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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

ESTABLISHMENT OF AN INTERNATIONAL REFERENCE DATA LIBRARY OF NUCLEAR ACTIVATION CROSS SECTIONS

Summary Report of the Second Research Co-ordination Meeting organized by the International Atomic Energy Agency in co-operation with the Instituto de Fusión Nucleár de la Universidad Politécnica de Madrid and held in Madrid, Spain, from 13 to 16 May 1996

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July 1997

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ABSTRACT

The present report contains the Summary of the Second IAEA Research Co-ordination Meeting of the Co-ordinated Research Programme on "Establishment of an International Reference Data Library of Nuclear Activation Cross Sections". The meeting was organized by the IAEA Nuclear Data Section with co-operation and assistance of local organizers from the Instituto de Fusión Nucleár de la Universidad Politécnica de Madrid, Spain, from 13 to 16 May 1996. Summarized are the conclusions and recommendations of the meeting together with a list of actions and deadlines. Attached are the detailed agenda and list of participants.

Prepared by
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July 1997

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Second IAEA Research Co-ordination Meeting

on

"Establishment of an International Reference Data Library of Nuclear Activation Cross Sections"

Madrid, Spain, 13 - 16 May 1996

organized in co-operation with the Instituto de Fusión Nucleár
de la Universidad Politécnica de Madrid

SUMMARY OF THE MEETING

(1) Introduction

In 1994 the IAEA launched a Co-ordinated Research Programme (CRP) with the aim of providing an universal database of neutron activation cross sections. For this purpose the IAEA Nuclear Data Section succeeded in obtaining the participation of eight laboratories from seven countries: China, Hungary, Japan, Netherlands, Russia, Spain and United Kingdom.

The new International Reference Data Library, IRDL, will be applicable to nuclear and fusion technology, environmental protection and the estimation of potential radiation hazards connected with any kind of nuclear installation and technique.

The first Research Co-ordination Meeting (RCM) was held in Debrecen, Hungary, in October 1994.

(2) Objectives and organization of the meeting

The second RCM was organized in co-operation with local organizers from the Instituto de Fusión Nucleár de la Universidad Politécnica de Madrid and held in Madrid, Spain, from 13 to 16 May 1996. The purpose of the RCM-2 was to discuss the status of work performed under the CRP, to provide a forum for discussion of related problems and to coordinate future activities. The detailed Agenda is given in Attachment 1.

The meeting was attended by Chief Scientific Investigators and programme members of all eight laboratories participating in the project, by one consultant and one observer. Participating laboratories were represented by Yu Baosheng (Beijing, China), J. Csikai (Debrecen, Hungary), T. Nakajima (Tokai, Japan), J. Kopecky (Petten, Netherlands),

O. Grudzevich and A. Ignatyuk (Obninsk, Russia), J.M. Perlado and J. Sanz (Madrid, Spain) and R. Forrest (Culham, UK). G. Reffo (Bologna, Italy) attended the meeting as an observer and K. Zolotarev served as a consultant. A. Ignatyuk of the Institute of Physics and Power Engineering, Obninsk, Russia, acted as Chairman of the meeting. The list of attendees and their affiliations is given in Attachment 2.

(3) Meeting proceedings and results

The meeting was opened by Professor Velarde, Director of the Instituto de Fusión Nucleár. After the welcome by A.B. Pashchenko on behalf of the Agency and the election of the meeting chairman, the participants discussed and adopted the meeting Agenda.

A considerable part of the actions resulting from the 1st RCM held in Debrecen, Hungary, in October 1994 has been successfully completed and results have been reported at the meeting.

One of the actions resulting from the RCM-1 was the preparation of a master list of important reactions to be considered for the IRDL. As agreed in Debrecen, this library should be suitable for many applications that require neutron induced activation cross sections. The reference library should not cover all possible reactions but concentrate on a limited number of very important reactions. In preparing the master list, the following applications were considered:

- Magnetic confinement fusion
- Inertial confinement fusion
- Fission reactors
- Geophysical and borehole logging
- Dosimetry
- Astrophysics

Various lists were prepared by CRP members for each application and R. Forrest compiled the master list based on contributions. The paper describing the preparation of the master list is given in Attachment 3.

The content of the master list and procedure for selection of candidate evaluations were discussed at the meeting, and the conclusions and recommendations, as well as a schedule of actions for the assembling of the IRDL starter file are summarized below. It was stressed that the starter file should be assembled at the NDS DEC Alpha computer and it should be maintained by NDS staff. The IRDL starter file should be accessed by users through the electronic networking system via "ftp".

The CRP members greatly appreciated the presence of G. Reffo, Chairman of the forthcoming International Conference on Nuclear Data for Science and Technology, Trieste, May 1997, as an observer to the meeting. In his presentation, G. Reffo provided information about NDST-97 and answered numerous questions. The meeting participants agreed that results of the CRP should be reported at this Conference. The paper should describe the range of applications to be covered by the IRDL, progress achieved in the assembling of the starter file and procedure for validation and testing of the starter file.

(4) Final CRP meeting

It was agreed that the 3rd and final CRP meeting should be organized at the IAEA Headquarters in Vienna in October/November 1997. The main task of the final meeting should be the preparation of a joint final report of CRP members to the IAEA, summarizing the results of the programme. In addition, an IAEA-NDS document should be produced after the final meeting that should contain the full description of the IRDL.

(5) Acknowledgements

The RCM had full and sufficient support from the local organizers. The meeting participants wish to thank the management of the Instituto de Fusión Nucleár de la Universidad Politécnica de Madrid for the warm hospitality and Professor Perlado for the efficient organization of the meeting.

CONCLUSIONS AND RECOMMENDATIONS

IRDL is a reference library for many applications. Astrophysics is one of the applications that should be considered. It was noted that the master list contains a list of reactions for astrophysics prepared by F. Kaeppeler. However, it appears that these selections are for reactions where more accurate data are required, rather than a complete list of reactions important for astrophysics. It was agreed that A. Pashchenko and A. Ignatyuk will communicate with F. Kaeppeler to obtain a more comprehensive list of reactions important for astrophysics. It will also be confirmed that the pointwise files (FENDL/A format) are suitable for use by the astrophysics community.

Dosimetry is another application that has been identified as relevant for IRDL. It was agreed that the current master list needs to be expanded to include additional dosimetry reactions. K. Zolotarev will take responsibility for extending the list. This new list will be presented at the next meeting of the Working Group on Reactor Dosimetry for VVER Type Reactors (Prague, 1-6 September 1996) and agreement from the dosimetry community obtained.

One of the recommendations of the 1st RCM (Debrecen) was that IRDL should include charged particle reactions. However because of the new IAEA CRP on charged particles it was agreed that all information on Development of Reference Charged Particle Cross Section Data Base for Medical Radioisotope Production already generated by the current CRP will be transfered to the new CRP. A. Pashchenko will be responsible for ensuring that this transfer is handled efficiently at the NDS.

The current energy range for the IRDL is 20 MeV. At this stage the energy range will not be extended to higher energies for all reactions, however if new files are submitted to NDS containing higher energy values then these data will be retained for that reaction. J. Csikai stated that several reactions for medical applications are required at energies greater than 20 MeV, it is the responsibility of the data producers to submit candidates containing higher enegy data if necessary.

J. Sanz noted that it is necessary to include a further reaction (^{192}Ir(n,n')) in the master list for inertial fusion applications. M. Perlado requested that a few additional capture reactions on fission products (^{90}Sr, ^{93}Zr, ^{79}Se, ^{126}Sn, ^{135}Cs, ^{137}Cs) be included in the master list as these appear to be very poorly known, yet are important for transmutation studies and fusion applications. Some additional reactions important for liquid metal fission reactors will be added after discussions at the next meeting of the Subgroup on Evaluation Co-operation (Argonne, June 1996). Several other additional reactions that should be added to the master list were noted. These will be communicated to A. Pashchenko.

It was noted that many of the evaluations presented by K. Zolotarev have involved renormalization of EXFOR data due to changes in monitor cross sections. It was agreed that such a procedure is very valuable and should be applied more generally.

File Format

Since much of the starter file for IRDL will use FENDL/A-2 as the data source it was proposed that the FENDL/A file format (as originally defined for the EAF libraries) be adopted for IRDL. This was accepted with the following conditions:

- FENDL/A format is an accepted format for the activation community, however other users of the data require data in ENDF-6 format. It was therefore agreed that IRDL will be available in both formats.
- All new candidate files will be supplied to the NDS in FENDL/A format.
- O. Grudzevich will take responsibility for converting the starter file (compiled by NDS) from FENDL/A to ENDF-6 format.
- J. Kopecky will provide A. Pashchenko with a complete description of the FENDL/A (EAF) format. This will be available on the NDS open area so that it may be obtained by FTP.
- A. Pashchenko will provide a brief description of the type of ENDF-6 format used. This will probably be MF=3 for the total cross sections and MF=10 for reactions split into isomeric daughter states.
- If available for a particular reaction, covariance data will be supplied in ENDF-6 format.

Deadlines

The following deadlines were agreed for the various tasks:

1/6/96	J. Kopecky to supply to NDS details of the FENDL/A (EAF) format
15/6/96	A. Pashchenko will supply whatever data are already available in the starter file to O. Grudzevich so that testing of the conversion procedure can be carried out. A. Pashchenko will provide a description of ENDF-6 format used
15/7/96	Final version of master list of reactions produced (R.A. Forrest) and distributed (A. Pashchenko)
1/9/96	Camera ready versions of contributions for publication in Proceedings of 2nd RCM sent to NDS
1/10/96	Candidates for inclusion in IRDL starter file available at NDS
1/11/96	Complete starter file available in FENDL/A format (A. Pashchenko)
1/12/96	Complete starter file available in ENDF-6 format (O. Grudzevich)
10/97	Possible date for final meeting of CRP in Vienna. Informal meeting of CRP members will be organised in Trieste (May 1997) at the Nuclear Data conference if possible

Selection procedure

The following procedure was agreed for selection of candidate data for the starter file:

- All reactions in the master list will have data in the starter file.
- By default all data will be extracted from the existing FENDL/A-2 library.
- If a new data source is agreed either at this meeting or in the future, then it is the responsibility of the author to supply the new data to the NDS in the FENDL/A format.
- It was agreed that the author of a new candidate for inclusion in the starter file must give a justification for the replacement of the existing evaluation by the new data.
- This justification will be circulated to the members of the CRP by A. Pashchenko and comments compiled. A. Pashchenko will be responsible for deciding (based on a majority decision) if the new data will be used in the starter file. E-Mail will be used for discussions whenever possible.

File production

- The IRDL starter file will be available from NDS in both the FENDL/A and ENDF-6 formats. The file is a point-wise file, no processing to form group-wise libraries will be undertaken by NDS; it is the responsibility of users to prepare working libraries from IRDL.
- Files will be stored on the NDS open area so that they can be accessed by users via FTP. Only NDS (A. Pashchenko) will have permission to edit data; all others will only be able to view/copy the data.
- Maintenance of the IRDL will be the responsibility of NDS.
- NDS will publicise the availability of the IRDL starter file through the existing channels of the Data Centre Network.

Candidate selection

The current master list of reactions (see Attachment 3) considers in detail only those reactions which were not already discussed by the FENDL/A selection panel (for recommendations of selection panel see reports INDC(NDS)-341 and 352, 1996). The decisions on the remaining reactions are shown in Table 1. The comments collected during the review process, are given in the "comments" column.

Table 1: Results of selection reached at the CRP meeting

Reaction	Source	Comments
$^{10}B(n,\alpha)$	FENDL/A-2 (IRDF 90.2)	
$^{12}C(n,n')$	Reaction removed	No isomeric state
$^{12}C(n,2n)$	FEI	
$^{16}O(n,n'\alpha)$	JENDL/A-3.2	
$^{16}O(n,n')$	Reaction removed	No isomeric state
$^{29}Si(n,d)$	FENDL/A-2 (ADL-3)	
$^{29}Si(n,n'p)$	FENDL/A-2 (ADL-3)	
$^{30}Si(n,\alpha)$	FEI	Need for new experimental work at 11 MeV. Also the slope of cross section function at 14 MeV is required to decide between evaluations
$^{31}P(n,p)$	FENDL/A-2 (IRDF 90.2)	
$^{35}Cl(n,2n)$	ADL-3	
$^{46}Ti(n,p)$	FEI	Better evaluation is available since the FENDL selection procedure
$^{47}Ti(n,d)$	FEI	Properly split by K. Zolotarev
$^{47}Ti(n,n'p)$	FEI	Properly split by K. Zolotarev
$^{48}Ti(n,d)$	FEI	Better evaluation is available since the FENDL selection procedure
$^{48}Ti(n,n'p)$	FEI	Better evaluation is available since the FENDL selection procedure
$^{48}Ti(n,p)$	FEI	Better evaluation is available since the FENDL selection procedure
$^{48}Ti(n,\alpha)$	FEI	Better evaluation is available since the FENDL selection procedure
$^{49}Ti(n,d)$	Reaction removed	Accuracy of available data not adequate for dosimetry applications
$^{49}Ti(n,n'p)$	Reaction removed	Accuracy of available data not adequate for dosimetry applications

Reaction	Source	Comments
^{49}Ti(n,t)	Reaction removed	Accuracy of available data not adequate for dosimetry applications
^{52}Cr(n,n')	Reaction removed	No isomeric state
^{52}Cr(n,2n)	FENDL/A-2 (IRDF 90.2)	
^{53}Cr(n,d)	FENDL/A-2 (EFF-4.2)	
^{53}Cr(n,n'p)	FENDL/A-2 (EFF-4.2)	
^{54}Cr(n,α)	FEI	
^{55}Mn(n,α)	FEI	New experimental data required. Recent measurements at 14 MeV suggest cross section much lower (23 mb) than current values
^{54}Fe(n,2n)	FEI	Properly split (isomers) by K. Zolotarev
^{59}Co(n,α)	FENDL/A-2 (IRDF 90.2)	Add dosimetry as an application
^{58}Ni(n,n')	Reaction removed	No isomeric state
^{58}Ni(n,p)	FEI	Result of collaboration between FEI and IRK Vienna
^{63}Cu(n,n')	Reaction removed	No isomeric state
^{69}Ga(n,α)	JENDL/A-3.2	New measurements at 14 MeV (22mb) suggest that JENDL/A-3.2 better than ADL-3
^{93}Nb(n,n')	FEI	
^{115}In(n,n')	IRDF 90.2	
^{115}In(n,γ)	IRDF 90.2	Add dosimetry as an application, O. Grudzevich will supply correctly split data
^{139}La(n,γ)		Add dosimetry as an application. The source of data may be changed to RDF, and A. Ignatyuk and K. Zolotarev will investigate
^{190}Os(n,α)	ADL-3	
^{197}Au(n,n')	FENDL/A-2 (ADL-3)	
^{197}Au(n,γ)		Add dosimetry as an application
^{158}Dy(n,p)	FENDL/A-2 (?)	
^{193}Ir(n,2n)	FENDL/A-2 (?)	

Other matters

It was agreed that a summary of progress in the CRP will be presented at the Trieste Nuclear Data Conference. A. Pashchenko, A. Ignatyuk and R.A. Forrest will be responsible for preparation of a paper.

It was recognised that the current CRP had encouraged several collaborations between groups, especially for data measurements. The collaborations are vital to ensure efficient use of the very restricted manpower and facilities available for work in the area of activation cross section measurements.

The members of the CRP greatly appreciate the presence of K. Zolotarev as a consultant at the meeting. His contribution on candidates for dosimetry reactions is considered vital for ensuring that IRDL is of the greatest use for the dosimetry community.

Attachment 1

2nd IAEA Research Co-ordination Meeting
on
Establishment of an International Reference Data Library
of Nuclear Activation Cross Sections

Madrid, Spain, 13 to 16 May 1996

Organized in co-operation with the Instituto de Fusion Nuclear
de la Universidad Politécnica de Madrid

AGENDA

Monday, 13 May

9:30-10:30 — Opening Session

- Opening of the meeting:
  Host (**G. Velarde,** Director, Instituto de Fusión Nuclear)
  IAEA (**A.B. Pashchenko**)
- Election of Chairman
- Adoption of Agenda and Time Schedule
- Announcement of Organizational Matters

10:30-13:30 — Session 1: Progress reports by CRP participants on improvements/selection of evaluations for the IRDL

Presentation by **R. Forrest**
"Preparation of master list of important neutron induced reactions for IRDL"

Presentation by **Yu. Baosheng**
"The CNDC candidate evaluations for the IAEA Reference Data Library and future of China Activation Cross Sections Library"

Presentation by **J. Kopecky**
"Candidate evaluations for IRDL from the IAEA FENDL/A-2.0 Library"

Presentation by **Y. Nakajima**
"Evaluation of cross sections for JENDL Activation Cross Sections File 96"

Presentation by **K. Zolotarev**
"Evaluation of threshold reactions for the IAEA Reference Data Library"

13:30-15:00 Lunch break

15:00-17:30 Session 1 (cont'd)

Presentation by **J. Kopecky**
"Capture cross sections in activation libraries"

Presentation by **A. Ignatyuk**
"Analysis of capture cross section evaluations for most important structural materials and fission products"

Coffee break.

Session 1 (cont'd)

- Discussion

Tuesday, 14 May

9:00-13:30 Session 2: Progress reports on measurement of activation cross sections, testing and validation of selected evaluations.

Presentation by **J. Csikai**
"Some measured, calculated and evaluated activation cross sections from threshold to 20 MeV neutron energy"

Presentation by **O. Grudzevich**
"Validation and testing of selected evaluations"

Coffee break

Session 2 (cont'd)

Presentation by **R. Forrest**
"Maintenance of the European Activation File with SYMPAL"

Presentation by **J.M. Perlado**
"Nuclear data influence in radiological assessment in recycling and waste management of inertial fusion reactors"

Presentation by **G. Reffo**
"Information about International Conference on Nuclear Data for Science and Technology, May 19-24, Trieste, Italy"

- Discussion

13:30-15:00 Lunch break

15:00-17:30 Session 3: General discussion. Starter File and Structure of IRDL. Coordination of Activity

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- General discussion on selected evaluation for inclusion to the Reference Library

- Creation of Starter File of IRDL:
  - format of evaluations,
  - structure of IRDL,
  - contributions and file exchange,
  - maintenance of IRDL,
  - access to the open area of IAEA/NDS Alpha server.

- Overview of current tasks, future scope of the CRP and coordination of activity

- Actions and deadlines

Wednesday, 15 May

9:00-13:30 Session 4: Conclusions and Recommendations

- Formation of Working Groups to draft the Conclusions and Recommendations
- Working group's sessions on drafting of meeting Conclusions and Recommendations

13:30-15:00 Lunch break

15:00-17:30 Session 4 (cont'd)

- Working group's sessions on drafting of meeting Conclusions and Recommendations

Thursday, 16 May

9:00-13:30 Session 4 (cont'd)

- Completion of Working Group Reports

13:30-15:00 Lunch break

15:00-17:00 Session 5: Final Considerations

- Discussion of Conclusions and Recommendations
- Corrections and Adoption of Final Report of the present meeting, including assignments and responsibilities for the Starter File and Final Report CRP members to the IAEA
- Adoption of the Schedule of Work and Future Meeting
- Closing of the RCM

Appendix 2

2nd IAEA RCM

Establishment of an International Reference Data Library of Nuclear Activation Cross Sections

13 - 16 May 1996, Madrid, Spain

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Preparation of master list of important neutron induced reactions

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Abstract

The contents of the master list of reactions, selected for consideration in the IAEA project to construct an international reference library of nuclear activation cross sections, are presented.

Introduction

One of the actions resulting from the First Research Co-ordination Meeting on the establishment of an international reference data library of nuclear activation cross sections held in Debrecen Hungary in October 1994 [1], was the preparation of a master list of important neutron induced reactions. This paper summarises the applications and presents the master list. Some recommendations about the sources of data for the library are presented.

Applications for data

The scope of the proposed library is that it should be relevant for any application that requires neutron induced activation cross sections. In preparing the master list the following applications were considered:

- Magnetic confinement fusion
- Inertial confinement fusion
- Fission reactors
- Geophysical and borehole logging
- Dosimetry
- Astrophysics

For each application a list of important reactions was prepared by experts attending the Debrecen meeting. Many reactions are important for more than one application and Table 1 was prepared showing the following information for each reaction:

Column heading	Explanation
ZAI	A number (10000*Z+10*A+Isomeric state) specifying the target nuclide
Target	Conventional symbol for target nuclide (m=1st isomeric state, n=2nd isomeric state)
Reaction	Reaction label
Daughter	Conventional symbol for daughter nuclide (m=1st isomeric state, n=2nd isomeric state)
F-2	1 indicates that the reaction has been assessed during the selection of the FENDL/A-2 library
Application_n	Application (n=1-4) for which reaction is of importance
Reason_n	Reason (n=1-4) that the reaction is important to corresponding application.

In some of the Reason_n columns information about the production of a nuclide is given. This is done where the reaction produces an intermediate nuclide that can subsequently react to produce a radionuclide important for that application.

It should be noted that for the targets Si-28, Si-29, Ti-47, Ti-48, Ti-49, Cr-53, Ni-58, Mo-92, Mo-93, Mo-94 and Mo-95, Table 1 shows the reaction (n,d); for these reactions it must be understood that the reaction (n,n'p) producing the same daughter is also required.

Table 1 includes a few (n,n') reactions where there is no well defined isomeric state. The targets are: C-12, O-16, Cr-52, Ni-58 and Cu-63, and the reactions are included for borehole applications. These inelastic cross sections are not included in activation libraries, and thus should not be included in the IAEA's reference activation library.

The column F-2 included in Table 1 indicates whether the reaction is included in the recent FENDL/A-2 activation library [2]. It is recommended that as these reactions have already received consideration by a panel of experts, the FENDL/A-2 data be used for these cases.

Since the compilation of the master list it has been suggested [3] that the following additional reactions important in production of long-lived radionuclides be added:

ZAI	Target	Reaction	Daughter	F-2
561370	Ba-137	(n,p)	Cs-137	1
631510	Eu-151	(n,2n)	Eu-150	1
631530	Eu-153	(n,2n)	Eu-152	1
631530	Eu-153	(n,2n)	Eu-152n	1
651590	Tb-159	(n,2n)	Tb-158	1
661580	Dy-158	(n,p)	Tb-158	
671650	Ho-165	(n,g)	Ho-166m	1
721790	Hf-179	(n,2n)	Hf-178n	1
741820	W-182	(n,n'a)	Hf-178n	1
771930	Ir-193	(n,2n)	Ir-192n	

It is suggested that the next IAEA meeting on this topic (Madrid, May 1996) decide on whether to add these reactions to Table 1.

For the reactions in Table 1 that have not already been considered during the selection of FENDL/A-2, the author recommends that data from EAF4.1 [4] be used. The split of these 56 reactions is (n,γ) 37, (n,α) 7, (n,2n) 4, (n,d+n'p) 3, (n,n') 2, (n,n'α) 1, (n,p) 1, (n,t) 1. It should be noted that especially in the case of capture reactions the EAF library is world class.

Acknowledgement This work was funded jointly by the UK Department of Trade and Industry and Euratom.

References

[1] AB Pashchenko, *'Establishment of an international reference data library of nuclear activation cross sections'*, IAEA report, **INDC(NDS)-320**, 1995.

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Table 1. Master list of reactions important for applications involving neutron induced activation.

ZAI	Target	Reaction	Daughter	F-2	Application_1	Reason_1	Application_2	Reason_2	Application_3	Reason_3	Application_4	Reason_4
10010	H-1	(n,g)	H-2		Borehole logging							
50100	B-10	(n,a)	Li-7		Borehole logging							
60120	C-12	(n,n')	C-12		Borehole logging							
60120	C-12	(n,g)	C-13		Borehole logging							
60120	C-12	(n,2n)	C-11		Dosimetry	High energies						
60130	C-13	(n,g)	C-14	1	Fission reactors	Decommissioning						
70140	N-14	(n,p)	C-14	1	Inertial Fusion	Waste	Magnetic Fusion	Waste				
80160	O-16	(n,n')	O-16		Borehole logging							
80160	O-16	(n,p)	N-16	1	Borehole logging							
80160	O-16	(n,n'a)	C-12		Borehole logging	Interfering						
90190	F-19	(n,2n)	F-18	1	Dosimetry		Magnetic Fusion	Safety/maintenance				
110230	Na-23	(n,2n)	Na-22	1	Magnetic Fusion	Safety/maintenance	Borehole logging					
110230	Na-23	(n,g)	Na-24	1	Geophysical	Detector	Magnetic Fusion	Safety/maintenance				
120240	Mg-24	(n,p)	Na-24	1	Geophysical	Interfering	Magnetic Fusion	Safety/maintenance				
120260	Mg-26	(n,g)	Mg-27	1	Geophysical	Detector						
130270	Al-27	(n,p)	Mg-27	1	Dosimetry		Magnetic Fusion	Safety	Geophysical	Interfering		
130270	Al-27	(n,2n)	Al-26	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
130270	Al-27	(n,na)	Na-23	1	Magnetic Fusion	Safety/maintenance						
130270	Al-27	(n,a)	Na-24	1	Geophysical	Interfering	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety (Na-22 from Si)		
130270	Al-27	(n,g)	Al-28	1	Geophysical	Detector						
140280	Si-28	(n,d)	Al-27	1	Magnetic Fusion	Waste	Inertial Fusion	Safety (Na-22 from Si)				
140280	Si-28	(n,p)	Al-28	1	Dosimetry	Fusion	Borehole logging					
140290	Si-29	(n,t)	Al-27	1	Magnetic Fusion	Tritium from SiC						
140290	Si-29	(n,p)	Al-29	1	Borehole logging							
140290	Si-29	(n,d)	Al-28		Geophysical	Interfering						
140300	Si-30	(n,a)	Mg-27		Geophysical	Interfering						
140300	Si-30	(n,g)	Si-31	1	Inertial Fusion	Safety	Magnetic Fusion	Safety	Borehole logging			
150310	P-31	(n,p)	Si-31		Dosimetry							
150310	P-31	(n,a)	Al-28	1	Geophysical	Interfering						
150310	P-31	(n,g)	P-32	1	Inertial Fusion	Safety	Magnetic Fusion	Safety				
160340	S-34	(n,p)	P-34	1	Borehole logging							
160360	S-36	(n,g)	S-37		Borehole logging							
170350	Cl-35	(n,2n)	Cl-34m		Borehole logging							
170350	Cl-35	(n,g)	Cl-36	1	Fission reactors	Decommissioning						
170370	Cl-37	(n,p)	S-37	1	Borehole logging	Interfering						
170370	Cl-37	(n,g)	Cl-38	1	Borehole logging							
170370	Cl-37	(n,a)	P-34	1	Borehole logging	Interfering						
180400	Ar-40	(n,g)	Ar-41	1	Magnetic Fusion	Safety/maintenance						
190390	K-39	(n,p)	Ar-39	1	Magnetic Fusion	Waste						
190410	K-41	(n,a)	Cl-38	1	Borehole logging	Interfering						
200400	Ca-40	(n,g)	Ca-41	1	Fission reactors	Decommissioning						
200440	Ca-44	(n,p)	K-44	1	Borehole logging							
200450	Ca-45	(n,a)	Ar-42	1	Magnetic Fusion	Waste						
200480	Ca-48	(n,g)	Ca-49	1	Borehole logging							
210450	Sc-45	(n,g)	Sc-46	1	Dosimetry							
220460	Ti-46	(n,p)	Sc-46	1	Dosimetry	PWR	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety		

ZAI	Target	Reaction	Daughter	F-2	Application_1	Reason_1	Application_2	Reason_2	Application_3	Reason_3	Application_4	Reason_4
220470	Ti-47	(n,d)	Sc-46	1	Dosimetry							
220470	Ti-47	(n,p)	Sc-47	1	Magnetic Fusion	Safety/maintenance						
220480	Ti-48	(n,d)	Sc-47	1	Dosimetry							
220480	Ti-48	(n,p)	Sc-48	1	Magnetic Fusion	Safety/maintenance						
220480	Ti-48	(n,a)	Ca-45	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
220490	Ti-49	(n,d)	Sc-48		Dosimetry							
220490	Ti-49	(n,t)	Sc-47		Dosimetry							
220500	Ti-50	(n,g)	Ti-51		Borehole logging	Interfering						
220500	Ti-50	(n,a)	Ca-47	1	Magnetic Fusion	Safety						
230500	V-50	(n,2n)	V-49	1	Magnetic Fusion	Waste						
230510	V-51	(n,g)	V-52	1	Geophysical	Detector	Magnetic Fusion	Safety	Astrophysics			
230510	V-51	(n,a)	Sc-48	1	Magnetic Fusion	Safety/maintenance						
230510	V-51	(n,p)	Ti-51	1	Borehole logging	Interfering						
240500	Cr-50	(n,g)	Cr-51	1	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety	Borehole logging			
240520	Cr-52	(n,n')	Cr-52		Borehole logging							
240520	Cr-52	(n,p)	V-52	1	Geophysical	Interfering						
240520	Cr-52	(n,2n)	Cr-51		Dosimetry		Magnetic Fusion	Safety/maintenance				
240530	Cr-53	(n,d)	V-52		Geophysical	Interfering						
240540	Cr-54	(n,a)	Ti-51		Borehole logging	Interfering						
250530	Mn-53	(n,g)	Mn-54	1	Geophysical	Detector						
250550	Mn-55	(n,g)	Mn-56	1	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety	Astrophysics		Borehole logging	Interfering
250550	Mn-55	(n,a)	V-52		Geophysical	Interfering						
250550	Mn-55	(n,2n)	Mn-54	1	Magnetic Fusion	Safety/maintenance	Fission reactors	Decommissioning	Borehole logging			
260540	Fe-54	(n,p)	Mn-54	1	Magnetic Fusion	Safety/maintenance	Fission reactors	Decommissioning				
260540	Fe-54	(n,g)	Fe-55		Fission reactors	Decommissioning						
260540	Fe-54	(n,2n)	Fe-53		Dosimetry	Fusion						
260560	Fe-56	(n,p)	Mn-56	1	Geophysical	Interfering	Magnetic Fusion	Safety/maintenance				
260560	Fe-56	(n,2n)	Fe-55	1	Magnetic Fusion	Safety	Inertial Fusion	Safety	Fission reactors	Decommissioning		
260560	Fe-56	(n,g)	Fe-57	1	Inertial Fusion	Safety/maintenance (Co-60 from Fe)	Magnetic Fusion	Safety/maintenance (Co-60 from Fe)				
260570	Fe-57	(n,g)	Fe-58	1	Inertial Fusion	Safety/maintenance (Co-60 from Fe)	Magnetic Fusion	Safety/maintenance (Co-60 from Fe)				
260580	Fe-58	(n,g)	Fe-59	1	Inertial Fusion	Safety/maintenance (Co-60 from Fe)	Magnetic Fusion	Safety/maintenance (Co-60 from Fe)				
270590	Co-59	(n,a)	Mn-56		Geophysical	Interfering						
270590	Co-59	(n,g)	Co-60	1	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety/maintenance	Astrophysics		Fission reactors	Decommissioning
270600	Co-60	(n,g)	Co-61	1	Magnetic Fusion	Waste (Ni-63 from Co)	Inertial Fusion	Waste (Ni-63 from Co)				
270600	Co-60	(n,p)	Fe-60	1	Inertial Fusion	Waste	Magnetic Fusion	Waste				
280580	Ni-58	(n,p)	Co-58	1	Dosimetry		Magnetic Fusion	Safety/maintenance	Fission reactors	Decommissioning		
280580	Ni-58	(n,d)	Co-57	1	Magnetic Fusion	Safety/maintenance	Fission reactors	Decommissioning				
280580	Ni-58	(n,n')	Ni-58		Borehole logging							
280580	Ni-58	(n,g)	Ni-59	1	Magnetic Fusion	Waste	Inertial Fusion	Waste	Fission reactors	Decommissioning		
280580	Ni-58	(n,2n)	Ni-57	1	Dosimetry							
280600	Ni-60	(n,p)	Co-60	1	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety/maintenance	Fission reactors	Decommissioning		
280600	Ni-60	(n,2n)	Ni-59	1	Magnetic Fusion	Waste						
280610	Ni-61	(n,g)	Ni-62	1	Magnetic Fusion	Waste (Ni-63 from Ni & Co)	Inertial Fusion	Waste (Ni-63 from Co)				
280620	Ni-62	(n,g)	Ni-63	1	Magnetic Fusion	Waste	Inertial Fusion	Waste	Fission reactors	Decommissioning		

ZAI	Target	Reaction	Daughter	F-2	Application_1	Reason_1	Application_2	Reason_2	Application_3	Reason_3	Application_4	Reason_4
280640	Ni-64	(n,2n)	Ni-63	1	Magnetic Fusion	Waste						
290630	Cu-63	(n,a)	Co-60	1	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety/maintenance				
290630	Cu-63	(n,p)	Ni-63	1	Magnetic Fusion	Waste						
290630	Cu-63	(n,g)	Cu-64	1	Magnetic Fusion	Safety			Astrophysics			
290630	Cu-63	(n,n')	Cu-63		Borehole logging							
290650	Cu-65	(n,2n)	Cu-64	1	Magnetic Fusion	Safety						
290650	Cu-65	(n,g)	Cu-66	1	Geophysical	Detector	Magnetic Fusion	Safety				
300640	Zn-64	(n,g)	Zn-65	1	Fission reactors	Decommissioning						
300640	Zn-64	(n,p)	Cu-64	1	Dosimetry							
300660	Zn-66	(n,p)	Cu-66	1	Geophysical	Interfering						
300680	Zn-68	(n,g)	Zn-69	1	Astrophysics							
310690	Ga-69	(n,a)	Cu-66		Geophysical	Interfering						
310710	Ga-71	(n,g)	Ga-71		Astrophysics							
360800	Kr-80	(n,g)	Kr-81		Astrophysics							
360840	Kr-84	(n,g)	Kr-85		Astrophysics							
360860	Kr-86	(n,g)	Kr-87		Astrophysics							
370850	Rb-85	(n,g)	Rb-85		Astrophysics							
380890	Sr-89	(n,g)	Sr-90		Fission reactors	Decommissioning						
400900	Zr-90	(n,2n)	Zr-89	1	Magnetic Fusion	Safety/maintenance						
400940	Zr-94	(n,g)	Zr-95	1	Magnetic Fusion	Safety/maintenance						
400960	Zr-96	(n,2n)	Zr-95	1	Magnetic Fusion	Safety/maintenance						
410930	Nb-93	(n,n')	Nb-93m	1	Dosimetry	Fission reactors	Magnetic Fusion	Safety/maintenance	Fission reactors	Decommissioning		
410930	Nb-93	(n,g)	Nb-94	1	Magnetic Fusion	Waste	Inertial Fusion	Waste	Fission reactors	Decommissioning		
410930	Nb-93	(n,2n)	Nb-92	1	Magnetic Fusion	Waste						
420920	Mo-92	(n,p)	Nb-92	1	Magnetic Fusion	Waste						
420920	Mo-92	(n,d)	Nb-91	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
420920	Mo-92	(n,g)	Mo-93	1	Magnetic Fusion	Waste						
420930	Mo-93	(n,d)	Nb-92	1	Magnetic Fusion	Waste						
420940	Mo-94	(n,d)	Nb-93m	1	Magnetic Fusion	Safety/maintenance	Inertial Fusion	Safety/maintenance				
420940	Mo-94	(n,p)	Nb-94	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
420940	Mo-94	(n,2n)	Mo-93	1	Magnetic Fusion	Waste						
420950	Mo-95	(n,d)	Nb-94	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
420950	Mo-95	(n,p)	Nb-95	1	Magnetic Fusion	Safety/maintenance						
420980	Mo-98	(n,g)	Mo-99	1	Magnetic Fusion	Safety /Waste (Tc-99 from Mo)	Inertial Fusion	Safety /Waste (Tc-99 from Mo)	Astrophysics		Fission reactors	Decommissioning (Tc-99 from Mo)
421000	Mo-100	(n,2n)	Mo-99	1	Magnetic Fusion	Safety /Waste (Tc-99 from Mo)						
421000	Mo-100	(n,g)	Mo-101	1	Astrophysics							
430990	Tc-99	(n,2n)	Tc-98	1	Magnetic Fusion	Waste						
440960	Ru-96	(n,g)	Ru-97		Astrophysics							
441020	Ru-102	(n,g)	Ru-103		Astrophysics							
441040	Ru-104	(n,g)	Ru-105		Astrophysics							
471070	Ag-107	(n,g)	Ag-108m	1	Magnetic Fusion	Waste	Inertial Fusion	Waste	Fission reactors	Decommissioning		
471090	Ag-109	(n,2n)	Ag-108m	1	Magnetic Fusion	Waste	Fission reactors	Decommissioning				
471100	Ag-109	(n,g)	Ag-110m	1	Fission reactors	Decommissioning						
481140	Cd-114	(n,g)	Cd-115		Astrophysics							
491150	In-115	(n,n')	In-115m		Dosimetry	D-D diagnostics						
501200	Sn-120	(n,g)	Sn-121m	1	Magnetic Fusion	Waste						

ZAI	Target	Reaction	Daughter	F-2	Application_1	Reason_1	Application_2	Reason_2	Application_3	Reason_3	Application_4	Reason_4
501210	Sn-121	(n,g)	Sn-122		Astrophysics							
501220	Sn-122	(n,2n)	Sn-121m	1	Magnetic Fusion	Waste						
501250	Sn-125	(n,g)	Sn-126	1	Magnetic Fusion	Waste						
511230	Sb-123	(n,g)	Sb-124	1	Astrophysics		Fission reactors	Decommissioning (production of Sb-125)				
511240	Sb-124	(n,g)	Sb-125	1	Fission reactors	Decommissioning						
521280	Te-128	(n,g)	Te-129		Astrophysics							
521300	Te-130	(n,g)	Te-131		Astrophysics							
531270	I-127	(n,g)	I-128		Astrophysics							
531280	I-128	(n,g)	I-129		Fission reactors	Decommissioning						
541340	Xe-134	(n,g)	Xe-135		Astrophysics							
541360	Xe-136	(n,g)	Xe-137		Astrophysics							
551330	Cs-133	(n,g)	Cs-134	1	Astrophysics		Fission reactors	Decommissioning				
551360	Cs-136	(n,g)	Cs-137		Fission reactors	Decommissioning						
561300	Ba-130	(n,g)	Ba-131	1	Astrophysics							
561320	Ba-132	(n,g)	Ba-133	1	Fission reactors	Decommissioning						
561380	Ba-138	(n,a)	Xe-135		Magnetic Fusion	Waste (Cs-135 from Ba)	Astrophysics					
571390	La-139	(n,g)	La-140		Astrophysics							
581430	Ce-143	(n,g)	Ce-144		Fission reactors	Decommissioning						
601460	Nd-146	(n,g)	Nd-147		Astrophysics							
601480	Nd-148	(n,g)	Nd-149		Astrophysics							
601500	Nd-150	(n,g)	Nd-151		Astrophysics							
621520	Sm-152	(n,g)	Sm-153		Astrophysics							
621540	Sm-154	(n,g)	Sm-155		Astrophysics							
631510	Eu-151	(n,g)	Eu-152	1	Astrophysics		Fission reactors	Decommissioning				
631530	Eu-153	(n,g)	Eu-154	1	Fission reactors	Decommissioning						
631540	Eu-154	(n,g)	Eu-155	1	Fission reactors	Decommissioning						
671650	Ho-165	(n,g)	Ho-166	1	Astrophysics							
681620	Er-162	(n,g)	Er-163		Astrophysics							
681640	Er-164	(n,g)	Er-165		Astrophysics							
681700	Er-170	(n,g)	Er-171		Astrophysics							
701760	Yb-176	(n,g)	Yb-177		Astrophysics							
711750	Lu-175	(n,g)	Lu-176		Astrophysics							
711760	Lu-176	(n,g)	Lu-177		Astrophysics							
731810	Ta-181	(n,3n)	Ta-179	1	Magnetic Fusion	Safety (Hf-178 from Ta)						
731810	Ta-181	(n,g)	Ta-182	1	Magnetic Fusion	Safety						
741820	W-182	(n,2n)	W-181	1	Magnetic Fusion	Safety/maintenance						
741830	W-183	(n,g)	W-184	1	Inertial Fusion	Waste (Re-186m from W)	Magnetic Fusion	Waste (Re-186m from W)				
741840	W-184	(n,g)	W-185	1	Magnetic Fusion	Safety	Inertial Fusion	Waste				
741860	W-186	(n,2n)	W-185	1	Magnetic Fusion	Safety						
741860	W-186	(n,g)	W-187	1	Geophysical	Detector	Magnetic Fusion	Safety	Inertial Fusion	Safety		
741860	W-186	(n,na)	Hf-182	1	Magnetic Fusion	Waste						
751850	Re-185	(n,2n)	Re-184	1	Magnetic Fusion	Maintenance						
751850	Re-185	(n,g)	Re-186m	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
751870	Re-187	(n,g)	Re-188	1	Inertial Fusion	Safety	Magnetic Fusion	Safety				

ZAI	Target	Reaction	Daughter	F-2	Application_1	Reason_1	Application_2	Reason_2	Application_3	Reason_3	Application_4	Reason_4
751870	Re-187	(n,2n)	Re-186m	1	Magnetic Fusion	Waste						
751870	Re-187	(n,p)	W-187	1	Geophysical	Interfering	Magnetic Fusion	Maintenance				
761880	Os-188	(n,g)	Os-189	1	Inertial Fusion	Waste	Magnetic Fusion	Waste				
761900	Os-190	(n,a)	W-187		Geophysical	Interfering						
761900	Os-190	(n,g)	Os-191	1	Inertial Fusion	Safety	Magnetic Fusion	Safety	Astrophysics			
761920	Os-192	(n,g)	Os-193	1	Astrophysics							
771910	Ir-191	(n,g)	Ir-192n	1	Inertial Fusion	Waste	Magnetic Fusion	Waste				
781920	Pt-192	(n,g)	Pt-193	1	Inertial Fusion	Waste	Magnetic Fusion	Waste	Astrophysics			
781940	Pt-194	(n,g)	Pt-195		Astrophysics							
781960	Pt-196	(n,g)	Pt-197	1	Astrophysics							
781980	Pt-198	(n,g)	Pt-199	1	Astrophysics							
791970	Au-197	(n,n')	Au-197		Borehole logging							
791970	Au-197	(n,g)	Au-198	1	Astrophysics		Borehole logging					
822040	Pb-204	(n,2n)	Pb-203	1	Magnetic Fusion	Safety/maintenance						
822060	Pb-206	(n,2n)	Pb-205	1	Magnetic Fusion	Waste						
822060	Pb-206	(n,a)	Hg-203	1	Magnetic Fusion	Safety/maintenance						
822080	Pb-208	(n,g)	Pb-209	1	Magnetic Fusion	Safety						
832090	Bi-209	(n,2n)	Bi-208	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				
832100	Bi-209	(n,g)	Bi-210m	1	Magnetic Fusion	Waste	Inertial Fusion	Waste				

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