore, it is not surprising that the cross-section predictions from the different evaluations vary so widely. From a practical point of view, these reaction channels seem to be relatively inconsequential for fusion applications, except possibly for estimating production of radioactive tritium.

Total H

Although (n,p) is reasonably well known, it appears that the poorly known (n,np) channel might be the most significant mechanism for producing hydrogen in vanadium. Until the cross sections for this reaction channel become better known, knowledge of hydrogen production in vanadium will remain very uncertain.

Total He

The (n,α) process clearly dominates here and it appears to be reasonably well known. Thus, helium production in vanadium is probably adequately understood.

5. STATUS OF NEUTRON CROSS SECTION DATA FOR ^{26}Al PRODUCTION

It is of general interest to fusion to consider neutron cross-section data for silicon since it is an element found in the reactor blanket as silicon carbide. We focus here on the role of silicon in the generation of ^{26}Al during operation of a D-T fusion reactor. This long-lived radioisotope decays by electron capture and the emission of β^+ and gamma rays. It could present a significant long-term waste-disposal problem for fusion-energy applications if significant quantities were to be produced over the operating lifetime of a reactor. For brevity, and in contrast to our earlier treatment of vanadium, we avoid discussing other categories of neutron reactions for silicon. Natural silicon consists mainly of the 92.23%-abundant isotope ^{28}Si. ^{26}Al cannot be produced directly by ^{28}Si(n,t)^{26}Al (Q = -16.161 MeV) at D-T fusion energies. The reactions ^{28}Si(n,np)^{27}Al (Q = -11.585 MeV) and ^{28}Si(n,d)^{27}Al (Q = -9.3583 MeV) are, however, both energetically favored for D-T fusion neutrons. Consequently, as mentioned in Section 1, the two-step process ^{28}Si(n,np+d)^{27}Al(n,2n)^{26}Al is potentially the most significant generator of radioactive ^{26}Al in a fusion reactor.

Our present work consisted of examining the cross sections for each of the individual reactions involved, namely, ^{28}Si(n,np)^{27}Al, ^{28}Si(n,d)^{27}Al, and ^{27}Al(n,2n)^{26}Al, in order to estimate their uncertainties. Before we began this investigation, we anticipated that the cross-section data for these reactions would probably be inadequately known. For the most part, our suspicions were confirmed by this study. However, the situation for ^{27}Al(n,2n)^{26}Al has been improved significantly relative to the status reflected in the contemporary evaluated data files. This development is a consequence of recent experimental work carried out in Europe and Russia that is not yet reflected in the evaluated data libraries. This situation offers a good example of the important impact that new, good-quality experimental data can have on technological applications. Furthermore, it is demonstrated why it is so important that such significant new results be incorporated as promptly as possible into those evaluated files that are widely used for analyses in nuclear-energy applications like the design of fusion reactors.

5.1 The (n,np) and (n,d) Reactions for ^{28}Si

Cross-section values at 14 MeV, and sums of these cross sections, are listed in Table 5. Averages of values extracted from the libraries, and corresponding standard deviations and fractional standard deviations (in %), are also included. Figures 2 and 3 illustrate the 14-, 14.5-, and 15-MeV cross-section values for these two reactions, to facilitate their comparison. The discrepancies between the various plotted evaluated cross sections are substantial for both reactions. Corresponding (n,d) cross sections vary by nearly an order of magnitude while values for the (n,np) reaction vary by more than a factor of 6. The sums of both reaction cross sections, which govern production of ^{27}Al, vary among the considered evaluations by a factor of nearly 2000! This huge discrepancy is a consequence of the very low value for hydrogen production found in the ACTL-82 library. There is obviously a need for good quality experimental data to resolve these discrepancies.

5.2 Other Reactions that Can Produce ^{27}Al in Silicon

Silicon has two minor stable isotopes, namely, ^{29}Si (4.67%) and ^{30}Si (3.10%) [13]. Thus, ^{27}Al can also be produced via the ^{29}Si(n,t)^{27}Al and ^{30}Si(n,α)^{27}Mg(β^-)^{27}Al processes. ^{29}Si(n,t)^{27}Al has a relatively small cross section of $\approx$ 1.6 millibarn at 14 MeV. There is a modest variation in the reported values from those evaluated data libraries where this cross section is tabulated, namely FENDL/A-1, FENDL/A-2, EAF-3, and ADL-3T. ^{30}Si(n,α)^{27}Mg has a fairly sizeable cross section of $\approx$ 71 millibarn. Values for this cross section are reported in ADL-3T, ACTL-82, FENDL/A-2, and JENDL-3. Again, the variation in these evaluated results is not very large. Due to low abundance, both ^{29}Si and ^{30}Si play minimal roles in ^{26}Al production.

5.3 The (n,2n) Reaction for ^{27}Al

This reaction has Q = -13.058 MeV. The cross section is small at 14 MeV, but it increases sharply with neutron energy above that point. An accurate description of the cross-section energy dependence in this region is needed to estimate the production of ^{26}Al in a typical D-T fusion environment since the neutron-energy spectrum is strongly dependent on plasma temperature. Table 6 exhibits the cross section values at 14, 14.5, and 15 MeV, as obtained from the several evaluated data sources previously enumerated. The average values, standard deviations, and fractional standard deviations (in %) of these tabulated values are also included. If we had to depend on estimating uncertainties based on the variations in corresponding values from these selected evaluations, we would have to conclude that our knowledge of the ^{27}Al(n,2n)^{26}Al cross section in the critical 14-15 MeV energy range is very uncertain. Fortunately, recent experimental work by Wallner *et al.* [19] has led to a significant improvement in the situation. Referring to Figure 2 in their work, we observe that the experimental cross sections are $\approx$ 6 millibarn at 14 MeV, $\approx$ 20 millibarn at 14.5 MeV, and $\approx$ 30 millibarn at 14.8 MeV. Their experimental errors appear to be no larger than 10-15%. However, these values do deviate from the existing evaluations by larger amounts, in most instances.

6. CONCLUSIONS

The present survey demonstrates that neutron cross sections near 14-15 MeV are inadequately known for several reaction channels of vanadium. Among them is the (n,np) process which is probably the most important contributor to hydrogen production in vanadium. By comparison, the (n,α) channel, which is the major contributor to helium production, is reasonably well known. Turning to radioactive ^{26}Al generation, it is found that the two-step process ^{28}Si(n,np+d)^{27}Al(n,2n)^{26}Al in silicon carbide, which may be found in the blanket of a fusion reactor, is the main source of this long-lived radio-isotope. It is a potential problem for radioactive-waste disposal. The uncertainty in ^{27}Al production from ^{28}Si(n,np+d)^{27}Al remains high. Based only on the existing evaluated files, it would appear that the uncertainties in the cross sections for ^{27}Al(n,2n)^{26}Al are also high. This could be further complicated by the fact that this cross section varies rapidly with neutron energy in the range 14-15 MeV, so in a fusion reactor the production of ^{26}Al depends strongly on plasma temperature. However, the uncertainty associated with the ^{27}Al(n,2n)^{26}Al cross section seems to have been reduced considerably by new data from a recent experiment carried out in Russia and Austria. This work reports experimental (n,2n) cross-section uncertainties of 10-15% in the critical energy range from 14-15 MeV. Since the (n,2n) cross section is still relatively small at these energies, any future revisions made to this reaction channel during the evaluation process should have a relatively small perturbing effect on the results for other remaining interaction channels.

Table 5: Cross section values at 14 MeV for the ^{28}Si(n,np)^{27}Al and ^{28}Si(n,d)^{27}Al reactions [a]

	ENDF/B-VI	JENDL-3	JEF-2	BROND-2	CENDL-2	ACTL-82	EAF-3
(n,np)	78.22	71.27	78.22	195.0	44.53	NA	271
(n,d)	18.88	NA	136.7	142.3	15.33	NA	143
Sum [c]	97.10	-	214.9	337.3	59.86	0.22 [b]	414

	ADL-3T	FENDL/A-1 [d]	FENDL/A-2 [d]	FENDL/A-2 [e]	Average [f]	Std. Dev. [f]	Std. Dev. (%) [f]
(n,np)	135.8	272	71	73.2	118.4	72.8	61.5
(n,d)	16.7	143	17	16.7	69.9	61.3	87.6
Sum [c]	152.5	316	88	89.9	170.7	133.5	78.2

[a] Cross sections given in millibarn. ^{28}Si cross sections: JENDL-3, ACTL-82, EAF-3, ADL-3T, FENDL/A-1,2. Natural silicon cross sections: ENDF/B-VI, JEF-2, CENDL-2, BROND-2. Since natural silicon consists of 92.23% ^{28}Si, the differences between the corresponding natural and isotopic cross section values are small.

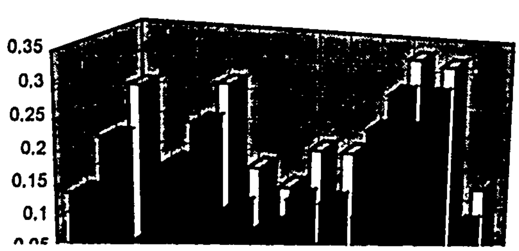
[b] The ACTL-82 library only gives values for total hydrogen production.

[c] "Sum" refers to the cross section for (n,np) + (n,d). It is this cross section which is important for ^{27}Al production.

[d] FENDL values derived from files in REAC format.

[e] FENDL values derived from files in ENDF format.

[f] Only include values from FENDL in ENDF format for calculation of averages. Since the JEF-2.2 (n,np) cross sections are identical to ENDF/B-VI, only one of these sources is used for the averaging procedure. The same is true for EAF-3 and FENDL/A-1.



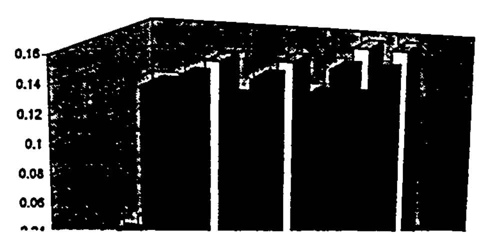


Table 6: Cross-section values for the $^{27}Al(n,2n)^{26}Al$ reaction from the selected libraries [a]

	ACTL-82	ADL-3T	EAF-3	FENDL/A-1 [b]	FENDL/A-2 [b]	FENDL/A-2 [c]	ENDF/B-VI
14 MeV	24	12.3	11	17.7	12.57	12.3	4.228
14.5 MeV	73	30.65	32	38.1	30.35	30.6	16.85
15 MeV	123	57.81	54	60	51.11	57.8	29.47

	JEF-2	CENDL-2	JENDL-3	Average [d]	Std. Dev. [d]	Std. Dev. (%) [d]
14 MeV	5.900	0.017	5.583	10.56	6.63	62.8
14.5 MeV	14.00	0.034	32.84	29.84	18.04	60.4
15 MeV	27.00	0.050	72.26	53.25	30.67	57.6

[a] Values are given in millibarn.
[b] FENDL derived from files in REAC format.
[c] FENDL derived from files in ENDF format.
[d] Include only values from FENDL files in REAC format for calculation of averages and standard deviations.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, Energy Research Programs, under Contract W-31-109-Eng-38.

REFERENCES

[1] D.L. Smith *et al* "Materials Integration Issues for High Performance Fusion Power Systems", ICFRM, Japan (1997).
[2] Evaluated Nuclear Structure Data File (ENSDF), NNDC, Brookhaven National Laboratory (1998).
[3] C. Wong *et al.*, *Fusion Technology* 19, 938 (1991).
[4] Evaluated Neutron Data File, ENDF/B-VI.3, NNDC, Brookhaven National Laboratory (1996).
[5] Japanese Evaluated Nuclear Data Library, JENDL-3.2, Nuclear Data Center, Japan Atomic Energy Research Institute (JAERI), Tokai, Ibaraki, Japan (1994).
[6] Joint Evaluated File, JEF-2.2, NEA Nuclear Data Bank, Nuclear Energy Agency, Paris, France (1992).
[7] Chinese Evaluated Nuclear Data Library, CENDL-2, Institute of Atomic Energy, Beijing, China (1992).
[8] Russian Nuclear Data Library, BROND-2.2, Russian Nuclear Data Center, Obninsk, Russia (1993).
[9] O.T. Grudzevich, A.V. Zeleneckij, A.V. Ignatjuk, and A.B. Pashchenko, Russian Activation Data Library, ADL-3T. Catalogue of ADL-3T library given in *Yadernye Konstanty*, 1993 (3-4). Copies are available from IAEA, Vienna, Austria. This documentation has an introduction in Russian and an abstract in English. The data library is available on tape or by WWW file transfer. Summary documentation is in Report IAEA-NDS-137.
[10] J. Kopecky and D. Nierop, European Activation File, EAF-3, Summary documentation in Report ECN-1-91-053, Petten, The Netherlands (1991). Version 3 of this library was issued in 1994.
[11] R.J. Howerton *et al.*, LLNL Evaluated Neutron Activation Cross-Section Library, ACTL-82, Lawrence Livermore National Laboratory (1982). Summary documentation in Reports IAEA-NDS-55 and IAEA-NDS-53. Eval. techniques, reaction index, and format description by M.A. Gardner and R.J. Howerton in Report UCRL-50400 (18), Lawrence Livermore National (1978).
[12] A.B. Pashchenko *et al.*, Fusion Evaluated Nuclear Data Library - Activation, FENDL/A-1 & 2, Report IAEA(NDS)-173, NDS, IAEA, Vienna, Austria (1997).
[13] J.K.Tuli, "Nuclear Wallet Cards", NNDC, Brookhaven National Laboratory (1995).
[14] R.D. Evans, *The Atomic Nucleus*, McGraw-Hill Book Company, Inc., New York (1955).
[15] V. McLane, C.L. Dunford, and P.F. Rose, *Neutron Cross Sections, Volume 2, Neutron Cross Section Curves (BNL-325)*, Academic Press, Inc., Boston (1988).
[16] Computer Index to Nuclear Data (CINDA), *An Index to the Literature on Microscopic Neutron Data (1935-1998)*, NDS, IAEA, Vienna, Austria (1998).
[17] S. Grimes, R. Haight, and J. Anderson, *Physical Review* C17, 508 (1978)
[18] L. Colli, I. Iori, S. Micheletti, and M. Pignanelli, *Nuovo Cimento* 21, 966 (1962).
[19] A. Wallner, S.V. Chuvaev, A.A. Filatenkov, W. Kutschera, G. Mertens, A. Priller, W. Rochow, P. Steier, and H. Vonach, "Study of the $^{27}Al(n,2n)^{26}Al$ Reaction", *International Conference on Nuclear Data for Science and Technology*, Conference Proceedings (59), Italian Physical Society, Bologna, Italy (1998).