



Brief History of the FENDL Nuclear Data Library for Fusion

U. Fischer

ex -KIT (Karlsruhe Institute of Technology)

E-mail: ulrich.fischer@t-online.de

Geneva 1985: The launch of an international effort on fusion

At the Geneva Superpower Summit in November 1985, when General Secretary Gorbachev of the former Soviet Union proposed to US President Ronald Reagan the idea of a collaborative international project to develop fusion energy for peaceful purposes.

One year later, an agreement was reached: the European Union (Euratom), Japan, the Soviet Union and the USA would jointly pursue the design for a large international fusion facility, ITER.



US President Reagan and General Secretary Gorbachev of the Soviet Union at the Geneva Superpower Summit (1985)

FENDL – Fusion Evaluated Nuclear Data Library

- ▶ FENDL project initiated and co-ordinated by the International Atomic Energy Agency, Nuclear Data Section (IAEA/NDS) – **Driving force: J. Schmidt, NDS Head**
 - ▶ *Following the recommendations of the IAEA International Nuclear Data Committee (INDC) and the International Fusion Research Council*
 - ▶ *Advisory Group Meeting (AGM) on “Nuclear Data for Fusion Reactor Technology”, Gaussig, GDR, **1-5 December 1986***
- ▶ Objective
Development of an evaluated nuclear data file dedicated to the design of the ITER fusion reactor
- ▶ **FENDL project kick-off**
*IAEA Specialists Meeting on “Fusion Evaluated Nuclear Data Library Related to the ITER Activity” IAEA Headquarters, Vienna, **16 -18 November 1987***

FENDL's Birth: IAEA Specialists Meeting on "Fusion Evaluated Nuclear Data Library Related to the ITER Activity" IAEA Headquarters, Vienna, 16 -18 Nov. 1987



Meeting Report: INDC(NDS)-201/GF, January 1988, prepared by V. Goulo and A. Lorenz

Candidate evaluations considered for FENDL-1

EL/IS	JENDL	BROND (ETUD)	EFF ENDL	ENDF/ B	EL/ IS	JENDL	BROND (ETUD)	EFF ENDL	ENDF/ B
H	2 a		a	V, a	IS		a	a	IV a
D	2 a	a	a	(LA)	T*			(a)	IV a
(T)				(LA)	V	2 a		a	25188
Li-6	2 a			V, a	Cv*	3 2/88	a	a 1RR	5188
Li-7	2 a		7188	V, a	Fe*	5188		a 2 1188	5188
Be	2 a		12188	V, a	Fe*	3 7 a	a	a 7RR	5188
B10	2 a			V, a	N*	3 2 a	a	a 1RR	5188
B11				V, a	Co	2 a		a 2188	5188
C	2 a			V, a	Cu*	7 a	3/88	a	5188
N				V, a	Zr*			(a)	5188
O	2 a			IV a	Nb*	7 a		a 7/88	5188
F	2 a			IV a	Mo*	2 a		(a)	IV a
Si	2 a			IV a	Sr*			(a)	5188
Al	2 a			IV a	Ba*			(a)	5188
W*	2 a			IV a				(a)	5188
U	2 a			IV a				(a)	5188
Pu	2 a			IV a				(a)	5188
Am	2 a			IV a				(a)	5188
Cm	2 a			IV a				(a)	5188
Bk	2 a			IV a				(a)	5188
Cf	2 a			IV a				(a)	5188
Es	2 a			IV a				(a)	5188
Fm	2 a			IV a				(a)	5188
Md	2 a			IV a				(a)	5188
No	2 a			IV a				(a)	5188
Lr	2 a			IV a				(a)	5188

Handwritten notes on the blackboard include: "D. Laurin" with arrows pointing to the H and D rows; "under way" near the C and N rows; "new evals. needed" near the bottom right; and various circled numbers and symbols (a, V, IV) indicating specific data points or evaluations.

Blackboard excerpt, IAEA Specialists Meeting, 16-18 November 1987

FENDL – 1

- ▶ **Data base:** National/regional Nuclear Data Libraries (as available in 1987)
ENDF/B-V, -VI, ENDL-84 (USA), JENDL-2, -3 (Japan), BROND-2 (USSR), EFF-1,-2 (EC)
- ▶ Selection procedure for adoption of data evaluations in FENDL-1: **Review, evaluation and final selection**
- ▶ Selection criteria
Quality of data evaluations, isotopic data, completeness and consistency, ENDF-6 data format
- ▶ Selection performed at several IAEA Specialists and Advisory Group Meetings, mainly 1989 -1991
 - ▶ *IAEA Specialists Meeting on Fusion Evaluated Nuclear Data Library (FENDL), Vienna, 8-11 May 1989; INDC(NDS)-223/GF*
 - ▶ *Consultants Meeting on the First Results of FENDL-1 Testing and Start of FENDL-2, Vienna, 25-28 June 1990; INDC(NDS)-241*
 - ▶ *IAEA Advisory Group Meeting on FENDL-2 and Associated Benchmark Calculations, Vienna, 18-22 Nov. 1991; INDC(NDS)-260*

FENDL/E – 1.0 Data Evaluations

► ENDF/B-VI

$^1,^3\text{H}$, $^6,^7\text{Li}$, ^9Be , $^{10,11}\text{B}$, C , ^{16}O , ^{19}F , ^{31}P , S , Cl , K , V , $^{50, 52-54}\text{Cr}$, ^{55}Mn , $^{54, 56-58}\text{Fe}$, ^{59}Co , $^{58, 60-62, 64}\text{Ni}$, $^{63, 65}\text{Cu}$, $^{134-138}\text{Ba}$, $^{182-184, 186}\text{W}$, $^{206-208}\text{Pb}$

► JENDL-3.1

^{23}Na , Mg , ^{27}Al , Ca , Ti , Mo , ^{181}Ta , ^{209}Bi

► BROND-2

^2H , $^{14,15}\text{N}$, Si , $^{90-92, 94, 96}\text{Zr}$, ^{93}Nb , Sn

- Photon-atom interaction cross-section data completely taken from ENDF/B-VI data file
- Activation, decay, charged particle & dosimetry data libraries

FENDL/A-1.1, FENDL/D-1.0, FENDL/C-1.0, FENDL/DS-1.0

FENDL – 1 Data Files

► Finally released in 1994

IAEA AGM on “Review of Uncertainty Files and Improved Multigroup Cross Section Files for FENDL”, Tokai-mura, Japan, 8-12 November 1993; summary report edited by S. Ganesan, INDC(NDS)-297.

IAEA AGM on “Improved Evaluations and Integral Data Testing for FENDL, Garching, Germany, 12-16 September 1994”; summary report by S. Ganesan, INDC(NDS)-312.

IAEA AGM on “Completion of FENDL-1 and Start of FENDL-2”, Del Mar, California, USA, 5-9 December 1995; summary report by A. Pashchenko INDC(NDS)-352

► Released data files

FENDL/E-1.0 general purpose library, ENDF-6 format (Nov. 1994)

FENDL/MG-1.0 multi-group data library (176 VITMIN-J group structure) processed by R. McFarlane with NJOY(Nov. 1994)

FENDL/MC-1.0 ACE formatted pointwise data library for MCNP calculations processed by R. MacFarlane with NJOY (Nov. 1994)

FENDL/A-1.1 neutron activation data (April 1993)

FENDL/C-1.0 charged particle data for fusion reactions (Nov. 1991)

FENDL/D-1.0 decay from ENDF/B-VI and ENSDF (Jan. 1992)

FENDL/DS-1.0 dosimetry data identical to IRDF-90, V2 (Oct. 1993)

FENDL – 1 Benchmarking

- ▶ Extensive benchmark task conducted after release of FENDL-1.0 working libraries

U. Fischer et al., "Benchmark Validation of the FENDL-1 Nuclear Data Library – A Co-ordinated International Effort, Fusion Technology 30, 1093-1100, December 1996

- ▶ Objective:
 - ▶ To validate FENDL-1 data prior to use in design calculations
 - ▶ To identify potential deficiencies and needs for improvements of data evaluations for FENDL-2
- ▶ Main results:
 - ▶ FENDL-1 shows high quality for fusion applications
 - ▶ Observed deficiencies in most cases not too serious
 - ▶ Calculated gamma-spectra and heating rates satisfactory with few exceptions
 - ▶ Recommendations for improvements in forthcoming FENDL-2 data file

FENDL – 2

- ▶ Definition of standards and selection procedure for improved FENDL library

IAEA AGM on “Review of Uncertainty Files and Improved Multigroup Cross Section Files for FENDL”, Tokai-mura, Japan, 8-12 Nov. 1993

- ▶ *List of candidate evaluations and review kit to be provided*

IAEA AGM on “Completion of FENDL-1 and Start of FENDL-2”, Del Mar, California, USA, 5-9 December 1995; INDC(NDS)-352

- ▶ Selection of data evaluations based on review kit and results of benchmark tests

IAEA Consultants Meeting on Selection of Basic Evaluations for the FENDL-2 Library, Karlsruhe, Germany, 24-28 June 1996; INDC(NDS)-256

*IAEA AGM on Extension and Improvement of the FENDL Library for Fusion Applications (FENDL-2), **Vienna, 3-7 March 1997**; INDC(NDS)-373 (**FENDL-2 close-out meeting**)*

- ▶ **Approval to release FENDL-2.0 with its sub-libraries** .../E (evaluated data), .../MG (processed multi-group data), .../MC (processed Monte Carlo library), .../A (activation data), .../D (dosimetry), and .../C (charged particle data).

FENDL/E-2.0, -MG, -MC released May 1998, others March 1997

FENDL – 2.1

- ▶ FENDL-2.0 has been extensively benchmarked and frozen. (“Best available and validated nuclear data library for fusion applications”). **Recommended as reference data library** in fusion reactor design calculations and related applications.

IAEA Consultants Meeting on Validation and Improvement of the FENDL-2.0 Transport Sub-libraries, Vienna, 12-14 October 1998, INDC(NDS)-395

- ▶ Procedure for inclusion of new evaluations in future FENDL updates: Superiority over FENDL-2.0 evaluation to be shown.

- ▶ **FENDL-2.1**

- ▶ Minor updates with only major omissions or inaccuracies in FENDL-2.0 corrected & obsolete evaluations replaced

IAEA Consultants Meeting “Maintain FENDL Library for Fusion Applications”, Vienna, 10-12 November 2003, INDC(NDS)-451

- ▶ *FENDL-2.1 compiled and processed (MG and MC data libraries) by the IAEA/NDS.*

FENDL-2.1, Update of an evaluated nuclear data library for fusion applications, D. Lopez Aldama and A. Trkov, INDC(NDS)-467, Dec. 2004

- ▶ **FENDL-2.1 adopted as reference nuclear data library for ITER design calculations**

FENDL – 3.0

- Developed in the frame of an IAEA CRP (Co-ordinated Research Programme) 2008 – 2012
- **Objective**
 - Update the current fusion reference library FENDL-2.1 with **improved (state-of-the-art) data evaluations**
 - Extend the **neutron energy range up to 150 MeV** to enable design analyses for IFMIF (International Fusion Material Irradiation Facility)
 - Include general purpose and activation **data libraries for p- and d-induced reactions** up to 150 MeV
 - 180 materials with all isotopic data (compared to 71 in FENDL-2.1)
 - Create **complementary library with co-variances** from nuclear model calculations
- FENDL-3.0 data libraries compiled and processed at IAEA/NDS
 - FENDL-3.0: **Processing the Evaluated Nuclear Data Library** for Fusion Applications, D. Lopez Aldama, R. Capote, INDC(NDS)-0611, Dec. 2011*
 - FENDL-3 Library **Summary documentation**, R.A. Forrest, et al., INDC(NDS)-0628, Dec. 2012*
 - FENDL-3 Library : Summary Report of the **Coordinated Research Project**, R.A. Forrest, INDC(NDS)-0645, Dec. 2013*

FENDL – 3.0 data libraries

- ▶ **Neutron induced general purpose data library**
 - ▶ H-1 to Bi-209 + Th-232, U-235, U-238
 - ▶ Upper energy limit 150/200 MeV (few exceptions: 60 MeV)
 - ▶ ENDF-, PENDF-, ACE-, GENDF + MATXS data files
- ▶ **Proton induced general purpose data library**
 - ▶ H-1 to Bi-209 + Th-232, U-235, U-238
 - ▶ Different sources: JENDL-HE, TENDL-2011 + ENDF/B-VII
 - ▶ Upper energy limit: 3 GeV, 200 MeV, + few others
 - ▶ ENDF-files, some ACE files (TENDL-2011)
- ▶ **Deuteron induced general purpose data library**
 - ▶ Li-6, -7, Be-9 to Bi-209 + Th-232, U-235, U-238
 - ▶ All from TENDL-2011 (200 MeV upper energy limit)
 - ▶ ENDF- and ACE files

FENDL – 3.0 data libraries

► Photo atomic data

- H to Bi + Th, U; all from ENDF/B-VI; ENDF + GENDF files

► Neutron shadow library with full covariance data

- Li-6, -7, Be-9 to Bi-209 + Th-232, U-235, U-238; all from TENDL-2010 (200 MeV upper energy limit); ENDF- files + few ACE files

► Neutron activation data

- Full EAF-2010 library including actinides; up to 60 MeV
- ENDF-, PENDF-, GENDF-, GND-, ACE- data files

► Proton activation data

- Li-6, Li-7, to Fm-257 (including all actinides); all from TENDL-2011, up to 200 MeV
- PENDF- + GENDF-data files

► Deuteron activation data

- Li-6, Li-7, to Fm-257 (including all actinides); all from TENDL-2011, up to 200 MeV
- PENDF- , GENDF-data files

FENDL – 3.0 Benchmarking

- Comprehensive Benchmark Analyses within CRP activities
 - On computational ITER Benchmark (as specified by M. Sawan, INDC(NDS)-316, Dec. 1994)
 - On a series of available 14 MeV neutron benchmark experiments (FNS, FNG, Oktavian)

U. Fischer et al, Benchmarking of the FENDL-3 Neutron Cross-Section Data Library for Fusion Applications, INDC(NDS)-0631, March 2014

- Main conclusions
 - In general, **FENDL-3, as compared to FENDL-2.1, shows an improved performance** for fusion neutronics applications.
 - It is thus **recommended to ITER to replace FENDL-2.1 as reference data library for neutronics calculation by FENDL-3.0**
- Official letter from NDS head R. Forrest to ITER formally requesting to adopt FENDL-3.0 as reference set of nuclear data (4 Nov. 2014)
- Letter by ITER Nuclear Analysis Co-ordinator M. Loughlin to DDG of ITER department for ITER project, R. Haange, to implement the IAEA recommendation (27 Nov. 2014)

FENDL – 3.1, b, c, d; 3.2, a, b

- Problems revealed in some evaluations and processing of data files (mostly found by Ch. Konno and s. Kwon, JAEA/QST) necessitated further updates of the FENDL-3 data library
 - FENDL-3.1 (Sept. 2015): DPA and KERMA corrected in MC and MG files
 - FENDL-3.1b (July 2016): TENDL-2010 files replace by -2014; several corrections in processing source files, QA procedure implemented.
 - FENDL-3.1c (Sept. 2017): A severe problem with K-39 data (found by R. Grove, ORNL) corrected; no other changes.
 - FENDL-3.1d (Jan. 2018): Substitution of minor K isotopes 40, 41 with TENDL-2015 for consistency; no other changes.
 - FENDL-3.2 (Jan. 2022): Several changes/updates including corrections of MF6/MT5 yields at 20 MeV (found by Ch. Konno), INDEN evaluations for Cr, Fe isotopes and O-16; deuteron ENDF files for Li-6, Li-7, Be-9, C-12, C-13 from JENDL/DEU-2020; IRDFFF-II (released Jan. 2020) recommended for neutron dosimetry.
 - FENDL-3.2a, -3.2b (Feb. 2022): O-16 neutron ENDF file updated at IAEA/NDS; TENDL-2017 recommended as activation data library
 - **FENDL-3.2b: Latest library version documented in “big NDS paper” including new benchmark and applications calculation results.**

Recent Meetings Related to post FENDL-3.0 activities

- ▶ The Fusion Evaluated Nuclear Data Library (FENDL), Consultants Meeting, IAEA Headquarters, Vienna, 1-4 August 2016, summary report by M. Fleming and A. Trkov, INDC(NDS)-0724
 - ▶ FENDL Library for Fusion Neutronics Calculations, Consultants Meeting, IAEA Headquarters, Vienna, 15-18 October 2018, summary report by L. Packer and A. Trkov, INDC(NDS)-0769
 - ▶ FENDL Library for Fusion Neutronics Calculations, Consultants Meeting, IAEA Headquarters, Vienna, 2-5 September 2019, summary report by D. Leichtle and A. Trkov, INDC(NDS)-0797
 - ▶ Further Development of the Fusion Evaluated Nuclear Data Library (FENDL), IAEA Headquarters, Vienna, 30 October – 2 November 20123
- Purpose:** *Discuss necessary extensions and improvements of FENDL, and technological innovations to facilitate and accelerate updating, verification and validation process of the library*

The future of FENDL

- Development versus a fully consistent and comprehensive data library based on/derived from TENDL-202x?
- Update of individual (major) evaluations with “in-depth evaluations” from major libraries/projects (e. g. ENDF/B, JEFF, JENDL, CENDL, INDEN)
- Consistency of transport, activation, dosimetry and uncertainty data
- Improvement of deuteron data files with advanced nuclear models
- Benchmarking & QA
 - Automated V&V of data files under development (in parallel with data evaluation)
 - JADE tool available, needs extension of data base (experiments, models; deuterons, activations)
- Modern techniques (“technological innovations”) in data evaluation and processing.