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COMPARISON OF ACTIVATION CROSS SECTION MEASUREMENTS AND EXPERIMENTAL TECHNIQUES FOR FUSION REACTOR TECHNOLOGY

Summary Report of the IAEA Specialists' Meeting organized by the International Atomic Energy Agency in cooperation with the Japan Atomic Energy Research Institute and held at the Tokai Research Establishment, JAERI, Japan, 15 to 17 November 1993

Prepared by
A.B. Pashchenko
IAEA Nuclear Data Section

July 1994

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ABSTRACT

The present report contains the Summary of the IAEA Specialists' Meeting (SPM) on "Comparison of Activation Cross Section Measurements and Experimental Techniques for Fusion Reactor Technology", held at the Tokai Research Establishment, JAERI, Japan, from 15 to 17 November 1993. This SPM was organized by the IAEA Nuclear Data Section (NDS) with the co-operation and assistance of the Japan Atomic Energy Research Institute.

The purpose of the Specialists' Meeting was to form an international programme for the comparison of activation cross section measurements and experimental techniques useful in reactor technology. It was agreed that new activation measurements be performed at the Fusion Neutronics Source Facility (FNS) of JAERI, neutron source facilities of the V.G. Khlopin Radium Institute, St. Petersburg, Russia, and in the Institute of Experimental Physics, Debrecen, Hungary. A list of the most important reactions has been prepared. Forteen experts from seven Member States attended the meeting.

The conclusions and recommendations are presented on the basis of discussions held by meeting participants.

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IAEA Specialists' Meeting on Comparison of Activation Cross Section Measurements and Experimental Techniques for Fusion Reactor Technology, Tokai Research Establishment, JAERI, Japan, 15 to 17 November 1993

(1) Introduction

Considering the current needs of the ITER Engineering Design Activity, the Nuclear Data Section (NDS) was advised by a group of experts to convene a Specialists' Meeting on "Comparison of Activation Cross Section Measurements and Experimental Techniques for Fusion Reactor Technology". It was proposed at many IAEA Meetings that it would be very timely to facilitate an international cooperation with the purpose to refine knowledge of activation cross sections by paying careful attention to experimental methods, corrections, data uncertainties, etc., ultimately leading to revisions of the evaluated files for these reactions.

(2) Objectives of the Meeting

The main purpose of the meeting was to discuss the proposed international project in detail: tasks, goals, time schedule, information exchange, facility visits, working meetings, etc. Therefore the meeting was devoted to discussions, and no oral presentation of papers was foreseen. The meeting agenda[*)] is given below as Attachment 1.

(3) Organization of the Specialists' Meeting and Meeting Proceedings

The Specialists' Meeting was organized by the IAEA NDS with the co-operation and assistance of local organizers of the Japan Atomic Energy Research Institute, JAERI, and held at Tokai-mura from 15 to 17 November 1993.

The participants elected Dr. Yu. Ikeda, the principal scientist of JAERI-FNS, as a Chairman of the meeting. The meeting was attended by 14 experts from seven Member States. The complete list of participants and their affiliations are presented in Attachment 2. The meeting had a full and excellent support from local organizers.

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* Dr. D. Smith of the Argonne National Laboratory was not present at the meeting but he significantly contributed to the development of the agenda in the stage of the meeting preparation. Two letters of Dr. Smith are given in Attachment 4.

The members of the Specialists' Meeting discussed the problems of future activation measurements both with respect to improve the measurement techniques and with respect to the data needs for fusion reactor technology. Two Working Groups (Activation Data Working Group and the Experimental Working Group) were formed to focus the discussion on each of the above mentioned subjects. The detailed reports of both Working Groups as well as the full conclusions and recommendations are presented in Attachment 3.

(4) Results of the Meeting

The main objectives of the Specialists' Meeting have been achieved to a large extent, and as result of discussions the next steps in the work programme have been worked out. In particular it was agreed that the experimental groups at JAERI-FNS (Japan), KRI-St.Petersburg (Russian Federation), and the Institute of Experimental Physics in Debrecen (Hungary) will join in a collaborative program on comparing their measuring technique and do measurements for reactions where discrepancies between their previous measurements exist.

It was pointed out that within the large body of measurements provided by the FNS-JAERI group in the last few years, a number of reactions were identified for which the FNS results were either the only existing data or strongly deviating from previous measurements. It was recommended that the groups at KRI and Debrecen consider measurements of these cross sections in order to clarify the situation.

Based on the recent lists of activation reactions considered as most important for fusion reactor applications (supplied by C. Ponti, J. Kopecky, R. Forrest, E.T. Cheng and D. Smith) the "Updated Most Important Activation Reactions List" was created by meeting participants and these reactions for which the data situation at present is unsatisfactory were identified.

Among the reactions given in this list, 17 of these were identified as being accessible to the experimental groups of the above mentioned collaboration. It was strongly recommended that these reactions be investigated by the collaboration.

In addition, a number of reactions were identified for which the cross sections at present can not be measured by activation because of the extremely long half-lives of the reaction products, but probably can be measured by other methods such as accelerator mass spectrometry (AMS). Therefore it was recommended that this list be sent to all members of the IAEA CRP on cross sections for long-lived activation products for consideration in their programs and discussions at their informal meeting at the forthcoming nuclear data conference at Gatlinburg, USA.

The meeting participants pointed out that due to the outstanding work at JAERI-FNS and other laboratories (e.g., in connection with the IAEA CRP on the cross sections of long-lived activation products) our knowledge of the 14 MeV cross sections has improved greatly in the last years. As a consequence of these efforts, the recommended values of the 14 MeV in the IAEA Handbook on Nuclear Activation Data (IAEA Technical Report No. 273, 1987) are now outdated. It was therefore recommended that an improved set of evaluated 14 MeV cross section values be created taking into account the presently available database. This set of new recommended evaluated cross section values should be made generally available by the IAEA/NDS.

The members of the Specialists' Meeting recommended that the experimental work in the future should be extended to the neutron energy range below 14 MeV. Two types of measurements were identified as especially urgent:

- Measurements of cross sections for threshold reactions in the MeV energy range; and
- Measurements of capture cross sections in the keV energy range.

(5) Future Meetings

It was recommended that a follow-up Specialists' Meeting be held in the second half of 1994 in St. Petersburg, Russia. This meeting should discuss the results obtained by then, the further work especially with respect to 14 MeV cross section measurements needed for fusion reactor technology and the extension of cross section work to energies below 14 MeV. It was recommended that the future meetings should be coordinated by the IAEA/NDS with the schedule of the future FENDL meetings and the planned IAEA CRP meetings on activation libraries in order to facilitate the participation in the various meetings for the interested scientists.

(6) Acknowledgement

The Participants are grateful to the Japan Atomic Energy Research Institute for the warm hospitality and wish to thank Drs. Yu. Ikeda, H. Maekawa and Y. Kikuchi for the efficient organization of the Agency's meeting.

Attachment 1

IAEA Specialists' Meeting

on

Comparison of Activation Cross Section Measurements and Experimental Techniques for Fusion Reactor Technology

Tokai Research Establishment
JAERI-Tokai-Mura, Japan
15 - 17 November 1993

Organized in co-operation with the
Japan Atomic Energy Research Institute

AGENDA

15 November

09:40 - 10:30 **Opening Session**

Opening Remarks

- Hosts: Y. Kikuchi, JAERI Nuclear Data Center
  H. Maekawa, Fusion Neutronics Laboratory

- IAEA Scientific Secretary: A.B. Pashchenko

Election of Chairman

Adoption of Agenda

10:30 - 12:00 **Session 2**: General discussion on the project

A. Goals and tasks of proposed collaboration
B. Measurement facilities available to activation research

12:00 - 13:00 **Lunch Break**

13:00 - 17:30 **Session 2** (continued)

C. List of common reactions
D. Experimental and analytical issues involved in deriving the cross sections from the data

<u>16 November</u>

09:40 - 12:00 **Session 2** (continued)

E. Common nuclear parameters
F. Accuracies to which various reactions can be measured on the basis of current technology

12:00 - 13:00 **Lunch Break**

13:00 - 16:30 **Session 2** (continued)

G. Contributions of collaboration members to the preparation of the IAEA Handbook of Evaluated 14 MeV Cross Sections for Applications
H. List of new measurements to be performed at available laboratories

16:30 - 17:30 **Session 3**: Conclusions and Recommendations

A. Discussion
B. Organization of Working Groups to draft the report of the meeting
C. Drafting of meeting Conclusions and Recommendations

<u>17 November</u>

09:40 - 12:00 **Session 3** (continued)

D. Completion of the Working Group Report

12:00 - 13:00 **Lunch Break**

13:00 - 17:30 **Session 4**: Final Considerations

A. Discussion of Conclusions and Recommendations
B. Corrections and adoption of the Final Reports
C. Adoption of the schedule of work and future meetings
D. Closing of the meeting

Attachment 2

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Attachment 3

CONCLUSIONS AND RECOMMENDATIONS

I. Report of Activation Data Working Group

Attendees:

E. Cheng	TSI (Chairman)
J. Kopecky	ECN (Secretary)
A. Blokhin	IPPE
Y. Kikuchi	JAERI-NDC
C. Konno	JAERI-FNS
F. Mann	WHC
H. Maekawa	JAERI
A. Pashchenko	IAEA/NDS
A. Rimski-Korsakov	KRI
Zhao Z.	CIAE

. Based on the list supplied by Dr. Kopecky, which was a merger of

(1) the original FENDL/A-1 "Most Important Activation Reactions" list;
(2) the additions by Drs. Ed Cheng and Donald Smith (ANL) (as published in the Julich proceedings);
(3) the NET "Most Important Activation Reactions" list assembled by Dr. C. Ponti (JRC Ispra); and
(4) corrections supplied by Dr. Robin Forrest (AEA Culham), the working group

(a) added and deleted reactions to create an "Updated Most Important Activation Reactions" list,
(b) assigned priorities (1 = highest, 2 = medium, 3 = low) to each of the reactions, and
(c) judged the adequacy of available experimental data (A =adequate, A* = adequate, but only one recent measurement, and I = inadequate).

This "Updated Most Important Activation List" was further reviewed by the entire membership of the Specialists Meeting and resulted in the final list which will be distributed in a separate*) report during the forthcoming Nuclear Data Conference at Gatlingburg, USA.

Dr. Ed Cheng produced explanations for the importance of those reactions deemed to have inadequate experimental data with high (1) and medium (2) priority. These explanations are given in Table 1.

*) See attachment 6

Table 1
List of Neutron Reactions
of Which Cross Section Measurements are Needed
for Fusion Reactor Technology

Compiled and Reviewed at the IAEA Specialists' Meeting on Comparison of Activation Cross Section Measurements and Experimental Techniques, Tokai Research Establishment, JAERI, Japan, 15-17 November 1993

Note: (n,np) is used also to represent (n,d)

I. Priority 1 Reactions

1. Si28(n,np)Al27 (stable)

   Needed to determine the production of Al26 (7.4e+05 y) in SiC for waste disposal assessment.

2. Ca45(n,α)Ar42 (33 y)

   Needed to determine the contact dose rate due to K42, a decay product by Ar42 in V-5Cr-5Ti. Ar42 is produced in Ti due to Ti48(n,α)Ca45(n,α). Ca45 is a radioactive target with half-life of 163.8 d.

3. Ti48(n,α)Ca45 (164 d)

   Needed to determine the contact dose rate due to K42, a decay product by Ar42 in V-5Cr-5Ti. Ar42 is produced in Ti due to Ti48(n,α)Ca45(n,α).

4. V50(n,2n)V49 (330 d)

   Needed to determine the activity level in V-alloy for waste disposal based on MBq/m3 criteria.

5. Cu63(n,p)Ni63 (100 y)

   Needed to determine the level of long-lived activity in Cu for waste disposal assessment.

6. Mo92(n,np)Nb91 (680 y)

   Needed to determine the level of long-lived activity in Mo containing materials for waste disposal assessment.

7. Sn120(n,γ)Sn121 (55 y)

   Needed to determine the level of long-lived activity in the superconductor Nb3Sn in the toroidal field coil for waste disposal assessment.

8. Sn122(n,2n)Sn121 (55 y)

   Needed to determine the level of long-lived activity in the superconductor Nb3Sn in the toroidal field coil for waste disposal assessment.

9. W186(n,n'α)Hf182 (9.0e+06 y)

   Needed to determine the level of long-lived activity in tungsten as a divertor material and structural materials containing tungsten such as low-activity ferritic steel for waste disposal assessment.

10. Pb204(n,p)Tl204 (3.78 y)

    Needed to determine the decay heat, early dose, and waste disposal if Pb83Li17 alloy is used in the blanket.

11. Cr50(n,γ)Cr51 (27.7 d)

    Status of measured data needs to be reviewed further.

II. Priority 2 Reactions

1. Al27(n,'α)Na23 (stable)

   Needed to determine the relatively long-lived activity of Na22 (2.6 y) in aluminum due to the multi-step reaction Na23(n,2n).

2. Si29(n,t)Al27 (stable)

   Needed to estimate the tritium inventory in SiC blanket.

3. K39(n,α)Cl36 (3.0e+05 y)

   Status needs to be checked. Potassium is a potential coolant for ITER.

4. V50(n,n'α)Sc46 (83.8 d)

   Needed to determine the early dose in V-alloy due to Sc46.

5. Cr50(n,np)V49 (330 d)

   Needed to determine the activity level in V-5Ti-5Cr for waste disposal assessment.

6. Mn54(n,2n)Mn53 (3.7e+06 y)

   Needed to estimate the level of long-lived activity in structural materials containing Mn for waste disposal assessment.

7. Fe54(n,np)Mn53 (3.7e+06 y)

   Needed to estimate the level of long-lived activity in structural materials containing Fe for waste disposal assessment.

8. Fe59(n,γ)Fe60 (1.5e+06 y)

   Needed to estimate the long-lived activity in structural materials containing Fe via multi-step reactions, Fe58(n,γ)Fe59(n,γ).

9. Co60(n,p)Fe60 (1.5e+06 y)

   Needed to estimate the long-lived activity in structural materials containing Ni via multi-step reactions, Ni60(n,p)Co60(n,p).

10. Ni64(n,n'α)Fe60 (1.5e+06 y)

    Needed to estimate the long-lived activity in structural materials containing Ni.

11. Zr94(n,n'α)Sr90 (28.5 y)

    Needed to determine the level of activity in Zr containing structural materials for waste disposal assessment.

12. Zr94(n,2n)Zr93 (1.5e+06 y)

    Needed to determine the level of activity in Zr containing structural materials for waste disposal assessment.

13. Tc98(n,2n)Tc97 (2.6e+06 y)

    Desirable for the determination of long-lived activity level in Mo containing materials. Note that Tc98 is a long-lived target (4.2e+06 y) produced from Tc99(n,2n) reactions.

14. Tc99(n,2n)Tc98 (4.2e+06 y)

    Desirable for the determination of long-lived activity level in Mo containing materials. Note that Tc99 is a long-lived target (2.1e+05 y) produced from the Mo98(n,γ) and Mo100(n,2n) reactions.

15. Sn116(n,γ)Sn117m (13.6 d)

16. Sn119(n,n')Sn119m (293 d)

17. Sn120(n,2n)Sn119m

18. Sn118(n,γ)Sn119m

19. Sn124(n,γ)Sn125

    Reactions 15 thru 19 are needed to determine the activation characteristics of Nb3Sn superconductor in the TF coil.

20. Ta180(n,t)Hf178m2 (31 y)

    Needed for the estimate of long-lived activity for Ta containing materials for waste disposal assessment.

21. W180(n,γ)W181 (121 d)

    Desirable for the decay heat estimate of W divertor.

22. Pt192(n,γ)Pt193 (50 y)

    Needed to determine the level of long-lived activity for waste disposal assessment. Pt could be an impurity.

23. Pt194(n,2n)Pt193 (50 y)

    Needed to determine the level of long-lived activity for waste disposal assessment. Pt could be an impurity.

II. Report of Experimental Working Group

Attendees:

Y. Ikeda	JAERI (Chairman)
J. Csikai	Debrecen
A. Filatenkov	KRI
H. Vonach	IRK
Y. Uno	JAERI

Observations and Recommendations:

(1) Based on the list of recent measured data at JAERI-FNS, KRI, and Debrecen, a summary given in Table 2 was prepared.

(2) A comparison of different techniques used for neutron energy determination was carried out. It was realized that for low energy threshold reactions, the characteristics of neutron fields should be determined for corrections of the data influenced by degraded/background neutrons.

(3) Methods for the determination of the mean energy and the energy spread of neutrons were discussed. In addition to the activation unfolding method, the use of neutron spectrometry based on either time-of-flight (TOF) or the pulse height response system is strongly recommended. For extended samples, the volume averaged flux density spectra should be determined. It is strongly recommended that the IAEA/NDS organize a Consultants' Meeting on the characterization of neutron fields related to cross section measurements from keV to ~20 MeV.

(4) It is recommended to develop new neutron sources based, for example, on the 45Sc(p,n) and Li7(p,n) reactions for the measurements of capture cross sections in the keV-MeV range.

(5) Integral experiments for capture reactions using special benchmark fields are suggested.

(6) For the measurements of activation cross sections between 1 and 20 MeV, sources such as those at Debrecen, JAERI, PTB Braunschweig, and Jülich, should be used.

(7) Just as was needed for the d+t reaction, it is recommended to develop energy and fluence monitors for d+d neutron dosimetry, including the 115In(n,n')115mIn and 238U(n,f) reactions as fluence monitors and the 64Zn(n,p), 58Ni(n,p), and 31P(n,p) reactions as energy monitors.

(8) It is strongly recommended to extend the measuring methods for the detection of X-rays in the decay of the residual nuclei.

(9) Recommended standard flux monitor reactions in the 14 MeV range are as follows:

- (a) 27Al(n,p)27Mg
- (b) 56Fe(n,p)56Mn
- (c) 27Al(n,α)24Na
- (d) 59Co(n,2n)58m+gCo
- (e) 63Cu(n,α)60m+gCo
- (f) 58Ni(n,p)58m+gCo
- (g) 93Nb(n,2n)92mNb

(10) Table 3 lists the plans by the groups at this Specialists' Meeting for the measurement of the high priority reactions identified by the Activation Data Working Group.

(11) Table 4 lists reactions to be checked by the groups at this Specialists' Meeting to resolve discrepancies.

(12) For the fast and efficient transfer of information, communication by E-mail is recommended.

TABLE 2 **List of Reactions measured at FNS, KRI and Debrecen**

		FNS	KRI	Debrecen
^{19}F	(n, 2n)	○		
^{23}Na	(n, 2n)	○	○	
^{24}Mg	(n, p)	○		
^{25}Mg	(n, p)	○		
	(n, n'p)	○		
^{27}Al	(n, p)	○		
	(n, α)		○	○
^{28}Si	(n, p)	○		○
^{29}Si	(n, p)	○		
	(n, np)	○		
^{30}Si	(n, α)	○		○*
^{34}S	(n, p)	○		
^{35}Cl	(n, 2n)^{m}	○		
^{39}K	(n, 2n)	○		
^{41}K	(n, p)	○		
	(n, α)	○		
^{42}Ca	(n, p)	○		
^{43}Ca	(n, p)	○		
^{44}Ca	(n, p)	○		
	(n, n'p)	○		
	(n, α)	○		
^{48}Ca	(n, 2n)	○		
^{45}Sc	(n, 2n)^{m}	○		
	(n, 2n)^{g}	○		
	(n, α)	○		○
^{46}Ti	(n, 2n)	○		
	(n, p)	○		
^{47}Ti	(n, p)	○		
	(n, p)	○		
^{48}Ti	(n, p)	○		○
	(n, n'p)	○		
^{49}Ti	(n, n'p)	○		
^{50}Ti	(n, p)	○		
	(n, α)	○		○
^{51}V	(n, p)	○		
	(n, α)	○	○	○
	(n, n' α)			○
^{50}Cr	(n, 2n)	○		
^{52}Cr	(n, 2n)	○	○	○
^{54}Cr	(n, p)	○		
	(n, α)	○		○
^{55}Mn	(n, 2n)	○	○	
	(n, α)			○
^{54}Fe	(n, p)	○	○	○

		FNS	KRI	Debrecen
	(n, α)	○	○	○
^{56}Fe	(n, p)	○	○	○
^{57}Fe	(n, p)	○		
	(n, n'p)	○	○	
^{59}Co	(n, 2n)$^{m+g}$	○	○	
	(n, 2n)^{m}		○	
	(n, p)	○	○	
	(n, α)	○	○	○
^{58}Ni	(n, 2n)	○	○	○
	(n, p)$^{m+g}$	○	○	○
	(n, n'p)		○	
	(n, p)^{m}		○	
	(n, α)	○	○	○
^{60}Ni	(n, p)$^{m+g}$	○	○	○
^{61}Ni	(n, p)	○		
^{62}Ni	(n, n'p)	○		
^{63}Cu	(n, α)$^{m+g}$	○	○	○
	(n, 2n)	○		
	(n, n'α)	○		
^{65}Cu	(n, 2n)	○	○	
	(n, p)	○	○	
	(n, α)^{m}	○		
	(n, α)^{g}	○		
^{64}Zn	(n, 2n)	○		
	(n, p)	○		
^{66}Zn	(n, 2n)	○		○
^{67}Zn	(n, p)	○		
^{68}Zn	(n, n'p)	○		
	(n, α)	○		
^{70}Ge	(n, 2n)	○		
^{72}Ge	(n, p)	○		
	(n, α)^{m}	○		
^{73}Ge	(n, p)	○		
	(n, n'p)	○		
^{74}Ge	(n, n'p)	○		
	(n, α)^{m}	○		
^{75}As	(n, 2n)	○		
	(n, p)	○		
	(n, α)	○		
^{69}Ga	(n, p)	○		
^{71}Ga	(n, p)^{m}	○		
	(n, p)^{g}	○		
	(n, α)^{m}	○		
	(n, α)^{g}	○		
^{70}Ge	(n, p)	○		

	FNS	KRI	Debrecen
^{76}Ge (n, p)	○		
(n, 2n)	○		
(n, n' α)	○		
^{74}Se (n, p)			○
^{76}Se (n, p)			○
^{78}Se (n, p)			○
(n, α)^{m}			○
(n, α)^{g}			○
^{80}Se (n, α)^{m}			○
(n, α)^{g}			○
^{85}Rb (n, 2n)^{m}	○		
(n, 2n)$^{m+g}$	○		
(n, p)^{m}	○		
(n, α)	○		
^{87}Rb (n, 2n)$^{m+g}$	○		
(n, p)	○		
^{84}Sr (n, 2n)	○		
(n, p)$^{m+g}$	○		
(n, n'p)	○		
^{86}Sr (n, 2n)^{m}	○		
(n, 2n)$^{m+g}$	○		
^{88}Sr (n, 2n)^{m}	○		
^{89}Y (n, 2n)	○		○
(n, α)			○
^{90}Zr (n, 2n)^{m}	○		
(n, 2n)$^{m+g}$	○	○	
(n, p)^{m}	○	○	○
(n, α)^{m}	○	○	○
^{91}Zr (n, p)^{m}	○	○	○
(n, n'p)^{m}	○		
^{92}Zr (n, p)	○	○	○
(n, n'p)^{m}	○		
^{94}Zr (n, p)	○		○
(n, α)	○	○	○
(n, n'p)	○		
^{96}Zr (n, 2n)	○	○	○
(n, α)	○		
(n, n'p)	○		
(n, n' α)	○		
^{93}Nb (n, 2n)^{m}	○	○	○
(n, α)^{m}	○	○	○
(n, n' α)	○		
^{92}Mo (n, 2n)^{m}	○	○	
(n, p)^{m}	○		○

	FNS	KRI	Debrecen
(n, np)^m	○		
(n, α)^m	○		○
(n, α)$^{m+g}$	○		
^{94}Mo (n, 2n)^m	○		
(n, p)^m	○		
^{95}Mo (n, p)^m	○		○
(n, p)^g	○		
^{96}Mo (n, p)	○		○
(n, n'p)^m	○		
(n, n'p)^g	○		
^{97}Mo (n, p)^m	○		
(n, p)$^{m+g}$	○		
(n, n'p)	○		
^{98}Mo (n, p)^m	○		○
(n, n'p)^m	○		
(n, n'p)$^{m+g}$	○		
(n, α)	○		○
^{100}Mo (n, 2n)	○	○	
(n, α)	○		○
^{96}Ru (n, 2n)	○		
(n, p)$^{m+g}$	○		
(n, n'p)^m	○		
(n, n'p)^g	○		
^{99}Ru (n, p)^m	○		
^{100}Ru (n, p)	○		
^{112}Sn (n, 2n)	○		
^{114}Sn (n, 2n)	○		
(n, p)^m	○		
^{116}Sn (n, p)^m	○		○
^{117}Sn (n, p)^m	○		○
(n, p)^g	○		
(n, n'p)^m	○		
^{118}Sn (n, 2n)^m	○		○
(n, p)			○
(n, α)^g			○
^{120}Sn (n, α)^m	○		○
(n, α)^g	○		○
^{124}Sn (n, 2n)^m	○		
^{114}Sn (n, α)	○		
^{102}Pd (n, 2n)	○		
(n, n'p)^m	○		
^{105}Pd (n, p)	○		
^{106}Pd (n, p)^m	○		
^{108}Pd (n, α)	○		
^{109}Ag (n, 2n)^m	○	○	○

	FNS	KRI	Debrecen
^{107}Ag (n, 2n)^{m}	○	○	
^{106}Cd (n, 2n)	○		
(n, p)^{m}	○		
(n, n'p)	○		
^{110}Cd (n, p)^{m}	○		○
^{111}Cd (n, p)			○
^{112}Cd (n, p)	○	○	○
^{113}Cd (n, p)	○		
(n, p)^{m}			○
^{114}Cd (n, p)^{m}		○	○
(n, α)^{m}			○
^{113}In (n, 2n)^{m}	○		
(n, n')^{m}	○	○	
^{115}In (n, n')^{m}	○	○	
(n, p)^{m}	○	○	○
(n, p)^{g}	○	○	○
(n, α)	○	○	○
(n, 2n)^{m}		○	○
^{130}Ba (n, 2n)$^{129m+g}$ Ba			
$\rightarrow$ ^{129}Cs	○		
^{132}Ba (n, 2n)$^{m+g}$	○		
(n, p)	○		
^{134}Ba (n, 2n)^{m}	○		
(n, 2n)$^{m+g}$	○		○
(n, p)	○		○
^{135}Ba (n, p)^{m}	○		
^{136}Ba (n, 2n)^{m}	○		
(n, p)	○		
^{137}Ba (n, n'p)	○		
(n, p)			○
^{138}Ba (n, 2n)^{m}	○		
(n, p)$^{m+g}$	○		
(n, α)$^{m+g}$	○		
^{130}Te (n, p)^{m}	○		
^{142}Nd (n, p)			○
(n, α)			○
^{144}Nd (n, α)			○
^{146}Nd (n, p)			○
(n, α)			○
^{151}Eu (n, 2n)^{150A}Eu	○	○	
(n, 2n)^{150B}Eu	○	○	
(n, α)^{m}	○	○	
^{153}Eu (n, 2n)^{m1}	○	○	
(n, 2n)^{m2}	○	○	
(n, 2n)$^{m2+g}$	○	○	

	FNS	KRI	Debrecen
(n, p)	○		
(n, α)	○	○	
^{159}Tb (n, p)	○		
^{169}Tm (n, 2n)	○		
^{178}Hf (n, α)	○		
^{179}Hf (n, n')^{m2}	○		
(n, p)	○		
^{180}Hf (n, 2n)^{m2}	○		
(n, n')^{m}	○		
(n, α)	○		
^{181}Ta (n, 2n)^{m}	○		
^{182}W (n, p)		○	○
^{183}W (n, p)			○
^{184}W (n, p)^{m}	○		○
(n, α)		○	○
^{186}W (n, α)	○		○
^{197}Au (n, 2n)^{m}	○	○	
(n, 2n)^{g}	○	○	
^{203}Tl (n, α)			○
^{204}Pb (n, 2n)	○		
^{206}Pb (n, α)	○		○
^{185}Re (n, 2n)^{m}	○	○	
(n, 2n)^{g}	○	○	
^{187}Re (n, p)	○		
(n, α)	○		
^{188}Os (n, p)	○		
(n, p)^{m}	○		
(n, α)^{m}	○		
^{192}Os (n, 2n)$^{m+g}$	○		
^{191}Ir (n, 2n)^{m2}Ir			
$\rightarrow^{190m}$Os	○		
(n, 2n)$^{190m1+m2+g}$Ir	○		
^{193}Ir (n, 2n)	○		
^{232}Th (n, 2n)	○		
^{238}U (n, 2n)	○		○

Table 3: High Priority Reactions, to be measured in the present project

Reaction	Priority	Present WG	Long-lived CRP	Others
28Si(n,np)	1			AMS/FNS
29Si(n,t)	2			FNS/Debrecen
39K(n,α)	2			Debrecen
45Ca(n,α)	1	I		
48Ti(n,α)	1	I		
50V(n,2n)	1	I		
50V(n,nα)	2	M(KRI:SI)		
50Cr(n,x)49V	2	M(KRI:SI)		
54Mn(n,2n)	2		CRP	
54Fe(n,x)53Mn	2		CRP	
60Co(n,p)	2	I(KRI)		
64Ni(n,nα)	2		CRP	
64Ni(n,α)	-	M		
94Zr(n,nα)	2	M(KRI)		
94Zr(n,2n)	2			AMS
92Mo(n,np)	1	M(KRI:SI)		
99Tc(n,2n)	2	I(KRI:SI metal)		
117Sn(n,n')	2	M		
119Sn(n,n')	2	M		
120Sn(n,2n)	2	M		
122Sn(n,2n)	1	M		
180Ta(n,t)	2	I(KRI:SI)		
186W(n,nα)	1			AMS
194Pt(n,2n)	2	I		
204Pb(n,p)	1	M(KRI:SI)		

I = Investigate possibility
M = To be measured
SI = Separated Isotopes

Priority; as established by Activation Data WG

Table 4 Reactions to be checked by the groups at this Specialists' Meeting

Reaction
$^{67}Zn(n,p)^{67}Cu$
$^{68}Zn(n,p)^{68}Cu$
$^{73}Ge(n,np)^{72}Ga$
$^{74}Ge(n,np)^{73}Ga$
$^{92}Mo(n,np)^{91m}Nb$
$^{96}Ru(n,np)^{95g}Tc$
$^{102}Pd(n,np)^{101m}Rh$
$^{102}Pd(n,2n)^{101}Pd$
$^{106}Pd(n,p)^{106m}Rh$
$^{106}Cd(n,2n)^{105}Cd$
$^{179}Hf(n,p)^{179}Lu$
$^{180}Hf(n,\alpha)^{177}Yb$
$^{187}Re(n,\alpha)^{184}Ta$
$^{191}Ir(n,2n)^{190m}Ir$

III. Conclusions and Recommendations

1. Experimental work on 14 MeV cross sections

Conclusions and recommendations are given below regarding the measurements of cross sections at 14 MeV energies.

1.1. **Comparison of experimental techniques.** The experimental group at JAERI-FNS (Japan), KRI-St.Petersburg (Russian Federation), and the Institute of Experimental Physics in Debrecen (Hungary) will join in a collaborative program on comparing their measuring technique (see Experimental Working Group report) and do measurements for reactions where discrepancies between their previous measurements exist.

1.2. **Cross section measurements for the confirmation of previous FNS results.** Within the large body of measurements provided by the FNS-JAERI group in the last few years, a number of reactions were identified (see Table 4) for which the FNS results were either the only existing data or strongly deviating from previous measurements. It is recommended that the groups at KRI and Debrecen consider measurements of these cross sections in order to clarify the situation.

1.3. **Cross section measurements for fusion applications.** Within the Activation Data Working Group, a list of reactions needed for fusion reactor technology was established and these reactions for which the data situation at present is unsatisfactory was identified (see Table 1). This list was discussed in detail by the full specialists' meeting concerning the possibilities of obtaining experimental data for these reactions. Among the reactions given in this list, 17 of these were identified (see Table 3) as being accessible to the experimental groups of the above mentioned collaboration. It is strongly recommended that these reactions be investigated by the collaboration.

In addition, a number of reactions were identified for which the cross sections at present can not be measured by activation because of the extremely long half-lives of the reaction products, but probably can be measured by other methods such as accelerator mass spectrometry (AMS). It is recommended that this list be sent to all members of the IAEA CRP on cross sections for long-lived activation products for consideration in their programs and discussions at their informal meeting at the next nuclear data conference at Gatlinburg, TN (USA) - (Action on IAEA/NDS). It must be noted that separated isotopes are needed to measure these reactions (see Table 3). KRI may be able to supply some of these separated isotopes.

2. Experimental work at energies below 14 MeV

It is recommended (see Experimental Working Group report) that the experimental work in the future should be extended to the neutron energy range below 14 MeV. Two types of measurements were identified as especially urgent:

(a) Measurements of cross sections for threshold reactions in the MeV energy range; and

(b) Measurements of capture cross sections in the keV energy range.

For the latter it is recommended to do a number of integral measurements at FNS in various moderated 14 MeV fields.

3. Recommended values for 14 MeV energy range

Due to the outstanding work at JAERI-FNS and other laboratories (e.g., in connection with the CRP on the production of long-lived activation products) our knowledge of the 14 MeV cross sections has improved greatly in the last years. As a consequence of these efforts, the recommended values of the 14 MeV cross sections in the IAEA Activation Handbook are now outdated. It is therefore recommended that an improved set of recommended 14 MeV cross section values be created taking into account the presently available data base. This set of new recommended evaluated cross section values should be made generally available by the IAEA/NDS.

4. Cooperation with the NEANSC Working Group on the international collaboration on activation cross section measurements

It is recommended that this question be discussed by the chairman of the NEANSC Working Group, Dr. Donald L. Smith, and chairman of the present Specialists' Meeting, Dr. Yujiro Ikeda, during the forthcoming visit of Dr. Smith to JAERI. The results of their discussions*) should be distributed to interested parties by the IAEA/NDS. The proposals by Drs. Smith and Ikeda should be discussed at the next Specialists' Meeting on Activation Cross Sections.

5. Future Meetings

It is recommended that a follow-up Specialists' Meeting be held in the second half of 1994 in St. Petersburg. This meeting should discuss the results obtained by then, the further work especially with respect to 14 MeV cross section measurements needed for fusion reactor technology (Table 3) and the extension of cross section work to energies below 14 MeV. It is recommended that the future meetings should be coordinated by the IAEA/NDS with the schedule of the future FENDL meetings and the planned CRP meetings on activation libraries in order to facilitate the participation in the various meetings for the interested scientists.

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* The summary of the discussions held during the visit of Dr. Smith to JAERI-FNS from 15 January to 25 February 1994 are given in Attachment 5.

Two Letters from Dr. D. Smith: Attachment 4

SEPTEMBER 20, 1993

TO: YUJIRO IKEDA
<IKEDA@FNSHP.TOKAI.JAERI.GO.JP>

FROM: DONALD SMITH
<B18245@ANLOS>

SUBJECT: IAEA SPECIALISTS' MEETING AT JAERI IN NOVEMBER

IN A RECENT E-MAIL MESSAGE YOU REQUESTED THAT I SPEND SOME TIME THINKING ABOUT WHAT ISSUES OUGHT TO BE DISCUSSED AT THE MEETING IN JAERI. UNFORTUNATELY, I WILL NOT BE ABLE TO ATTEND THAT MEETING.

IT APPEARS TO ME THAT THE MAIN OBJECTIVE OF THIS MEETING IS TO LAUNCH A COORDINATED RESEARCH PROGRAM WHICH WILL DEAL WITH THE GENERAL ISSUE OF IMPROVING THE OVERALL UNDERSTANDING OF 14-MEV CROSS SECTIONS. YOUR LABORATORY (JAERI) AND THE KHLOPIN RADIUM INSTITUTE (KRI) HAVE ACCUMULATED THE MOST COMPREHENSIVE SET OF 14-MEV CROSS SECTION DATA IN RECENT TIMES. A FEW YEARS AGO, J.W. MEADOWS AND I ALSO MEASURED SEVERAL REACTIONS. THE RESULTS WERE ULTIMATELY PUBLISHED IN A JOURNAL ARTICLE: J.W. MEADOWS ET AL., ANNALS OF NUCLEAR ENERGY 14, 489 (1987). OUR GROUP ALSO UNDERTOOK AN EVALUATION OF 14-MEV CROSS SECTIONS WHICH WAS REPORTED IN ANL/NDM-89 (1985). ON THE BASIS OF THESE CONTRIBUTIONS, JAERI, KRI AND ANL WERE CHOSEN AS PRINCIPAL CONTRIBUTORS TO THIS IAEA INITIATIVE. FDWARD CHENG HAS ALSO BEEN INCLUDED BECAUSE OF HIS KNOWLEDGE OF THE DATA NEEDS FOR FUSION, AND FRED MANN BECAUSE OF HIS CONTRIBUTIONS TO THE REAC LIBRARY AND HIS NUCLEAR MODELING HOW SHOULD THIS GROUP OF PEOPLE GO ABOUT THIS TASK? WHAT SHOULD BE THE SPECIFIC ACTIVITIES. SUCH AN INTERCOMPARISON OF TECHNIQUES WAS CARRIED OUT UNDER THE AUSPICES OF AN NEANDC WORKING GROUP ON ACTIVATION CROSS SECTIONS DURING 1990-91. THE RESULTS WERE REPORTED AT THE JUELICH CONFERENCE IN 1991 (D.L. SMITH ET AL., PAGE 282). THIS EXERCISE COULD SERVE AS A GUIDE FOR THE PRESENT UNDERTAKING. ANOTHER EXAMPLE IS THE CURRENT COLLABORATION BETWEEN ARGONNE AND JAERI, IN WHICH A CAREFUL INTERCOMPARISON IS BEING MADE BETWEEN RESULTS OBTAINED AT BOTH LABORATORIES FOR THE SAME REACTIONS. BELOW I WILL OFFER A NUMBER OF SUGGESTIONS OF THINGS THAT SHOULD BE DONE IN THE FUTURE, NOT NECESSARILY IN ANY PARTICULAR ORDER:

TASK 1:

IDENTIFY ALL THE REACTIONS IN COMMON BETWEEN THE JAERI AND KRI THAT ARE AVAILABLE FOR DETAILED COMPARISON IN THE 13-15 MEV RANGE. THE DATA FROM ARGONNE CAN ALSO BE INCLUDED BUT IT IS A LESS EXTENSIVE SET. THE AGREEMENT AND DIFFERENCES SHOULD BE NOTED, BUT AGREEMENT SHOULD NOT BE A CAUSE FOR LEAVING MATTERS AS THEY ARE. THERE MAY BE AGREEMENT DUE TO CHANCE SO IT IS NECESSARY TO INCLUDE ALL THE REACTIONS IN THE FOLLOWING STEPS.

PREPARE A SPREADSHEET AND EXAMINE THE EXPERIMENTAL AND ANALYTICAL ISSUES INVOLVED IN DERIVING THE CROSS SECTIONS FROM THE DATA. THESE CONCERNS APPLY FOR MEASUREMENTS INVOLVING THE STANDARDS AS WELL AS THE UNKNOWNS. ISSUES TO BE CONSIDERED ARE:

1. BASIC NUCLEAR RADIOACTIVE DECAY PARAMETERS

1a. HALF LIVES AND THEIR IMPACT ON THE ANALYSIS, INCLUDING EFFECTS RELATED TO IRRADIATION TIMES, COUNT TIMES, WAIT TIMES, ETC.

1b. BRANCHING FACTORS FOR THE MEASURED DECAY RADIATION

2. DETAILS RELATED TO THE SAMPLES

2a. CHEMICAL CHARACTERIZATION AND PURITY

2b. ISOTOPIC ABUNDANCES. WERE THE SAMPLES ENRICHED? WHAT VALUESWERE USED FOR ISOTOPIC ABUNDANCES IN CASE OF NATURAL SAMPLES?

2c. SAMPLE GEOMETRY AND UNIFORMITY

2d. SAMPLE MASSES-HOW DETERMINED

3. STANDARD CROSS SECTIONS

4. NEUTRON FIELD

4a. METHOD OF DETERMINING THE PRIMARY SPECTRUM

4b. NEUTRON ENERGY SCALE (AVERAGE NEUTRON ENERGY OF THE PRIMARY SPECTRUM AND EFFECTIVE RESOLUTION). THIS IS VERY IMPORTANT FOR REACTIONS WITH STRONG ENERGY DEPENDENCE

4c. METHODS FOR CORRECTING FOR NONUNIFORMITY OF FLUX (ABSORPTION, NEUTRON MULTIPLE SCATTERING).

5. SAMPLE ACTIVITY MEASUREMENT

5a. NATURE OF THE COUNTING APPARATUS (GEOMETRY, ETC.)

5b. DETERMINATION OF DETECTOR EFFICIENCY

5c. CORRECTIONS FOR DEADTIME, BACKGROUND AND ELECTRONICS PERTURBATIONS SD. INTERCALIBRATE DETECTION APPARATUS BETWEEN THE LABORATORIES (THIS IS NO LONGER POSSIBLE FOR ARGONNE). THIS CAN BE DONE BY PREPARING A VERY WEAK SAMPLE WITH WELL KNOWN DECAY PROPERTIES AND ADEQUATE HALF LIFE (E.G., C0-58) AND SEND IT TO EACH LABORATORY TO BE COUNTED. THE RESULTS CAN BE INTERCOMPARED TO SEE IF THERE M E ANY BIASES. IF THE SAMPLE ACTIVITY IS VERY WEAK AND INVOLVES A SOLID METAL SAMPLE, THEN IT CAN BE SHIPPED BY MAIL WITHOUT INCURRING ANY SERIOUS PROBLEMS. SO LONG AS THE ACTIVITY IS RELATIVE1Y LONG-LIVED THERE SHOULD BE NO DIFFICULTY WITH THIS.

6. ERROR SOURCES

6a. EACH LABORATORY SHOULD SPECIFY THE PARTIAL ERRORS ASSOCIATED WITH EACH ASPECT OF THE DATA ANALYSIS AND TABULATE THESE ERRORS

6b. POSSIBLE SOURCES OF CORRELATED ERROR SHOULD BE EXAMINED, E.G., IN THE USE OF LIKE STANDARDS, HALF LIVES, ETC.

6c. THE ERRORS SHOULD FORM THE BASIS FOR EXAMINING THE RELATIVE RELIABILITY OF EACE DATA SET

TASK 2:

1. **ADJUST THE EXISTING RESULTS**

   ALL OF THE INFORMATION GATHERED IN TASK 1 SHOULD BE USED AS A BASIS FOR RENORMALIZATION OF ALL THE DATA SETS TO COMMON NUCLEAR PARAMETERS-WHEREVER APPLICABLE. IF CERTAIN DATA SETS HAVE NOT BEEN CORRECTED, E.G., FOR MULTIPLE SCATTERING, THEN THESE CORRECTIONS SHOULD BE DETERMINED AND APPLIED. THEN, THE RESULTING VALUES SHOULD BE INTERCOMPARED WITHIN THE CONTEXT OF THE QUOTED ERRORS (TASK 1-ITEM 6). CAREFUL ATTENTION SHOULD BE PAID TO ALL INSTANCES WHERE THE RESULTS ARE DISCREPANT (BEYOND THE ERRORS, E.G., BY MORE THAN 2 STANDARD DEVIATIONS). THESE CASE HAVE TO BE EXAMINED ISSUE BY ISSUE UNTIL THE SOURCE OF DISCREPANCY IS FOUND FROM EXAMINING THE AVAILABLE DATA. IF AN ANSWER IS NOT FOUND, THEN IT MAY BE NECESSARY TO UNDERTAKE SOME NEW MEASUREMENTS-IF THAT IS FEASIBLE.

2. **ESTABLISH THE ACCURACIES** TO WHICH VARIOUS REACTIONS CAN BE MEASURED ON THE BASIS OF CURRENT TECHNOLOGY, I.E., GIVEN THE AVAILABLE DECAY DATA, SAMPLE CHARACTERIZATIONS AND EXPERIMENTAL TECHNIQUES AT TWO OR MORE LABORATORIES.

TASK 3:

A REASONABLE GOAL FOR THE IAEA WOULD BE TO PREPARE A HANDBOOK OF EVALUATED 14-MEV CROSS SECTIONS FOR APPLICATIONS. DEVELOPMENT OF A COMPREHENSIVE DATA BASE WOULD ENTAIL:

1. CONDUCT OF A THOROUGH LITERATURE SEARCH (BASED ON CINDA)

2. EVALUATION OF THE EXISTING EXPERIMENTAL DATA BASE-INCLUDING MANY OLD VALUES WILL HAVE TO BE REJECTED IF THE DOCUMENTATION IS INADEQUATE

3. DEVELOPMENT OF SYSTEMATICS FOR PREDICTING UNMEASURED, UNMEASURABLE, OR POORLY MEASURED VALUES. SOME NUCLEAR MODELING MAY BE REQUIRED

4. ESTABLISH UNCERTAINTIES FOR ALL THE RESULTS PREDICTED IN THE HANDBOOK (BASED ON STATISTICAL ANALYSIS OF DATA, MODELING OR SYSTEMATICS UNCERTAINTIES, ETC.)

TASK 4:

PREPARE A SUGGESTED LIST OF NEW MEASUREMENTS TO BE PERFORMED AT THE AVAILABLE LABORATORIES (KRI AND JAERI). DEFINE THE SAMPLE NEEDS, ETC. MAKE A PLAN FOR UNDERTAKING THESE MEASUREMENTS. DEFINE THE NUCLEAR PARAMETERS TO BE USED BY EACH LABORATORY IN THE DATA ANALYSIS (INCLUDING STANDARDS).

THIS IS PROBABLY AN INCOMPLETE LIST, BUT IT WOULD PROVIDE THE BASIS FOR SOME CONCRETE EFFORTS TO BE CARRIED OUT BY THE PARTICIPANTS OF THE IAEA PROGRAM. I THINK IT IS IMPORTANT TO HAVE A WELL DEFINED PRODUCT FROM THIS PROGRAM, E.G., A HANDBOOK, AS MOTIVATION FOR THE EFFORT. IT WILL TAKE QUITE A WHILE TO COMPLETE THIS UNDERTAKING BUT I THINK IT WILL BE WELL WORTHWHILE. SO MUCH OF THE LITERATURE ON 14-MEV RESULTS IS FILLED WITH DISCREPANT DATA THAT IT WOULD BE A MAJOR ACHIEVEMENT TO SHOW THAT TWO DIVERSE LABORATORIES CAN OBTAIN RESULTS IN GOOD AGREEMENT IF CARE IS TAKEN IN THE ANALYSIS AND THE DETAILS ARE INTERCOMPARED. A HANDBOOK OF RECOMMENDED 14-MEV CROSS SECTIONS WOULD BE EXTREMELY VALUABLE TO MANY FIELDS.

COPY TO:

ANATOLY PASCHCHENKO, IAEA, VIENNA, <RNX@IAEA1>
ANATOLY FILATENKOV, KRI, ST. PETERSBURG, <ARK@RI.SPB.SU>

November 2, 1993

To: Anatoly Pashchenko

From: Don Smith
Argonne-EP

Subject: **Agenda for Specialists' Meeting**

I got your message, also directed to Yujiro Ikeda about the meeting. I feel badly about not being there. It will be a good meeting. The Agenda is fine as it stands. I do have some thoughts about the 14 MeV Activation Handbook as follows. Here are the issues to be addressed:

(1) There is a need for a unified set of standards to use in evaluating the enormous data base from experimental measurements. A guide for the approach is in my report ANL/NDM-89. Of course this work is now old and a new look at the standards is required.

(2) A great deal of work will be needed to gather the experimental data from the literature, to make copies of papers from the literature, etc. CINDA and the EXFOR system will be very useful here.

(3) The experimental data need to be evaluated by the method of least squares. The question that has to be answered is to whether this handbook should try to provide an evaluation for each reaction considered over the range 13-15 MeV or to pick a single reference energy, say 14.7 MeV and transfer all data to that energy using shape information, etc. This is a key question which will set the structure of the handbook.

(4) Clearly not all reactions are amenable to evaluation by data only. There will be need for studies of systematics and modelling. This is essential and it must be well done. There are people who could do a good job of this. Vonach is one. Perhaps Kopecky. Mark Chadwick, if he could be interested.

(5) Some attention needs to be given to whether some new measurements could be undertaken in the next year or two to fill in some important gaps. The St. Petersburg and Tokai Groups could address these if the samples are available.

I am not a theorist so I would not be able to make much of a contribution to item number 5. I would be interested in participating in the other aspects, particularly the statistical evaluation procedure. It is too big a job for one person alone so a lot of thought needs to be given to how to go about this. One possibility you might consider is for the Agency to provide a fellowship to an individual from a developing country to come and work on the project under tutelage of one of the experienced people in this field. Professor F.A.N. Osadebe from Ile-Ife, Nigeria, told me that he would very much like to come to Argonne for a year to work on this project. I believe he would be very competent to do this work, particularly the task of extracting data from the literature and doing the statistical evaluations. He also has a background in theory. I have mentioned this to Charlie Dunford before. It is worth some thought. Unfortunately, I do not have the funds at Argonne to support Professor Osadebe.

Good luck with your meeting at Tokai.

Attachment 5

SUMMARY OF DISCUSSIONS HELD BETWEEN Y. IKEDA (JAERI-FNS) AND D. SMITH (ARGONNE NATIONAL LABORATORY)

These discussions were held during the visit of Donald Smith to JAERI-FNS (15 January - 25 February, 1994). The topics of these discussions were:

(i) the newly undertaken activity on "Comparison of Activation Cross Section Measurements and Experimental Techniques" and,

(ii) the Specialists' Meeting on this same topic which was held at JAERI-Tokai on 15-17 November 1993. Yujiro Ikeda attended this meeting but Donald Smith was not able to be present. Here are the main conclusions that we reached:

(1) The framework for this activity which has been established by the IAEA-NDS is important by its own nature in encouraging the continuation of neutron activation research by the participating members. Clear needs for such data have been established and the formal declaration of these needs by the IAEA is a useful tool for administrative purposes. We strongly support the maintenance of this framework.

(2) It is our belief that participation in this activity should also include appropriate representatives from the People's Republic of China. Laboratories in the PRC have been producing extensive data which are relevant to this topic, and it would be an oversight to not include them in a cooperative arrangement involving laboratories in Japan, Russia, Hungary and the U.S.

(3) The cause of nuclear data development can be best served by encouraging those laboratories which have the facilities to do this work to continue to devote their precious personnel resources to activities which produce new data relevant to the emerging technologies which will benefit from these results. Time is always limited and the experiments, which remain to be done, are often difficult ones. Care must be taken to insure that the valuable time of trained researchers be spent doing what they do best and are well equipped to do, namely, to produce new results. The expenditure of time on activities which are of marginal worth must be carefully avoided.

(4) One of the most difficult problems that has to be dealt with in producing good quality neutron activation data is the acquisition of appropriate samples. In many cases, this involves the utilization of isotopically enriched materials. The availability, accessibility and cost factors associated with sample acquisition by the participating laboratories should be discussed. This is a fertile area for beneficial cooperation between the participants.

(5) A careful review of data acquisition and analysis procedures, and the quality of the raw data, for previously conducted experiments would be beneficial but it is a very time-consuming task. We believe it is not advisable for researchers to devote valuable time to such an activity instead of working in the laboratory to obtain new results. However, such an activity could be pursued by an individual supported by the IAEA to specifically address such a project. In particular, a fellow might be provided to a well-qualified individual who is not actively working in a laboratory which produces data and who is willing to undertake such a task with input from the measurers. Perhaps this objective could be met by endowing such a fellowship to a qualified scientist from a developing country. It is important to stress that such an individual be well qualified to do the work that this project would entail.

(6) It is recommended that the activities of this IAEA-sponsored comparison activity be brought to the attention of the NEANSC Activation Working Group, and that opportunities for coordination between these two groups be sought. Donald Smith will bring up this matter with the NEANSC Activation Working Group. It should be noted that several members of the NEANSC Activation Working Group are also participating in the IAEA-sponsored comparison effort.

(7) In many cases, the procedures and specific measurements previously made have been documented in the literature via reports and journal articles. It would be very useful to compile a bibliography of such materials as is relevant to this project. Participants could send their contributions to this list (and copies of the papers) to the IAEA-NDS for compilation and retention. Then, participants who wish to obtain a report mentioned in the bibliography that is not generally available in the open literature could request that the IAEA-NDS send a copy by mail or fax.

Attachment 6

March 1994 EAF-Doc-004

List of neutron activation reactions important for fusion power plant technology with their priorities and experimental status

compiled by

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J. Kopecky (ECN Petten), F. M. Mann (Westinghouse Hanford)

1. Selection procedure:

The starting list for the selection of important reactions has been based on the following studies:

[1] Selection by C. Ponti for REAC-ECN-5 library:
J. Kopecky and H.A.J. van der Kamp, Evaluation of cross sections and uncertainties for important reactions, ECN-89-181 (1989).

[2] D.L. Smith and E.T. Cheng, A Review of Nuclear Data Needs and their Status for Fusion Reactor Technology with some Suggestions on Strategy to satisfy the Requirements, ANL/NDM - 123 (1991).

[3] E.T. Cheng and D.L. Smith, Nuclear Data Needs and Status for Fusion Reaction Technology, Nuclear Data for Science and Technology, (Spring-Verlag, Berlin, 1992) p. 273.

[4] C.B.A. Forty, R.A. Forrest, D.J. Compton and C. Rayner, Handbook of Fusion Activation Data,
Part 1: Elements Hydrogen to Zirconium, AEA FUS 180 (1992)
Part 2: Elements Niobium to Bismuth, AEA FUS 232 (1993).

The authors of this report have reviewed the starting list and revised its content and priorities in order to reflect the state of the art of cross section data and the present design choices for fusion energy systems. There are now 386 reactions (ignoring any splitting to isomers).

The following elements are not considered as targets: H, He, B, Li, Ne, P, Ga, Ge, As, Se, Br, Kr, Rb, Sr, Tc, Ru, Rh, Pd, Cd, In, Sb, Te, I, Xe, Cs, La, Ce, Pr, Nd, Pm, Sm, Tb, Dy, Er, Tm, Yb, Lu.

2. Priority assignment (P):

P=1 --> high - important materials
P=2 --> medium - possibly important materials
P=3 --> low - impurities and less important materials

The basis of prioritization can be expanded to include the following:

High priority (P=1) reactions are those that are most likely to impact the design and assessment of fusion energy systems. Priority 1 reactions include as targets those elements that are most likely to constitute candidate fusion materials and impurities that are likely to cause the production of large quantities of long-lived residual activities.

Medium priority (P=2) reactions are those similar to P=1 but less probable to impact fusion energy development. The target elements correspond to less relevant candidate fusion materials.

Low priority (P=3) reactions have only minor impact on the design and assessment of fusion energy devices, but, may still be needed for completeness, and also to remove doubt on the impact of very poorly known reactions.

3. Experimental status (ES):

A --> adequate, A* --> only one measurement, I --> inadequate

For (n,γ) reation the status "I" reflects the missing experimental information of the resolved resonance data.

4. Notes on justifications (remark):

1. Safety: potential radiological hazards due to materials that might be released during a power plant accident such as early dose; or decay heat, which could provide the driving energy to release nuclides responsible for the potential radioactive hazards.

2. Maintenance: usually the γ-dose rate is the most important quantity. Normally this is needed after shutdown of a power plant. However, in some occasions, it is important during the power plant operation, particularly when a liquid coolant is in place.

3. Waste (disposal): concerns for waste disposal are related to the effects of nuclides with long half-life.

TABLE 1. LIST OF NEUTRON ACTIVATION REACTIONS IMPORTANT FOR FUSION POWER PLANT TECHNOLOGY

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Be- 9(n,g) Be-10	1.6x10+6y	2	A	(Be-10 from Be)
C -13(n,a) Be-10		3	I	waste

N -14(n,np)C -13	st	3	I	waste
N -14(n,d) C -13		3	I	waste
O -16(n,a) C -13		3	A*	(Be-10 from F)
O -17(n,na)C -13		3	I	(Be-10 from Na)

C -13(n,g) C -14	5.73x10+3y	3	A	waste
N -14(n,p) C -14		2	A	waste
N -15(n,np)C -14		3	I	waste (C-14 from F)
N -15(n,d) C -14		3	I	waste (C-14 from F)
O -17(n,a) C -14		3	I	waste
O -18(n,na)C -14		3	I	waste

N -14(n,2n)N -13	9.96m	3	A	(N-13 from O)

N -15(n,2n)N -14	st	3	I	(N-13 from O)

F -19(n,na)N -15	st	3	I	(Be-10 from F C-14 from F)
O -16(n,np)N -15		3	I	waste (N-13 from O)
O -16(n,d) N -15		3	A*	waste (N-13 from O)

F -19(n,a) N -16	7.13s	3	A	maintenance
O -16(n,p) N -16		3	A	maintenance (dose rate during operation if water is the coolant)

F -19(n,nt)O -16	st	3	I	(Be-10 from F)

Ne-20(n,a) O -17	st	3	A	(Be-10 from Na)

F -19(n,p) O -19	27s	3	A	(O-19 from F)

F -19(n,2n)F -18	1.83h	3	A	safety (early dose, d.heat); maintenance (dose rate)

F -19(n,g) F -20	11s	3	A	safety (decay heat)
Na-23(n,a) F -20		3	A	

Na-23(n,p) Ne-23	37s	3	A	(Ne-23 from Na)

Na-23(n,2n)Na-22	2.602y	1	A	safety/maintenance
Mg-24(n,t) Na-22		3	I	safety/maintenance
Al-26(n,na)Na-22		2	I	(Na-22 from Si)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Mg-24(n,np)Na-23	st	3	I	safety/maintenance (Na-22 prod.)
Mg-24(n,d) Na-23		3	I	safety/maintenance (Na-22 prod.)
Al-27(n,na)Na-23		1	I	safety/maintenance (Na-22 prod.)

Na-23(n,g) Na-24	[14.659h/20ms]	1	A	safety/maintenance
Mg-24(n,p) Na-24		1	A	safety/maintenance
Mg-25(n,np)Na-24		3	A	safety/maintenance
Mg-25(n,d) Na-24		3	A	safety/maintenance
Al-27(n,a) Na-24		1	A	safety/maintenance

Si-28(n,na)Mg-24	st	3	I	(Na-24/Na-22 prod.)

Mg-26(n,g) Mg-27	9.46m	3	A	waste (Al-26 prod.)
Al-27(n,p) Mg-27		2	A	safety (decay heat)
Si-28(n,2p)Mg-27		2	I	(Mg-27 from Si)

Si-29(n,2p)Mg-28	20.9h	3	I	(Mg-28 from Si)

Al-27(n,2n)Al-26	[7.2x10+5y/6.3s]	1	A	waste

Si-28(n,np)Al-27	st	1	A	waste (Al-26 prod.)
Si-28(n,d) Al-27		1	A	waste (Al-26 prod.)
Si-29(n,t) Al-27		1	I	(Ti prod. in SiC)

Al-27(n,g) Al-28	2.2m	3	A	(Al-28 from Al)
Si-28(n,p) Al-28		3	A	(Al-28 from Si)
P -31(n,a) Al-28		3	A	(Al-28 from S)

Si-29(n,p) Al-29	6.56m	3	A	(Al-29 from Si)

Si-30(n,g) Si-31	2.622h	3	A	
S -32(n,2p)Si-31		3	I	(Si-31 from S)
S -34(n,a) Si-31		3	I	(Si-31 from S)

S -33(n,2p)Si-32	172y	3	I	waste (impurity)

S -32(n,np)P -31	st	3	I	(Al-28 from S)
S -32(n,d) P -31	st	3	I	(Al-28 from S)

S -32(n,p) P -32	14.282d	3	A	safety
Cl-35(n,a) P -32		3	A	safety
P -31(n,g) P -32		3	A	safety

Cl-36(n,a) P -33	25.3d	3	I	(P-33 from K)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
S -34(n,p) P -34	12.4s	3	A	(P-34 from S)
Cl-35(n,2p)P -34		3	I	(P-34 from Cl)
Cl-37(n,a) P -34		3	A	(P-34 from Cl)

S -34(n,g) S -35	87.5d	3	A	safety
Cl-35(n,p) S -35		3	A	safety
Cl-36(n,np)S -35		3	I	(S-35 from K & Cl)
Cl-36(n,d) S -35		3	I	(S-35 from K & Cl)

Cl-37(n,p) S -37	5.05m	3	A	(S-37 from Cl)

Cl-35(n,g) Cl-36	3.01x10+5y	2	A	waste (impurity)
Cl-37(n,2n)Cl-36		3	I	waste (Cl-36 from Ca)
K -39(n,a) Cl-36		2	I	waste

Cl-37(n,g) Cl-38	[37.24m/715ms]	3	A	(Cl-38 from Cl & Ca)
K -39(n,2p)Cl-38		3	I	
K -41(n,a) Cl-38		2	A	(Cl-38 from K)

Ar-39(n,p) Cl-39	55.6m	3	I	(Cl-39 from K & Cl)

Ar-38(n,2n)Ar-37	35.04d	3	I	(Ar-37 from K)
Ca-40(n,a) Ar-37		3	A	safety

K -39(n,d) Ar-38	st	3	I	(Ar-37 from K)
K -39(n,np)Ar-38		3	I	(Ar-37 from K)

Ar-38(n,g) Ar-39	269y	3	I	(Ar-39 from Cl)
K -39(n,p) Ar-39		1	A	waste
Ca-42(n,a) Ar-39		3	I	waste (impurity)
Ca-40(n,2p)Ar-39		3	I	waste (impurity)
Ca-43(n,na)Ar-39		3	I	waste (impurity)

Ar-40(n,g) Ar-41	1.83h	1	A	safety/maintenance (cover gas)
K -41(n,p) Ar-41		2	A	safety/maintenance
Ca-44(n,a) Ar-41		3	A	safety/maintenance (less significant in a concrete shield)

Ca-43(n,2p)Ar-42	33y	2	I	waste (Ar-42 from Ti)
Ca-45(n,a) Ar-42		1	I	waste
Ca-46(n,na)Ar-42		2	I	waste (Ar-42 from Cr,Ti)

K -39(n,2n)K -38	7.6m	3	A	(K-38 from K)

Ca-40(n,d) K -39	st	3	I	(Cl-36 from Ca)
Ca-40(n,np)K -39		3	I	(Cl-36 from Ca)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
K -39(n,g) K -40	1.277x10+9y	3	A	waste (K-40 from K)
K -41(n,2n)K -40		3	I	waste (K-40 from V,Ti & Sc)
Ca-40(n,p) K -40		3	A	waste (K-42, Ar-41 & K-40 from Ca)

K -40(n,g) K -41	st	3	A	(K-42 from Ca)
Sc-45(n,na)K -41		2	I	(imp. route for K-40)

K -41(n,g) K -42	12.36h	3	A	safety/maintenance
Ca-42(n,p) K -42		3	A	safety/maintenance (K-42 from Ca)
Sc-45(n,a) K -42		3	A	safety/maintenance

Ca-44(n,p) K -44	22.1m	2	A	(K-44 from Ca)

Ca-40(n,g) Ca-41	1.03x10+5y	2	A	waste
Ca-42(n,2n)Ca-41		2	I	waste (Ca-41 from Ti, V, Sc & Ca)

Ca-43(n,2n)Ca-42	st	2	?	waste (Ca-41 from Ti, V, Sc & Ca)
Ti-46(n,na)Ca-42		2	I	waste (34% of Ca-41 by this route)

Ti-46(n,a) Ca-43	st	2	A*	(Ar-42 from Ti)

Ti-47(n,a) Ca-44	st	3	I	(K-40 from Ti, V & Sc)

Ca-44(n,g) Ca-45	164d	3	A	safety
Sc-45(n,p) Ca-45		3	A	safety
Ti-48(n,a) Ca-45		1	A*	waste (recycling of V-alloy Ar-42 prod.)

Ti-49(n,a) Ca-46	st	2	I	(Ar-42 from Cr)

Ca-48(n,2n)Ca-47	4.563d	3	A	safety
Ti-50(n,a) Ca-47		1	A	safety (Ca-47 main contributor to early dose in V-alloy)

Ca-48(n,g) Ca-49	8.7m	3	A	(Ca-49 from Ca)

Sc-45(n,2n)Sc-44	[3.93h/2.442d]	3	A	safety

Ti-46(n,d) Sc-45	[st/0.3s]	3	A*	(K-42 from Cr & V)
Ti-46(n,np)Sc-45		3	I	(K-42 from Cr & V)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Sc-45(n,g) Sc-46	[83.83d/18.7s]	3	A	safety/maintenance
Ti-46(n,p) Sc-46		1	A	safety/maintenance
V -49(n,a) Sc-46		3	I	(Sc-46 from Cr & V)
V -50(n,na)Sc-46		2	I	safety/maintenance
Ti-47(n,np)Sc-46		2	A	safety/maintenance
Ti-47(n,d) Sc-46		2	A	safety/maintenance

Ti-47(n,p) Sc-47	3.341d	1	A	safety/maintenance
Ti-48(n,d) Sc-47		2	A*	safety/maintenance (Sc-47 from Ti)
Ti-48(n,np)Sc-47		2	A	safety/maintenance (Sc-47 from Ti)
V -50(n,a) Sc-47		2	I	safety/maintenance (Sc-47 from V)
V -51(n,na)Sc-47		2	A	safety/maintenance (Sc-47 from V)

Ti-48(n,p) Sc-48	1.821d	1	A	safety/maintenance
V -51(n,a) Sc-48		1	A	safety/maintenance

Cr-50(n,na)Ti-46	st	3	A	(K-42 from Cr & V)

Cr-50(n,a) Ti-47	st	2	A*	(Sc-46 from Cr & V)

Cr-52(n,a) Ti-49	st	2	A*	(Ar-42 from Cr)

V -51(n,p) Ti-51	5.76m	2	A	safety (decay heat in early operation stage)

V -50(n,2n)V -49	330d	1	I	waste
Cr-50(n,np)V -49		2	A	safety/maintenance
Cr-50(n,d) V -49		2	A	safety/maintenance

V -51(n,2n)V -50	1.3x10+17y	3	I	(important route for Sc-47, V-49, Sc-46)

V -51(n,g) V -52	3.75m	1	A	safety (decay heat)
Cr-52(n,p) V -52		3	A	safety

Cr-53(n,p) V -53	1.61m	3	A	(V-53 from Cr)

Cr-52(n,2n)Cr-51	27.704d	1	A	safety/maintenance
Cr-50(n,g) Cr-51		1	A	safety/maintenance
Fe-54(n,a) Cr-51		2	A	safety/maintenance (Cr-51 from Fe)

Cr-54(n,g) Cr-55	3.497m	2	A	(Mn-54 from Cr)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Mn-54(n,2n)Mn-53	3.74x10+6y	3	I	waste
Fe-54(n,d) Mn-53		2	A	waste
Fe-54(n,np)Mn-53		2	A	waste

Mn-53(n,g) Mn-54	312.2d	3	I	(Mn-54 from Fe)
Mn-55(n,2n)Mn-54		1	A	safety/maintenance
Fe-54(n,p) Mn-54		1	A	safety/maintenance

Mn-55(n,g) Mn-56	2.578h	1	A	safety/maintenance
Fe-56(n,p) Mn-56		1	A	safety/maintenance

Fe-56(n,2n)Fe-55	2.73y	1	A	safety
Ni-58(n,a) Fe-55		2	A	safety

Fe-56(n,g) Fe-57	st	2	A	(Co-60 from Fe)

Fe-57(n,g) Fe-58	st	3	A	(Co-60 from Fe)

Fe-58(n,g) Fe-59	44.5d	2	A	maintenance (Co-60 prod.)
Co-59(n,p) Fe-59		3	A	(Fe-59 from Co)

Fe-59(n,g) Fe-60	105y	2	I	waste
Co-60(n,p) Fe-60		2	I	waste
Ni-63(n,a) Fe-60		2	I	waste (Fe-60 from Cu & Zn)
Ni-64(n,na)Fe-60		2	I	waste

Ni-58(n,d) Co-57	271.77d	1	A	safety/maintenance (for Ni-alloys)
Ni-58(n,np)Co-57		1	A	safety/maintenance (for Ni-alloys)

Ni-58(n,p) Co-58	[70.92d/9.2h]	1	A	safety/maintenance (for Ni-alloys)
Co-59(n,2n)Co-58		3	A	impurity

Co-58(n,g) Co-59	st	2	I	(Co-60g/m from Ni)

Co-59(n,g) Co-60	[5.271y/10.47m]	1	A	safety/maintenance
Ni-60(n,p) Co-60		1	A	safety/maintenance
Cu-63(n,a) Co-60		1	A	safety/maintenance

Co-60(n,g) Co-61	1.65h	1	I	(Ni-63 from Co)

Ni-58(n,2n)Ni-57	1.503d	2	A	safety/maintenance (Co-57 prod.)

Ni-58(n,g) Ni-59	7.5x10+4y	1	A	waste
Ni-60(n,2n)Ni-59		1	A*	waste

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Zn-64(n,na)Ni-60	st	3	I	(dominant route for Ni-59 prod.)

Ni-61(n,g) Ni-62	st	1	A	(Ni-63 from Ni & Co)

Ni-62(n,g) Ni-63	100y	1	A	waste (Ni-63 Cu)
Ni-64(n,2n)Ni-63		1	I	waste (Ni-63 Co)
Cu-63(n,p) Ni-63		1	A*	waste
Zn-64(n,2p)Ni-63		3	I	waste (Ni-63 & Fe-60 from Zn)
Zn-66(n,a) Ni-63		3	I	waste

Cu-65(n,p) Ni-65	2.52h	2	A	safety (decay heat)

Cu-63(n,2n)Cu-62	9.74m	2	A	safety

Zn-64(n,np)Cu-63	st	3	A*	(39% of Co-60 from Zn)
Zn-64(n,d) Cu-63		3	I	

Cu-63(n,g) Cu-64	12.701h	1	A	safety
Cu-65(n,2n)Cu-64		1	A	safety
Zn-64(n,p) Cu-64		3	A	safety

Cu-65(n,g) Cu-66	5.1m	1	A	safety
Zn-66(n,p) Cu-66		3	A	safety (Cu-66 from Zn)

Zn-64(n,2n)Zn-63	38.1m	3	A	safety

Zn-64(n,g) Zn-65	244.1d	3	A	safety
Zn-66(n,2n)Zn-65		3	A	safety

Zn-68(n,g) Zn-69	[56m/13.76h]	3	A	safety

Y -89(n,a) Rb-86	[18.6d/1.017m]	3	A	safety (impurity)

Zr-91(n,2p)Sr-90	28.5y	3	I	waste (Sr-90 from Zr)
Zr-93(n,a) Sr-90		3	I	waste (Sr-90 from Zr)
Zr-94(n,na)Sr-90		2	I	waste

Y -89(n,2n)Y -88	106.61d	3	A	safety (impurity)
Nb-91(n,a) Y -88		3	I	(minor route for Y-88 from Mo)

Nb-93(n,na)Y -89	[st/16.06s]	3	A	safety/maintenance (86% of Y-88 by this route)

Y -89(n,g) Y -90	[2.671d/3.19h]	3	A	safety (impurity)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Zr-90(n,2n)Zr-89	[3.268d/4.18m]	1	A	safety/maintenance (possible breeder LiZrO3 material)
Mo-92(n,a) Zr-89		3	A	maintenance

Zr-92(n,g) Zr-93	1.5x10+6y	2	A	waste
Zr-94(n,2n)Zr-93		2	I	waste

Zr-94(n,g) Zr-95	64.02d	1	A	safety/maintenance
Zr-96(n,2n)Zr-95		1	A	safety/maintenance
Mo-98(n,a) Zr-95		3	A	(dominant route for production of Zr-95)

Mo-92(n,2n)Mo-91	[15.5m/65s]	2	A	waste (important for Mo-91 and Nb-91)

Mo-92(n,na)Zr-88	83.4d	2	A*	maintenance

Mo-92(n,g) Mo-93	[3.5x10+3y/6.8h]	1	A	waste
Mo-94(n,2n)Mo-93		1	A	waste

Nb-91(n,2n)Nb-90	[14.6h/18.8s]	2	I	(Nb-90 important for dose at short times)

Mo-92(n,np)Nb-91	[680y/62d]	1	A	waste
Mo-92(n,d) Nb-91		1	A	waste

Nb-93(n,2n)Nb-92	[3.6x10+7y/10.15d]	1	A	waste
Mo-93(n,np)Nb-92		1	I	waste
Mo-93(n,d) Nb-92		1	I	waste
Mo-92(n,p) Nb-92		1	A	waste
Nb-91(n,g) Nb-92		3	I	(route from Mo-92)

Nb-93(n,n')Nb-93m1	[st/13.6y]	1	A	safety/maintenance
Mo-94(n,d) Nb-93		1	A*	(Routes for 61% of
Mo-94(n,np)Nb-93		3	A	Nb-93m from Mo)
Nb-92(n,g) Nb-93		3	I	(Route for 15% of Nb-93m from Mo)
Nb-94(n,2n)Nb-93		3	I	(Route for 5% of Nb-93m from Mo)

Nb-93(n,g) Nb-94	[2x10+4y/6.26m]	1	A	waste (impurity)
Mo-94(n,p) Nb-94		1	A	waste (main concern)
Mo-95(n,np)Nb-94		1	A*	waste
Mo-95(n,d) Nb-94		1	A*	waste

Nb-94(n,g) Nb-95	[34.97d/3.61d]	2	I	waste (recycling)
Mo-95(n,p) Nb-95		1	A	safety/maintenance
Mo-96(n,np)Nb-95		2	A*	safety/maintenance
Mo-96(n,d) Nb-95		2	A	safety/maintenance

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Mo-96(n,p) Nb-96	23.4h	2	A	safety (dose at short times)

Mo-95(n,g) Mo-96	st	2	A	Nb-95 & Nb-96 prod.

Mo-98(n,g) Mo-99	2.7477d	1	A	safety (Mo-99)/waste (Tc-99)
Mo-100(n,2n)Mo-99		1	A	safety (Mo-99)/waste (Tc-99)

Mo-100(n,g)Mo-101	14.6m	3	A	safety

Tc-98(n,2n)Tc-97	[2.6x10+6y/90d]	2	I	waste

Tc-99(n,2n)Tc-98	[2.13x10+5y/6.006h]	1	A	waste

Tc-99(n,g) Tc-100	15.8s	3	I	safety

Pd-106(n,g) Pd-107	[6.5x10+6y/21.3s]	3	A	(Pd-107 from Ag
Ag-107(n,p) Pd-107		3	A	(Pd-107 from Ag)

Ag-107(n,2n)Ag-106	[24m/8.36d]	3	A	(Ag-106g/m from Ag)

Ag-107(n,g) Ag-108	[2.37m/432y]	1	A	waste (main concern)
Ag-109(n,2n)Ag-108		1	A	waste (main concern)

Ag-109(n,g) Ag-110	[250d/25s]	3	A	safety

Cd-108(n,g) Cd-109	462d	3	A	(Cd-109 & Ag-109m from Ag)
Cd-110(n,2n)Cd-109		3	A*	(Cd-109 & Ag-109m from Ag)

Cd-110(n,g) Cd-111	[st/48.5m]	3	A	safety (impurity)

Sn-116(n,g) Sn-117	[st/13.61d]	2	I	safety (needed in S/C)
Sn-117(n,n')Sn-117m1		2	A*	safety
Sn-118(n,2n)Sn-117		2	A	safety

Sn-119(n,n')Sn-119m1	[st/293d]	2	I	safety
Sn-120(n,2n)Sn-119		2	I	safety
Sn-118(n,g) Sn-119		2	I	safety

Sn-120(n,g) Sn-121	[1.128d/55y]	1	I	waste (superconductor)
Sn-122(n,2n)Sn-121		1	A*	waste (superconductor)
Sb-121(n,p) Sn-121		3	I	waste

Sn-122(n,g) Sn-123	[129.2d/40.1m]	2	A	safety (superconductor)
Sn-124(n,2n)Sn-123		3	A	safety (superconductor)

REACTION		T$_{1/2}$ [g,m1,m2]	P	ES	Remark
Sn-124(n,g)	Sn-125	[9.64d/9.52m]	2	I	safety
Sn-125(n,g)	Sn-126	105y	1	I	waste
Sb-121(n,g)	Sb-122	[2.7d/4.21m]	3	A	safety (impurity)
Sb-123(n,g)	Sb-124	[60.2d/1.6m/20.2m]	3	A	safety (impurity)
Sb-124(n,g)	Sb-125	2.73y	3	I	(Sb-126g/m from Sn)
Sb-125(n,g)	Sb-126	[12.4d/19m/11s]	3	I	(Sb-126g/m from Sn)
Ba-138(n,a)	Xe-135	[9.19h/15.29m]	1	A*	waste (Ba in concrete; dominant route for Cs-135 from Ba)
Cs-133(n,g)	Cs-134	[2.1y/2.9h]	2	A	(dominant route for Cs-134 from Ba)
Ba-136(n,p)	Cs-136	[13.2d/19s]	2	A	safety
Ba-137(n,p)	Cs-137	30.1y	2	A*	waste
Ba-138(n,d)	Cs-137		2	I	waste
Ba-138(n,np)	Cs-137		2	I	waste
Ba-130(n,g)	Ba-131	[11.8d/14.6m]	2	A	safety
Ba-132(n,g)	Ba-133	[10.5y/39h]	2	I	waste
Ba-134(n,2n)	Ba-133		2	A	waste
Ba-135(n,n')	Ba-135m1	[st/28.7h]	3	A*	safety
Ba-136(n,2n)	Ba-135		2	A	safety
Ba-137(n,n')	Ba-137m1	[st/2.55m]	3	A	safety
Ba-138(n,2n)	Ba-137		2	A	safety
Ba-138(n,g)	Ba-139	83m	3	A	safety
Eu-151(n,2n)	Eu-150	[12.6h/36y]	2	A	waste
Eu-151(n,g)	Eu-152	[13.33y/9.32h/1.6h]	2	A	waste
Eu-153(n,2n)	Eu-152		2	A	waste
Eu-152(n,g)	Eu-153	st	2	A	(prod. many nucl.)
Eu-153(n,g)	Eu-154	[8.8y/46m]	3	A	waste
Eu-154(n,g)	Eu-155	4.96y	3	A	(as Eu-152(n,g))
Eu-155(n,g)	Eu-156	15.2d	3	A	(as Eu-152(n,g))

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Gd-151(n,2n)Gd-150	1.79x10+6y	3	I	waste

Gd-152(n,2n)Gd-151	124d	3	A*	safety (impurity)

Gd-156(n,g) Gd-157	st	3	A	(Gd-159 from Eu)

Gd-157(n,g) Gd-158	st	3	A	impurity

Gd-158(n,g) Gd-159	18.6h	3	A	safety
Gd-160(n,2n)Gd-159		3	A	safety

Tb-159(n,2n)Tb-158	[150y/10.5s]	2	A	waste

Tb-159(n,g) Tb-160	72.3d	3	A	safety

Ho-164(n,2n)Ho-163	[4570y/1.1s]	3	I	(Ho-163 from Ho & Eu)

Ho-165(n,2n)Ho-164	[29m/37.5m]	3	A	(Ho-163 from Ho & Eu)

Ho-165(n,g) Ho-166	[1.117d/1.2x10+3y]	2	A	waste

Er-164(n,2n)Er-163	75m	3	A	safety

Er-166(n,g) Er-167	[st/2.27s]	3	A	(Er-169 from Ho)

Er-167(n,g) Er-168	st	3	A	(Er-169 from Ho)

Er-168(n,g) Er-169	9.4d	3	A	(Er-169 from Ho)

Tm-169(n,g) Tm-170	128.6d	3	A	(Tm-170 from Ho)

Hf-176(n,g) Hf-177	[st/1.1s/51.4m]	3	A	safety

Hf-177(n,g) Hf-178	[st/4.0s/31y]	2	A	waste
Hf-179(n,2n)Hf-178		2	A	waste
Ta-180(n,t) Hf-178		2	I	waste
W -182(n,na)Hf-178		2	A	waste

Hf-178(n,g) Hf-179	[st/18.7s/25.1d]	3	A	(prod. many nucl.)
Ta-181(n,t) Hf-179		3	A*	waste (Hf-178)
Ta-181(n,nd)Hf-179		3	A*	waste (Hf-178)

Hf-179(n,g) Hf-180	[st/5.519h]	3	A	safety

Hf-180(n,g) Hf-181	42.4d	3	A	safety

W -186(n,na)Hf-182	[9x10+6y/1.02h]	1	I	waste

Ta-181(n,3n)Ta-179	1.79y	1	A*	safety (Hf-178 from Ta alloys)

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Ta-181(n,g) Ta-182	[115d/283ms/15.8m]	1	A	safety (Ta alloys)
W -184(n,t) Ta-182		3	I	safety
Re-185(n,a) Ta-182		3	I	safety
Ta-182(n,g) Ta-183	5.1d	3	A	(many nucl. from Ta,Hf)
Ta-183(n,g) Ta-184	8.7h	3	I	(Ta-184 from Ta)
Re-187(n,a) Ta-184		3	A	maintenance (dose rate)
W -180(n,g) W -181	121.2d	2	I	safety/maintenance
W -182(n,2n)W -181		1	A	safety/maintenance
W -183(n,g) W -184	st	3	A	(Important step in of Re prod. from W
W -184(n,g) W -185	[75.1d/1.67m]	1	A	safety
W -186(n,2n)W -185		1	A	safety
W -186(n,g) W -187	23.9h	1	A	safety
Re-187(n,p) W -187		1	A	maintenance
Re-185(n,2n)Re-184	[38.0d/165d]	1	A	maintenance
Re-185(n,g) Re-186	[3.777d/2x10+5y]	1	A	waste
Re-187(n,2n)Re-186		1	A	waste
Ir-191(n,na)Re-187	4.6x10+10y	3	I	waste (route for Re-186g/m)
Re-187(n,g) Re-188	[19.68h/18.6m]	2	A	safety
Os-188(n,p) Re-188		3	A	safety
Os-186(n,2n)Os-185	93.6d	3	A	(Os-185 from Re, Re-186g/m from Os)
Os-188(n,g) Os-189	[st/5.8h]	2	A	(many nucl. from W)
Os-190(n,2n)Os-189		3	I	safety
Os-189(n,g) Os-190	[st/9.9m]	3	A	safety
Os-190(n,g) Os-191	[15.4d/13.1h]	3	A	(impurity)
Os-192(n,2n)Os-191		3	A	(impurity)
Os-192(n,g) Os-193	1.2d	3	A	(impurity)
Ir-191(n,g) Ir-192	[73.83d/1.45m/241y]	3	A	waste
Ir-192(n,g) Ir-193	[st/10.53d]	3	I	(impurity)
Ir-193(n,g) Ir-194	[19.5h/171d]	3	I	safety/maintenance

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Pt-192(n,g) Pt-193	[50y/4.33d]	2	I	waste
Pt-194(n,2n)Pt-193		2	I	waste
Hg-196(n,a) Pt-193		3	I	waste

Hg-198(n,na)Pt-194	st	3	I	(Pt-193 from Hg)

Pt-196(n,2n)Pt-195	[st/4.02d]	3	A	(impurity)

Pt-195(n,g) Pt-196	st	3	A	(step in many Pt nuclides)

Pt-196(n,g) Pt-197	[18.3h/1.57h]	3	A	safety (impurity)

Pt-198(n,g) Pt-199	[30.8m/13.6s]	3	A	safety (impurity)

Au-195(n,2n)Au-194	38.02h	3	I	safety (Au-194 from Hg)

Hg-196(n,np)Au-195	[186.09d/30.5s]	3	I	maintenance
Hg-196(n,d) Au-195		3	I	maintenance

Hg-196(n,p) Au-196	[6.18d/8.1s/9.7h]	3	I	safety/maintenance

Au-197(n,g) Au-198	[2.69d/2.3d]	3	A	safety (Au-198 from Hg)

Hg-200(n,p) Au-200	[48.4m/18.7h]	3	A*	maintenance

Hg-196(n,2n)Hg-195	[9.9h/41.6h]	3	A	safety (u-194 from Hg)

Hg-198(n,2n)Hg-197	[2.672d/23.8h]	3	A	safety

Hg-198(n,g) Hg-199	[st/42.6m]	3	I	safety/maintenance
Hg-200(n,2n)Hg-199		3	A*	safety/maintenance

Hg-202(n,g) Hg-203	46.6d	3	I	safety/maintenance
Hg-204(n,2n)Hg-203		3	A*	safety/maintenance
Pb-206(n,a) Hg-203		1	A	safety/maintenance

Tl-203(n,2n)Tl-202	12.23d	3	A	safety

Tl-203(n,g) Tl-204	3.78y	3	A	safety
Tl-205(n,2n)Tl-204		3	A	safety
Pb-204(n,p) Tl-204		2	I	safety (Pb-Li blanket)

Pb-208(n,p) Tl-208	3m	3	A	(short dose rates)

Pb-204(n,2n)Pb-203	[51.87h/6.3s/480ms]	1	A	safety/maintenance
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Pb-204(n,n')Pb-204m1	[st/1.12h]	3	A	safety
Pb-205(n,2n)Pb-204		2	I	safety

REACTION	$T_{1/2}$ [g,m1,m2]	P	ES	Remark
Pb-204(n,g) Pb-205	1.9x10+7y	3	A	waste (Pb-205 from Hg)
Pb-206(n,2n)Pb-205		1	A*	waste

Pb-208(n,g) Pb-209	3.25h	1	A	safety (important)

Bi-207(n,2n)Bi-206	3.2d	3	A*	safety

Bi-208(n,2n)Bi-207	32y	3	A	safety/maintenance (waste)

Bi-209(n,2n)Bi-208	3.68x10+5y	1	A	waste

Bi-209(n,g) Bi-210	[5.013d/3x10+6y]	1	A	waste

Th-232(n,f)		2	A	waste

U -235(n,f)		2	A	waste

U -238(n,f)		2	A	waste

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