Precursors and decay events with EASY-II

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Research Councils UK Energy
For a Low Carbon Future

CCFE is the fusion research arm of the United Kingdom Atomic Energy Authority.
This work was funded by the RCUK Energy Programme [grant number EP/I501045] .

CCFE
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EASY-II framework

- FISPACT-II is a modern engineering prediction tool for activation-transmutation, depletion inventories, etc.
- The EASY-II system has been guided by TALYS n-TAL collaboration, which provides ***complete*** nuclear data libraries.
- FISPACT-II was designed to be a functional replacement for FISPACT-2007 but significant development has produced a substantially superior, more mature code
- a, g, d, p, n-Transport Activation Library: TENDL-2014 from the TENDL collaboration, but also ENDF/B, JENDL, JEFF
- Nuclear data processing done with (including cross-checks) NJOY (LANL), PREPRO (LLNL), and CALENDF (CEA-CCFE)


European Activation SYstem
EASY-II
Astrophysic
Depletion
Fission
Criticality
Fusion
Burnup
Source terms
Material Science
Inventory
Activation
Shielding
Pile
Reactor
Medical
Transmutation
UK Atomic Energy Authority
$\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i\varphi) + \sum_{j \neq i} N_j(\lambda_{ij} + \sigma_{ij}\varphi)$

Physics

- All problems are multi-physics but usually decomposed into single physics ones
- The nuclear data, processing steps answers the needs of single physics codes (mainly reactor physics)
- Advanced simulation methods rely upon multi-physics codes with complex feedback
- This ***requires*** integrated, multifaceted processing steps able to deliver rich, interconnected type of nuclear data forms and correlated uncertainty
- This in turn requires the basic nuclear data to be complete but unique, robust, technological based with variance-covariance for every quantities across all energy ranges and decay schemes

Theory: H. Bateman, Cambridge 1910

- Set of stiff Ordinary Differential Equations to be solved

$$\frac{dN_i}{dt} = -N_i(\lambda_i + \sigma_i \varphi) + \sum_{j \neq i} N_j(\lambda_{ij} + \sigma_{ij} \varphi)$$

- Here λ_i and σ_i are respectively the total decay constant and cross-section for reactions on nuclide i
- σ_{ij} is the cross-section for reactions on nuclide j producing nuclide i, and for fission it is given by the product of the fission cross-section and the fission yield fractions, as for radionuclide production yield
- λ_{ij} is the constant for the decay of nuclide j to nuclide i

Rate equations: numerical aspects

- LSODES, Livermore Solver for Ordinary Differential Equations with general sparse Jacobian matrices
  - Backward Differentiation Formula (BDF) methods (Gear's method) in stiff cases to advance the inventory
  - Adams methods (predictor-corrector) in non stiff case
  - makes error estimates and automatically adjusts its internal time-steps
  - Yale sparse matrix efficiently exploits the sparsity
  - ability to handle time-dependent matrix
  - no need for equilibrium approximation
  - handles short (1ns) time interval and high fluxes
- LSODES wrapped in portable Fortran 95 code
  - dynamic memory allocation
  - minor changes to Livermore code to ensure portability

EASY-II TENDL's libraries – 200 MeV

- n-tendl-2014 (2013), multi temperature, 709 groups library; 2632 targets
  - ✓ full set of covariance
  - ✓ probability tables in the RRR and URR
  - ✓ xs, dpa, kerma, gas, radionuclide production
- JENDL-4.0u, ENDF/B-VII.1, JEFF-3.2, 709 groups libraries; circa 400 targets each

- g-tendl-2013, 162 groups xs library, 2629 targets
- p-tendl-2013, 162 groups xs library, 2629 targets
- d-tendl-2013, 162 groups xs library, 2629 targets
- a-tendl-2013, 162 groups xs library, 2629 targets

EASY-II other libraries

- ✓ Decay-2012, 3873 isotopes (23 decay modes; 7 single and 16 multi-particle ones)
- ✓ Ingestion and inhalation, clearance and transport indices libraries, 3873 isotopes
- ✓ JEFF-3.1.1 DD and FY, UKFY4.2 fission yields, GEF
- ✓ ENDF/B-VII.1 DD and FY (??)
- ✓ JENDL FPD/FPY (??) 2011

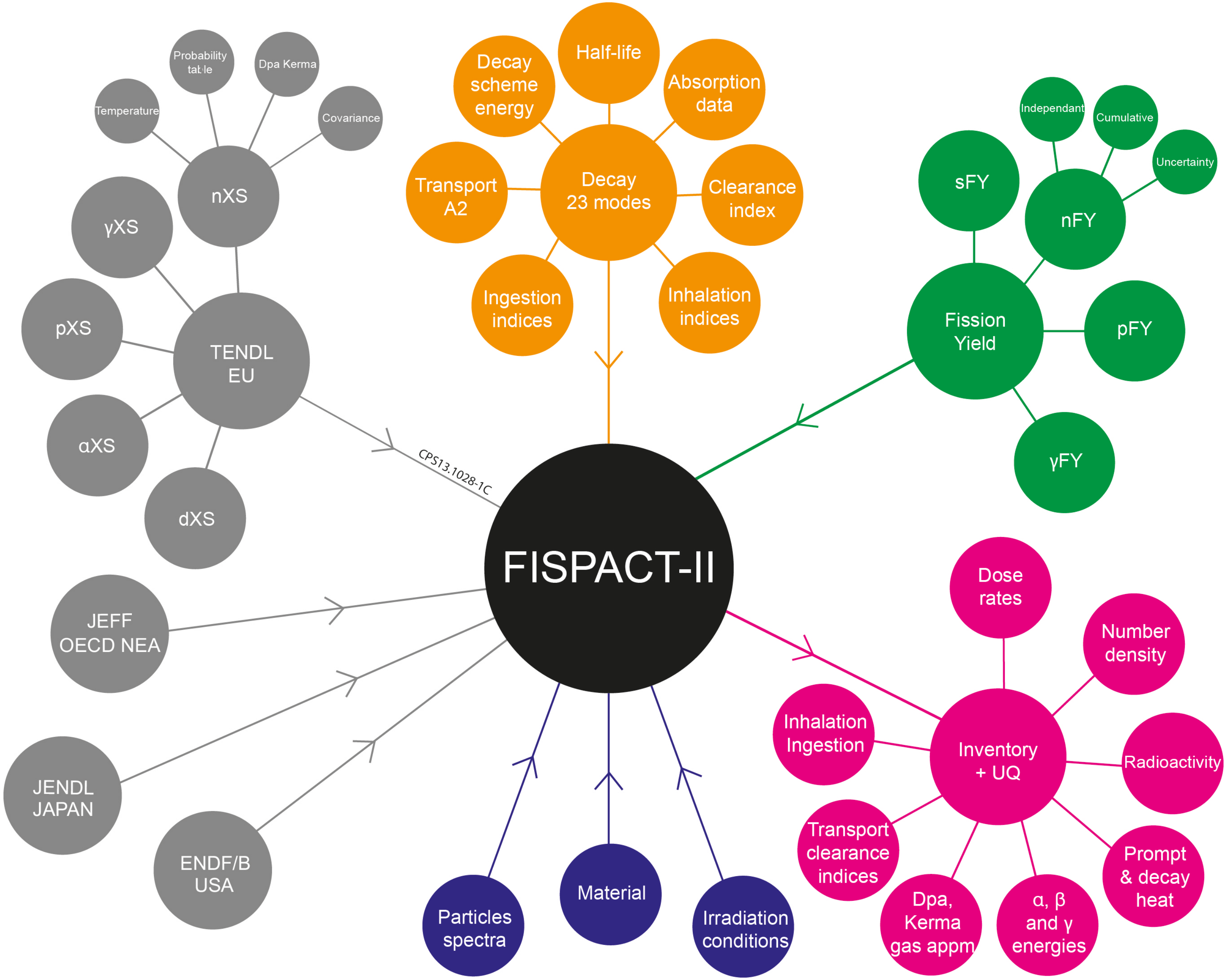
- ✓ EAF-2010 decay data: 2233 isotopes
- ✓ EAF-2010 ingestion and inhalation, clearance and transport indices libraries, 2233 isotopes
  - ✓ EAF's uncertainty files

- ✓ Decay-2015, at the assemblage level

FISPACT-II versus FISPACT-2007

	FISPACT-II	FISPACT-2007
Solver	Numerical - LSODES 2003	Numerical - EXTRA 1976
Incident particles	α, γ, d, p, n (5)	d, p, n (3)
EAF's libraries: EAF-2010, 2007, 2005, 2003	✔ XS data (816 targets) ✔ Decay Data (2233 isotopes)	✔ XS data (816 targets) ✔ Decay Data (2233 isotopes)
ENDF's libraries: TENDL-2014, ENDF/B-VII.1, JEFF-3.2, JENDL-4.0	✔ XS data (2632 targets) ✔ Decay data (3873 isotopes)	✗
Dpa, Kerma, Gas prod., radionuclide yields	✔	✗ (Gas production)
Uncertainty	✔ Variance-covariance	✔ 1 to 3 broad groups
Temperature	0, 294, 600, 900 K,…30 KeV	294 K
Self-shielding	✔ Resolved and Unresolved Resonance Range	✗ infinitely dilute cross section
Energy range	1.0 10^{-5} eV – 200 MeV	1.0 10^{-5} eV - 55 MeV
Sensitivity	✔ Monte Carlo	✔ sensitivity coefficient
Pathways	✔ multi steps	✔ single step
Thin, thick targets yields	✔	✗

EASY-II & TENDL & ENDF/B-VII, JENDL-4.0, JEFF-3.2



Nuclear observables

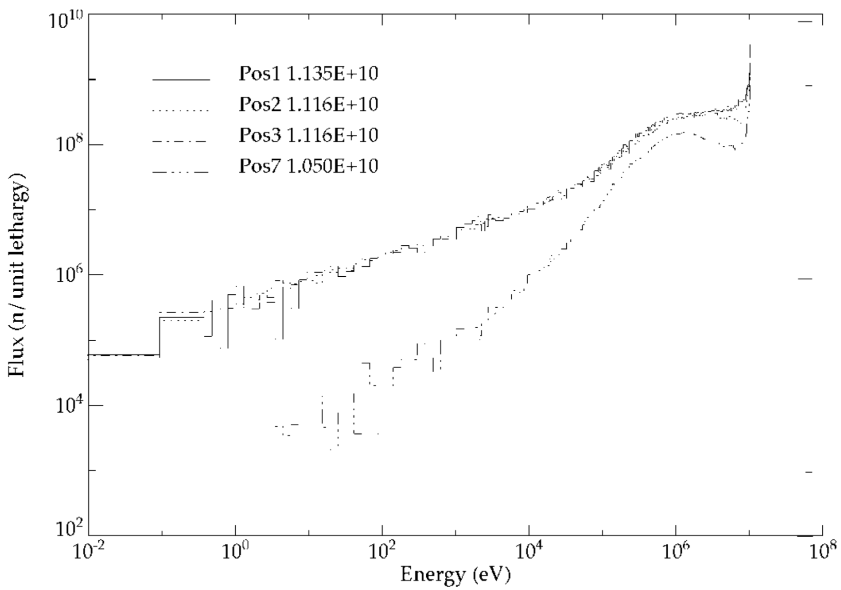
➢ For all targets nuclei, incident particles and daughters

- Cross sections, angular distribution, emitted spectra
- Half life, masse, energy levels and schemes
- Decay schemes and energies
- Spontaneous, induced fission yields (single/cumulative)
- Resonance Integrals, Maxwellian, thermal
- Correlated uncertainty
- Spallation products

- Inhalation, ingestion hazards
- Transport, clearance indices

JAEA FNS Assembly; decay heat

14 MeV neutrons are generated by a 2 mA deuteron beam impinging on a stationary tritium bearing titanium target; Fusion Neutron Source



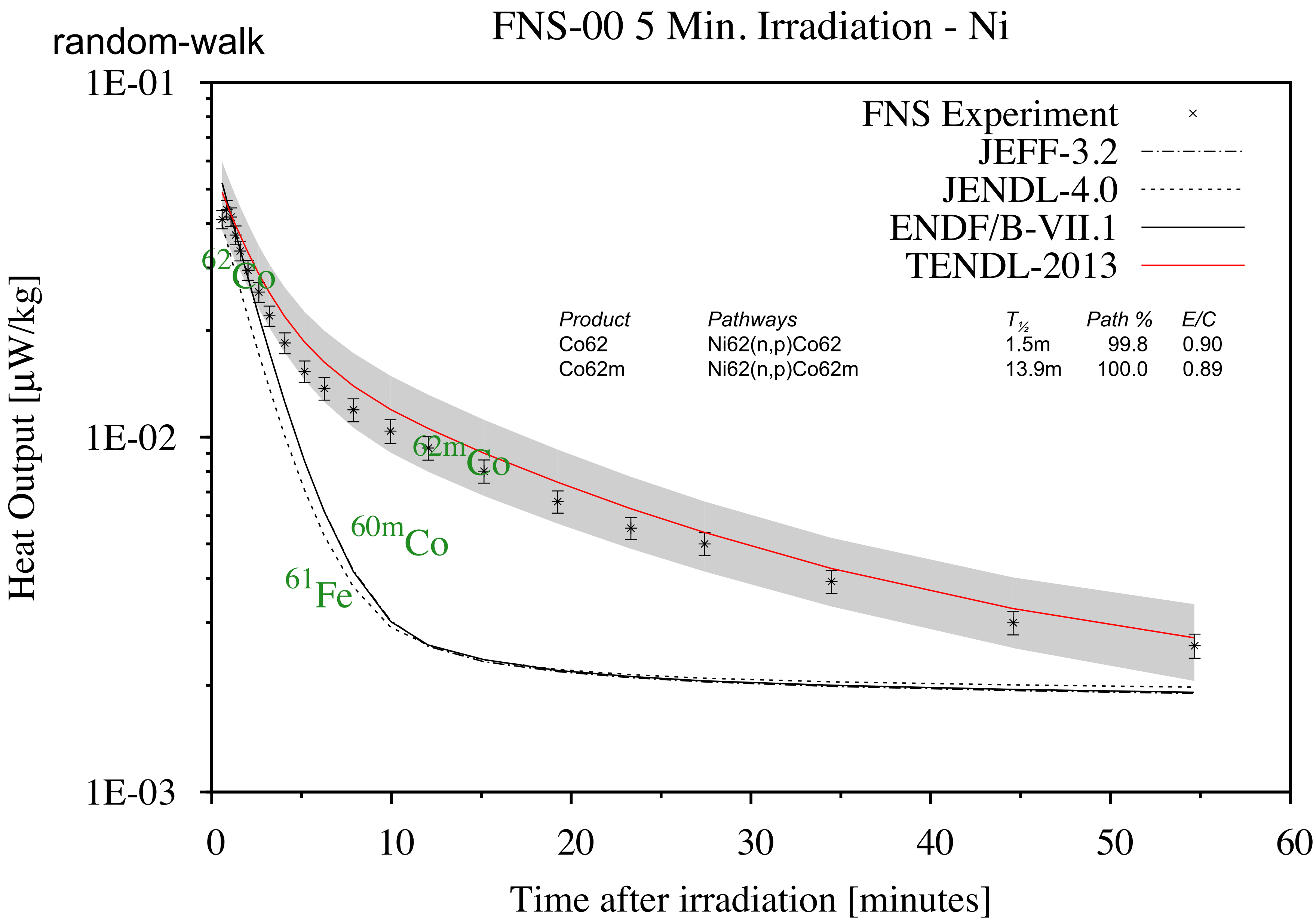
Z	Element	Form	Z	Element	Form
9	Fluorine	CF_2	46	Palladium	Metallic Foil
11	Sodium	Na_2CO_3	47	Silver	Metallic Foil
12	Magnesium	MgO	48	Cadmium	Metallic Foil
13	Aluminium	Metallic Foil	49	Indium	Metallic Foil
14	Silicon	Metallic Powder	50	Tin	SnO_2
15	Phosphorus	P_3N_5	51	Antimony	Metallic Powder
16	Sulphur	Powder	52	Tellurium	TeO_2
17	Chlorine	$C_2H_2Cl_2$	53	Iodine	IC_6H_4OH
19	Potassium	K_2CO_3	55	Caesium	Cs_2O_3
20	Calcium	CaO	56	Barium	$BaCO_3$
21	Scandium	Sc_2O_3	57	Lanthanum	La_2O_3
22	Titanium	Metallic Foil	58	Cerium	CeO_2
23	Vanadium	Metallic Foil	59	Praseodymium	Pr_6O_{11}
24	Chromium	Metallic Powder	60	Neodymium	Nd_2O_3
25	Manganese	Metallic Powder	62	Samarium	Sm_2O_3
26	Iron	Metallic Foil	63	Europium	Eu_2O_3
Alloy	SS304	Metallic Foil	64	Gadolinium	Gd_2O_3
Alloy	SS316	Metallic Foil	65	Terbium	Tb_4O_7
27	Cobalt	Metallic Foil	66	Dysprosium	Dy_2O_3
Alloy	Inconel-600	Metallic Foil	67	Holmium	Ho_2O_3
28	Nickel	Metallic Foil	68	Erbium	Er_2O_3
Alloy	Nickel-chrome	Metallic Foil	69	Thulium	Tm_2O_3
29	Copper	Metallic Foil	70	Ytterbium	Yb_2O_3
30	Zinc	Metallic Foil	71	Lutetium	Lu_2O_3
31	Gallium	Ga_2O_3	72	Hafnium	Metallic Powder
32	Germanium	GeO_2	73	Tantalum	Metallic Foil
33	Arsenic	As_2O_3	74	Tungsten	Metallic Foil
34	Selenium	Metallic Powder	75	Rhenium	Metallic Powder
35	Bromine	BrC_6H_4COOH	76	Osmium	Metallic Powder
37	Rubidium	Rb_2CO_3	77	Iridium	Metallic Powder
38	Strontium	$SrCO_3$	78	Platinum	Metallic Foil
39	Yttrium	Y_2O_3	79	Gold	Metallic Foil
40	Zirconium	Metallic Foil	80	Mercury	HgO
41	Niobium	Metallic Foil	81	Thallium	Tl_2O
42	Molybdenum	Metallic Foil	82	Lead	Metallic Foil
44	Ruthenium	Metallic Powder	83	Bismuth	Metallic Powder
45	Rhodium	Metallic Powder			

FNS Neutron spectra, neutron fluence monitored by $^{27}Al(n,\alpha)Na^{24}$

Two experimental campaigns: 1996 and 2000; 74 materials

Decay power: FNS JAERI Ni

random-walk

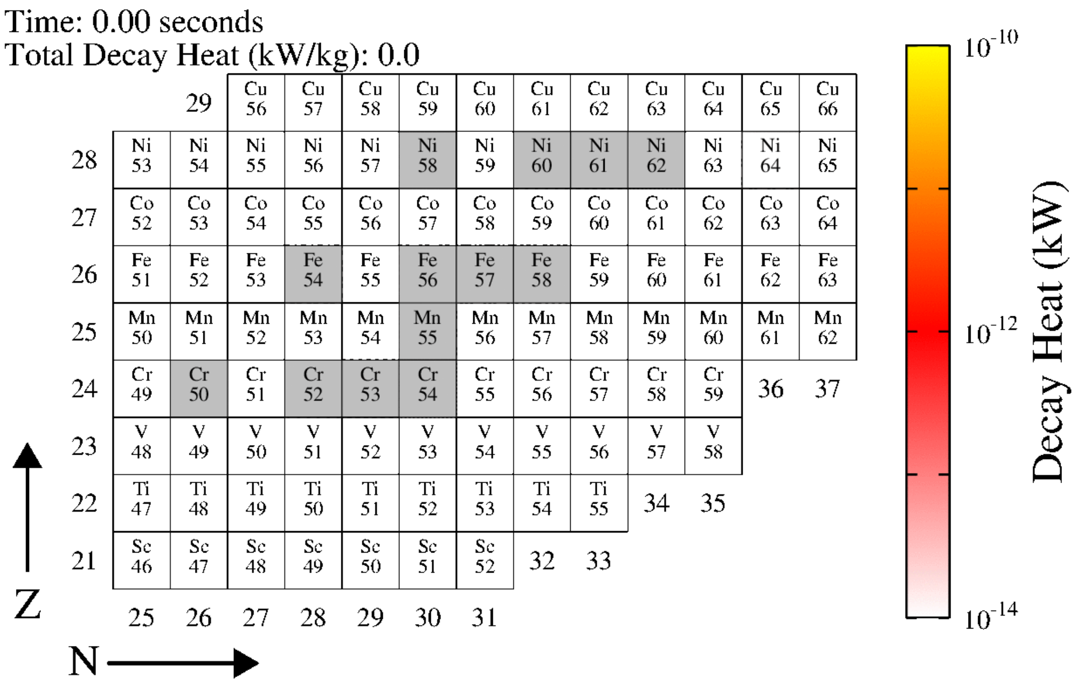


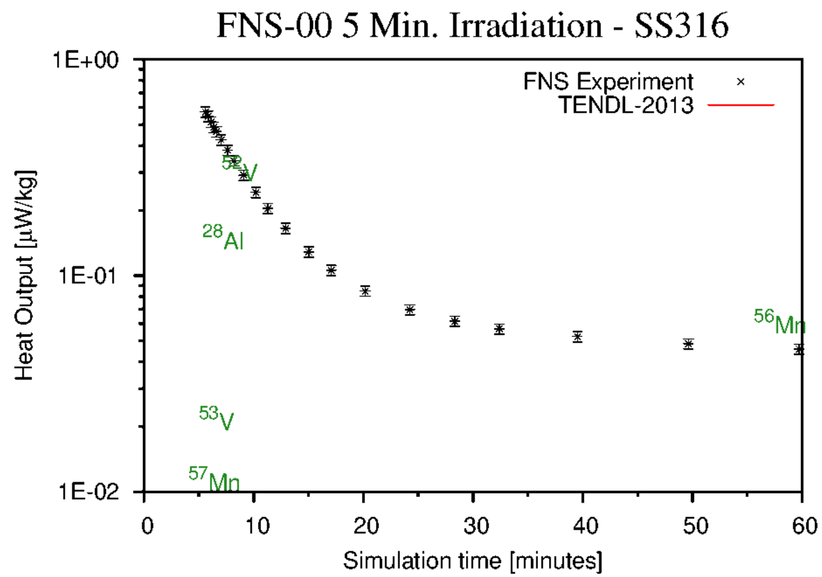
Product	*Pathways*	*T½*	*Path %*	*E/C*
Co62	Ni62(n,p)Co62	1.5m	99.8	0.90
Co62m	Ni62(n,p)Co62m	13.9m	100.0	0.89

Decay power: FNS JAERI Ni

Times	FNS EXP. 5 mins		TENDL-2013			ENDF/B-VII.1	JEFF-3.2	JENDL-4.0
Min.	μW/g		μW/g		E/C	E/C	E/C	E/C
0.58	4.11E−02	+/-6%	4.90E−02	+/-22%	0.84	0.79	0.79	1.04
0.83	4.38E−02	+/-6%	4.55E−02	+/-22%	0.96	0.94	0.94	1.23
1.08	4.18E−02	+/-6%	4.24E−02	+/-21%	0.99	1.00	1.00	1.30
1.33	3.71E−02	+/-6%	3.95E−02	+/-21%	0.94	0.99	0.99	1.29
1.58	3.35E−02	+/-6%	3.70E−02	+/-21%	0.90	0.99	0.99	1.29
2.02	2.95E−02	+/-6%	3.32E−02	+/-20%	0.89	1.05	1.05	1.35
2.62	2.56E−02	+/-6%	2.89E−02	+/-20%	0.89	1.17	1.17	1.49
3.22	2.20E−02	+/-7%	2.55E−02	+/-20%	0.86	1.27	1.27	1.60
4.07	1.84E−02	+/-7%	2.19E−02	+/-21%	0.84	1.46	1.46	1.82
5.17	1.53E−02	+/-7%	1.86E−02	+/-22%	0.83	1.79	1.79	2.16
6.27	1.37E−02	+/-7%	1.63E−02	+/-23%	0.84	2.22	2.22	2.60
7.88	1.19E−02	+/-7%	1.39E−02	+/-24%	0.86	2.85	2.84	3.15
9.95	1.04E−02	+/-8%	1.20E−02	+/-24%	0.87	3.44	3.42	3.57
12.05	9.32E−03	+/-8%	1.06E−02	+/-24%	0.88	3.59	3.62	3.59
15.15	8.02E−03	+/-7%	9.02E−03	+/-24%	0.89	3.40	3.44	3.40
19.25	6.58E−03	+/-7%	7.47E−03	+/-24%	0.88	2.99	3.01	2.97
23.32	5.54E−03	+/-7%	6.29E−03	+/-23%	0.88	2.62	2.64	2.59
27.42	5.00E−03	+/-7%	5.39E−03	+/-22%	0.93	2.43	2.45	2.39
34.48	3.92E−03	+/-8%	4.27E−03	+/-22%	0.92	1.96	1.97	1.92
44.58	3.00E−03	+/-8%	3.29E−03	+/-23%	0.91	1.54	1.55	1.50
54.68	2.58E−03	+/-8%	2.72E−03	+/-24%	0.95	1.35	1.36	1.31

Product	**Pathways**	**$T_{1/2}$**	**Path %**	**E/C**	**ΔE%**
Co62	Ni62(n,p)Co62	1.5m	99.8	0.90	6%
Co62m	Ni62(n,p)Co62m	13.9m	100.0	0.89	7%



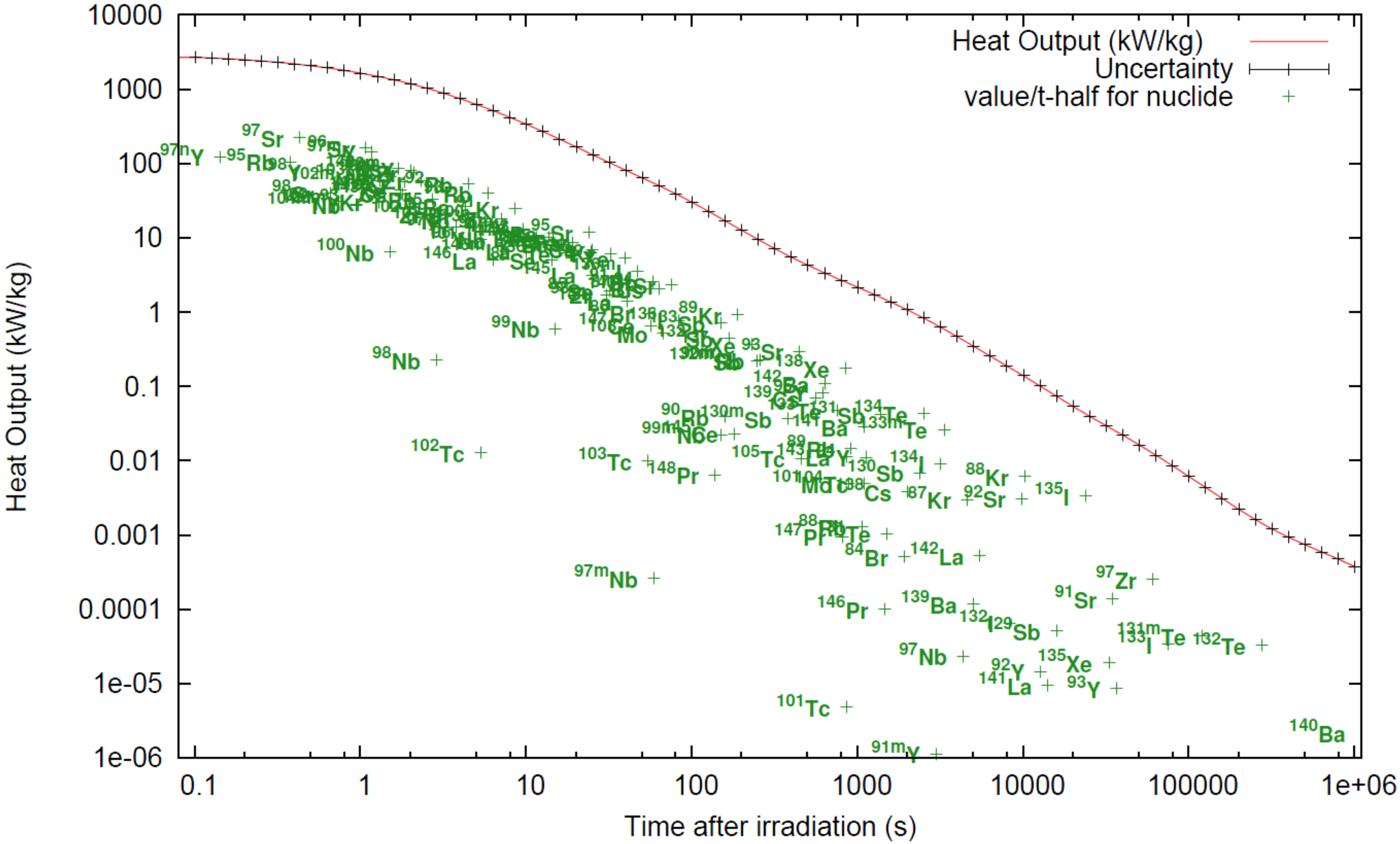


Simulation of SS316 irradiated in JAEA FNS
m - metastable state(s) > 50%

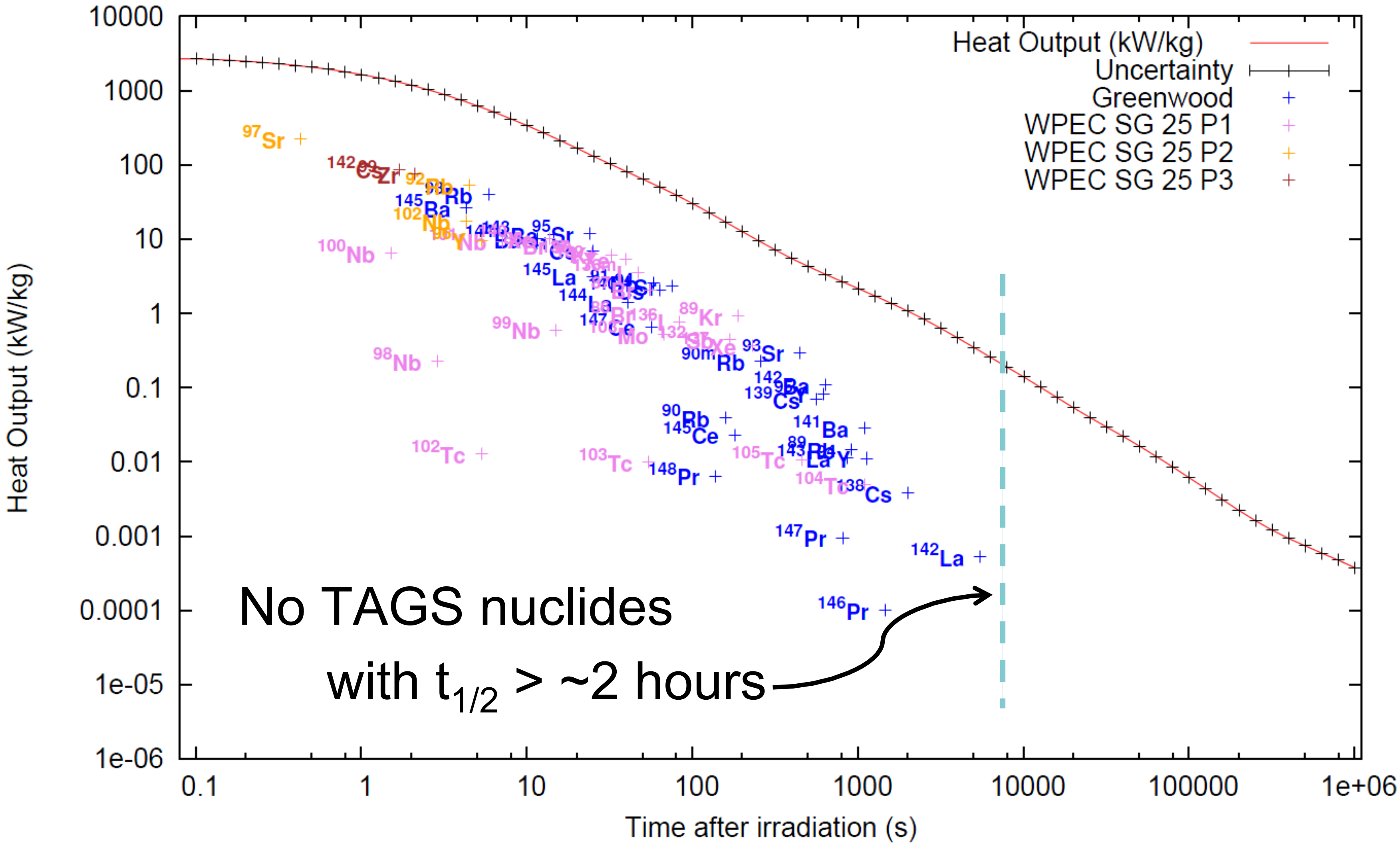
M.R. Gilbert & J.-Ch. Sublet CCFE-R(14)21 *JAEA FNS Decay heat validation*
M. R. Gilbert et al., "Inventory Visualisation techniques" *Nucl. Sci. Eng* (2014)

Thermal ^{235}U pulse generates a large inventory...

Each nuclide at $(x,y)=(t_{1/2},\text{heat}(t_{1/2}))$



Blue = Greenwood nuclides and WPEC SG 25 P1, P2, P3 are priority 1, 2, 3 nuclides with requested TAGS by subgroup 25



Fission pulse

Fission decay experiments

- Selection of experiments usually used in validation of decay heat simulations
- Tobias is meta-analysis with exp from 1950s onward and modification of uncertainties to make fits

Author	Method	Nuclide	Irrad. (s)	Year
Yarnell, LANL	Calor.	$^{235}U_{th}$ $^{239}Pu_{th}$ $^{233}U_{th}$	2E4	1980
Dickens, ORNL	β,γ spec.	$^{235}U_{th}$ $^{239}Pu_{th}$ $^{241}Pu_{th}$	1.-100.	1980
Baumung, KfK	Calor.	$^{235}U_{th}$	200	1981
Akiyama, YAYOI	β,γ spec.	$^{232}Th_f$ $^{233}U_f$ $^{235}U_f$ $^{238}U_f$ $^{239}Pu_f$	10.-300.	1982
Johansson, Uppsala	β,γ spec.	$^{235}U_{th,}$ $^{239}Pu_{th,}$ $^{238}U_f$	4.-120	1987
Schier, Lowell	β,γ spec.	$^{235}U_{th}$ $^{238}U_f$ $^{239}Pu_{th}$	<1	1997
Ohkawachi, YAYOI	β,γ spec.	$^{235}U_f$ $^{237}Np_f$	10.-300	2002
Tobias, CEGB	Meta-analysis	$^{235}U_{th}$ $^{239}Pu_{th}$	Pulse-1E5	1989

Decay heat from fission events

- Many fission decay heat experiments
- Different fission rate calculation methodologies
- Many nuclides: U235, U238, Pu239, Pu241, Th232, Np237
- Even more experimental fluxes - ORNL ‘thermal flux’ ≠ Karlrushe ‘thermal flux’ ≠ LANL ‘thermal flux’ ≠ …
- Even more irradiation schedules
  - Dickens 1 s irrad followed by 2 s waiting
  - Akiyama 10 s irrad followed by 6 s waiting
  - Karlrushe 200 s irrad followed by 15 s waiting
- ‘Correction factors’ in experiments to get burst function, fission rate normalisation, capture correction, epithermal contribution …

Preliminary comments on nFY/decay data

- Each major library contains different sets of nuclides within decay sub-libraries, nFY and sFY

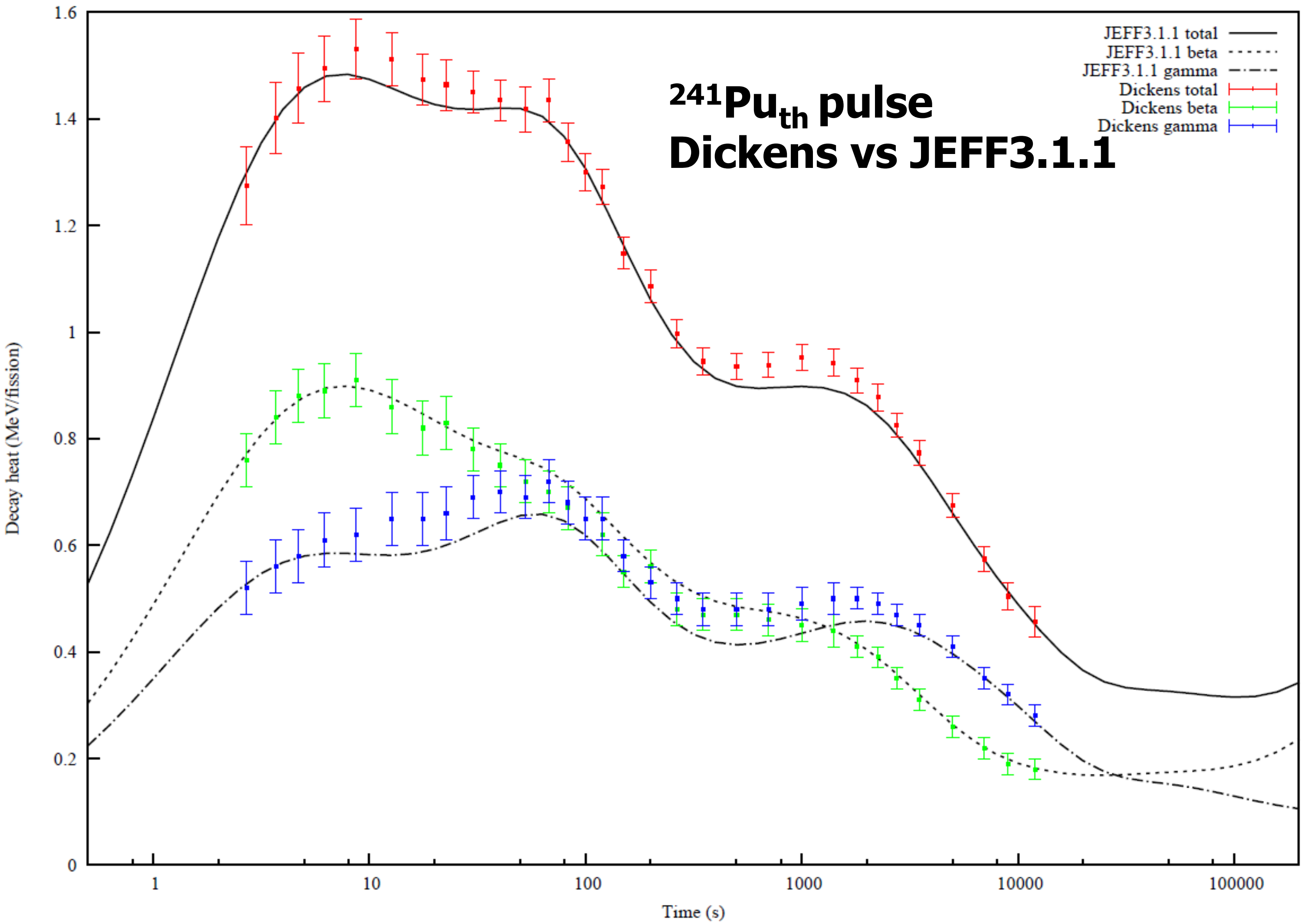
	ENDF/B-VII.1	JENDL-4.0	JEFF γ
Decay data	3821	**1285**	3851
nFY	31	31	**19**
sFY	9	9	**3**

- nFY is function of incident neutron energy
  - Number of bins and placement chosen for simple applications
  - 3 nFY incident-energies ***will not be sufficient*** for more demanding analysis
- How do we obtain high-fidelity fine-grid nFY(E)??

Comments on subsequent calcluations

- nFY in calculations are cumulative over 1ms pulse and thermal with mono-energetic 0.025 eV
- To focus on decays **all nFY data here = JEFF3.1.1 nFY**
- Calculations employ cumulative fission yields and are *necessarily "contaminated" with the decay data used*
- Small differences in decays of precursors can dramatically affect longer-term decays and heat
- **Future work**: will consider single fission event calculations to probe short timescale affects not possible in cumulative

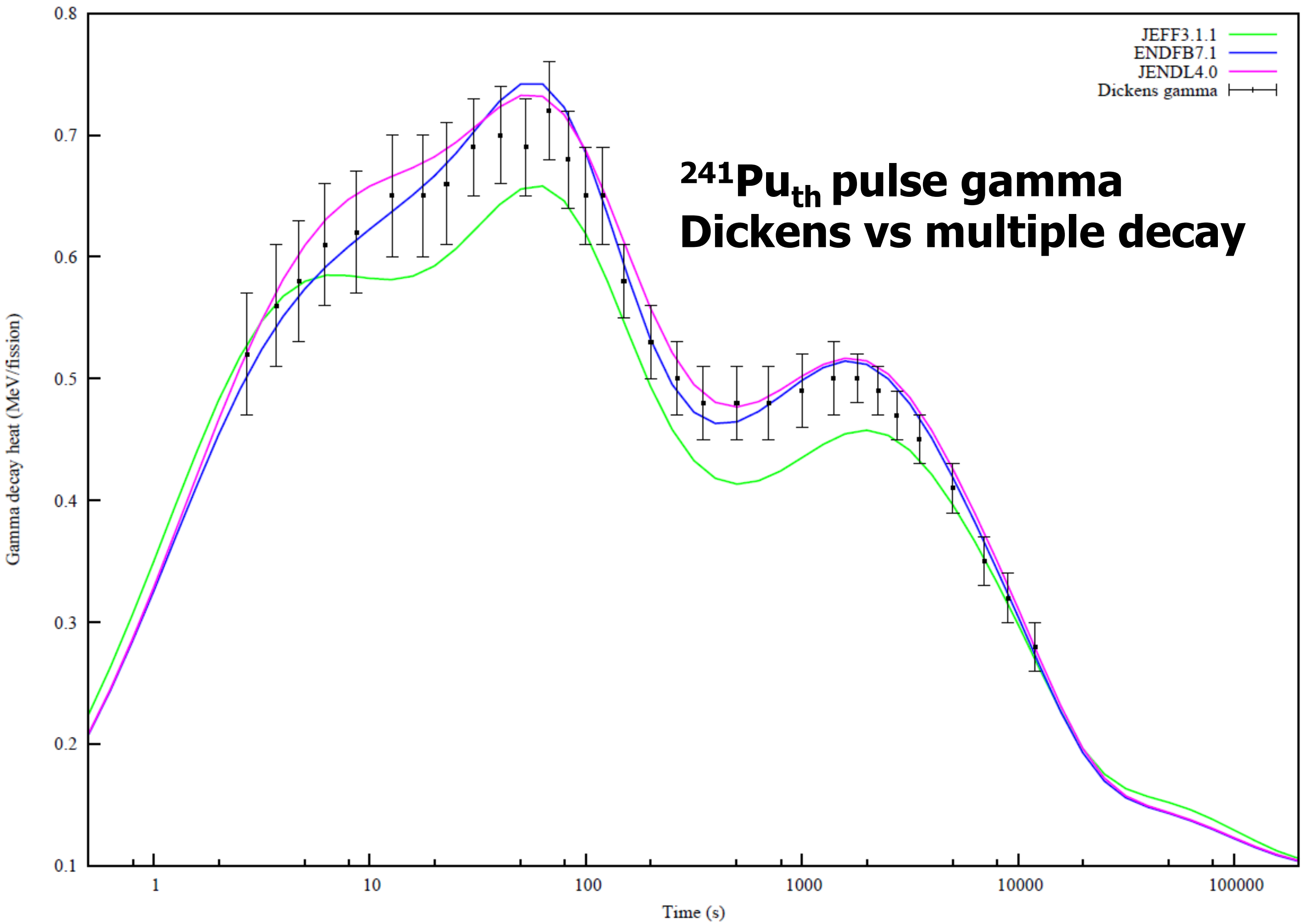
Decay heat following a pulse of thermal neutrons



- All measurements shown. Under-estimation of gammas consistently
- Potential contamination from capture events and chain fissile decays!!

Comparison of decay libraries

- Better agreement with JENDL-4 and ENDF/B-VII for **gamma**



Dominant nuclide heat production for $^{241}Pu_{th}$

- Below are the dominant nuclides and their ***gamma*** heat contribution at 250s after pulse for $^{241}Pu_{th}$ in kW (normalised relative to ENDF/B-VII)
- The Tc nuclides are very different for JEFF-3.1.1dd!
- Non-negligible Cs140 and Sb133 increases for JENDL

Nuclide	ENDF/B-VII.1	Nuclide	JENDL-4.0	Nuclide	JEFF3.2/3.1.1
Tc105	**21.4**	**Tc105**	**21.5**	**Sb133**	**16.9**
Tc104	**18.5**	**Sb133**	**21.2**	I136	15.8
Sb133	**16.7**	**Tc104**	**18.5**	Sb132	14.3
I136	15.7	**Cs140**	**16.7**	**Cs140**	**12.6**
Sb132	14.3	I136	15.6	Sr93	11.0
Cs140	**14.1**	Sb132	14.9	**Tc104**	**10.8**
Sr93	10.8	Tc103	10.9	⋮	⋮
Pr148	10.4	Sr93	10.0	**Tc105**	**7.9**

Dominant nuclide heat production for $^{241}Pu_{th}$

- Below are the dominant nuclides and their ***beta*** heat contribution at 250s after pulse for $^{241}Pu_{th}$ in kW
- Sb133 beta same while gamma different for JENDL?
- Tc differences reflected in beta as well

Nuclide	ENDF/B-VII.1	Nuclide	JENDL-4.0	Nuclide	JEFF3.2/3.1.1
Xe137	25.9	Xe137	25.9	Xe137	25.9
Tc103	**19.3**	Rh108	19.1	**Tc103**	**19.3**
Rh108	18.5	Tc102	15.5	Rh108	18.6
Tc102	15.6	Cs139	15.1	Tc102	15.6
Cs139	15.2	**Tc103**	**13.8**	**Tc105**	**15.4**
⋮	⋮	⋮	⋮	Cs139	15.2
Tc105	**9.0**	**Tc105**	**8.4**	⋮	⋮
Tc104	**5.3**	**Tc104**	**4.9**	**Tc104**	**9.2**
Sb133	**5.3**	**Sb133**	**5.1**	**Sb133**	**5.1**

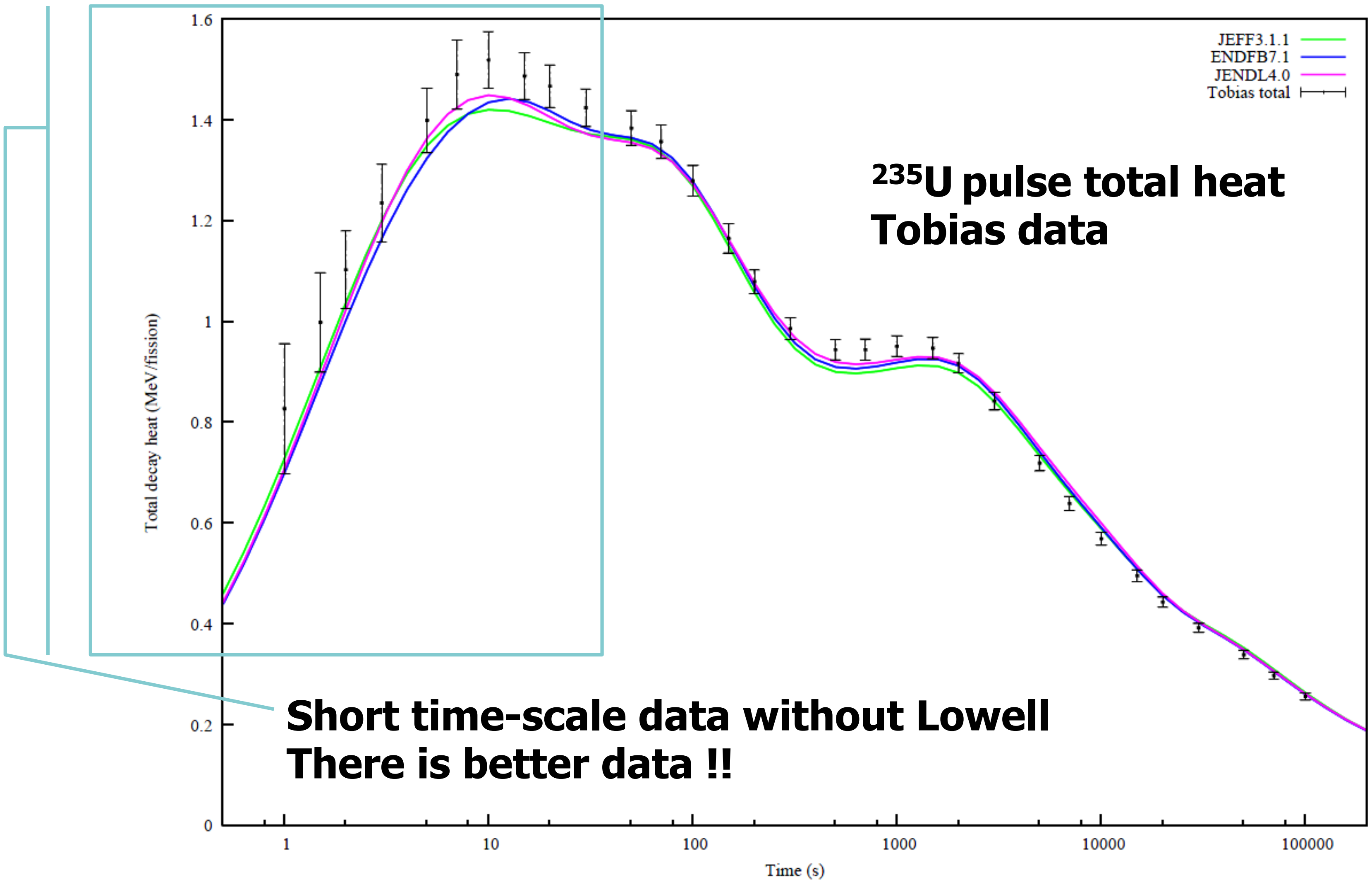
Dominant nuclide heat production for $^{241}Pu_{th}$

- 250s after pulse for $^{241}Pu_{th}$ in kW (x10 vs previous slides)
- Typically gamma +/- is reflected in beta -/+ ***but not all!***
- Total should add, but sometimes do not
- The more nuclides considered, the more differences found!

Nuclide	ENDF γ	JENDL γ	JEFF γ	ENDF β	JENDL β	JEFF β
Pr148	104	**72.5**	104	75.1	**98.9**	79.1
Mo103	81.3	93.6	**53.2**	97.4	92.9	**110**
Rb90	**84.8**	70.5	74.1	71.1	64.9	62.5
Ce145	76.5	89.9	**52.2**	53.4	46.5	66.2
Tc103	48.8	**109**	48.9	193	**138**	193
Nb99m	30.5	**82.4**	31.2	66.0	56.8	68.0
La144	66.7	**46.3**	65.3	21.6	**27.0**	20.9
La143	20.1	**12.5**	21.0	58.2	**71.2**	59.0
Rb90m	**18.4**	28.8	34.3	**5.32**	12.5	9.93

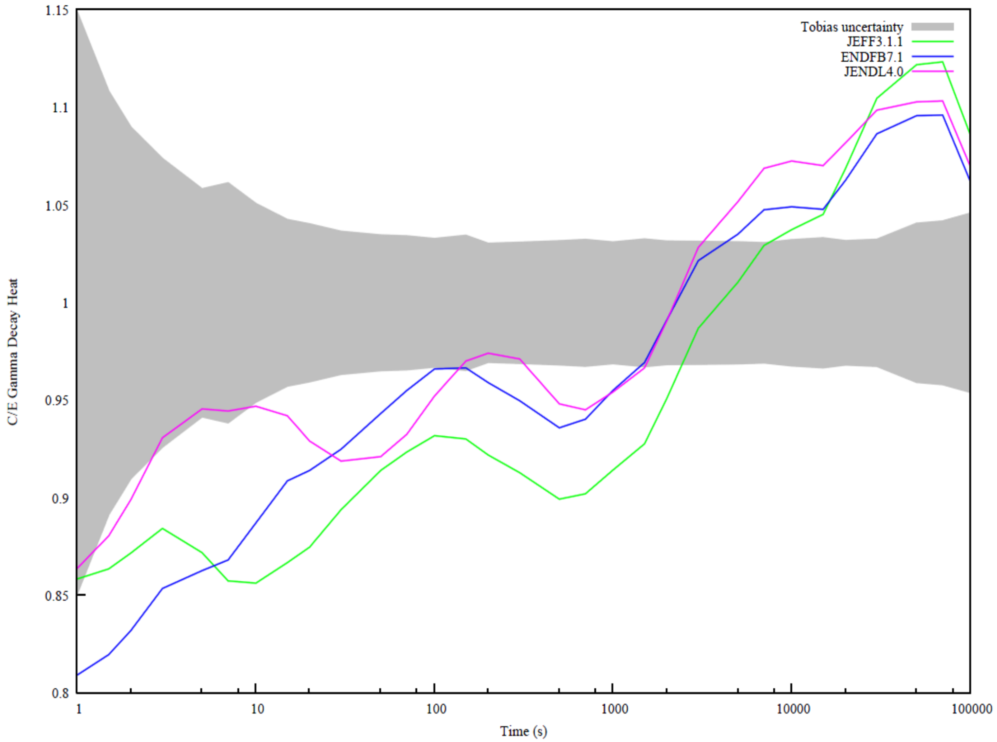
Example: U235 thermal pulse

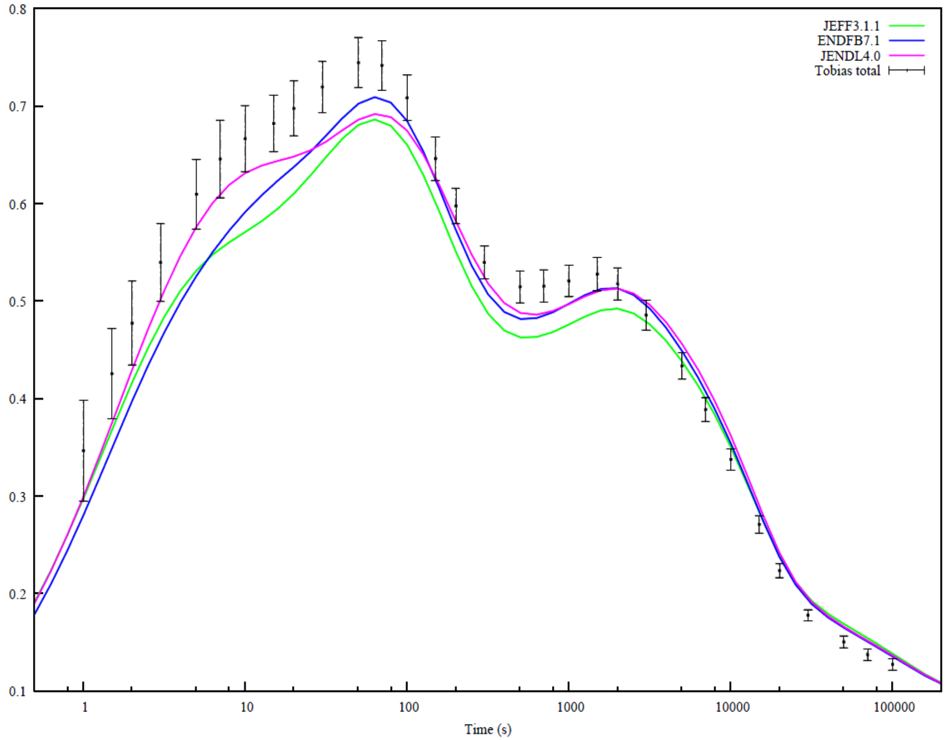
- Compared against Tobias U235 thermal pulse compilation



U235 thermal gamma C/E vs Tobias

- Comparison with gamma heat shows clear discrepancies
- ***Nota bene*** No Lowell data in Tobias for short time-scales, Tobias overestimates below 100s
- <20 s Generally larger uncertainties with fewer measurements and more corrections/modifications





Dominant nuclide heat production for $^{235}U_{th}$

- C/C comparisons
- Below are the dominant nuclides and their ***gamma*** heat contribution at 4s after pulse for $^{235}U_{th}$ in kW
- JENDL Rb94, Y96, Nb102m ↔ Nb102 (all have both)

Nuclide	ENDF/B-VII.1	Nuclide	JENDL-4.0	Nuclide	JEFF3.2/3.1.1
Rb92	**80.4**	**Rb92**	**80.5**	**Rb92**	**65.4**
Rb93	61.6	Rb93	55.4	Rb93	63.8
Zr99	46.5	**Rb94**	**47.2**	**Nb102**	**60.6**
Y98m	43.8	Zr99	46.3	Y98m	52.7
Nb102	**40.9**	Y98m	43.8	Zr99	46.3
Y97m	34.7	**Y96**	**43.4**	**Rb94**	**35.4**
⋮	⋮	Y97	42.2	Y97m	34.4
Rb94	**24.5**	**Nb102m**	**36.8**	⋮	⋮
Nb102m	**14.6**	⋮	⋮	**Nb102m**	**16.8**
Y96	**2.8**	**Nb102**	**16.8**	**Y96**	**2.9**

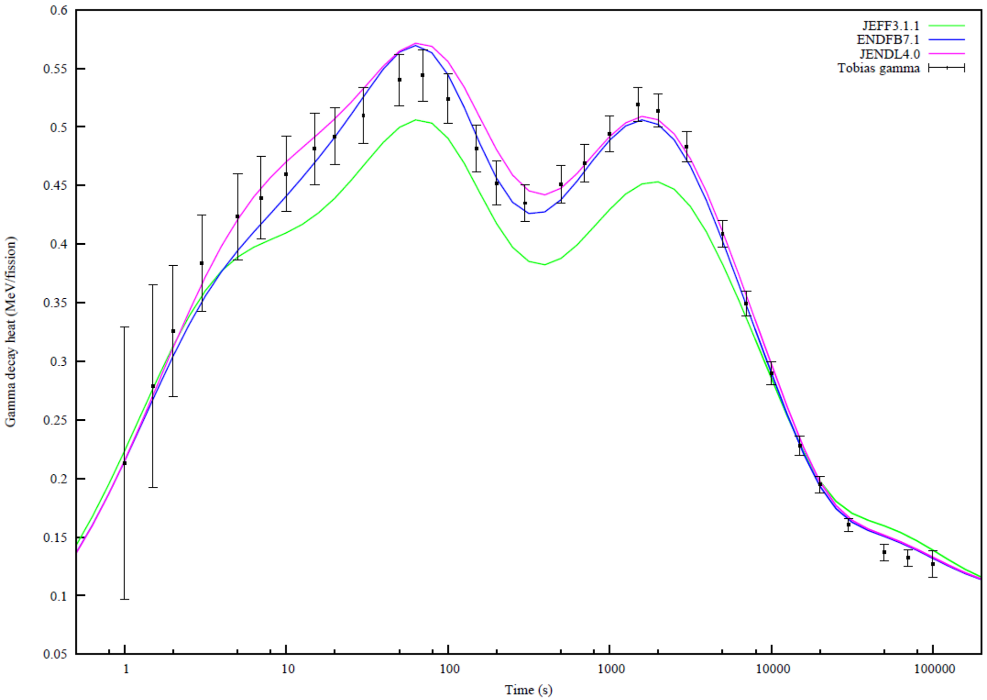
Dominant nuclide heat production for $^{235}U_{th}$

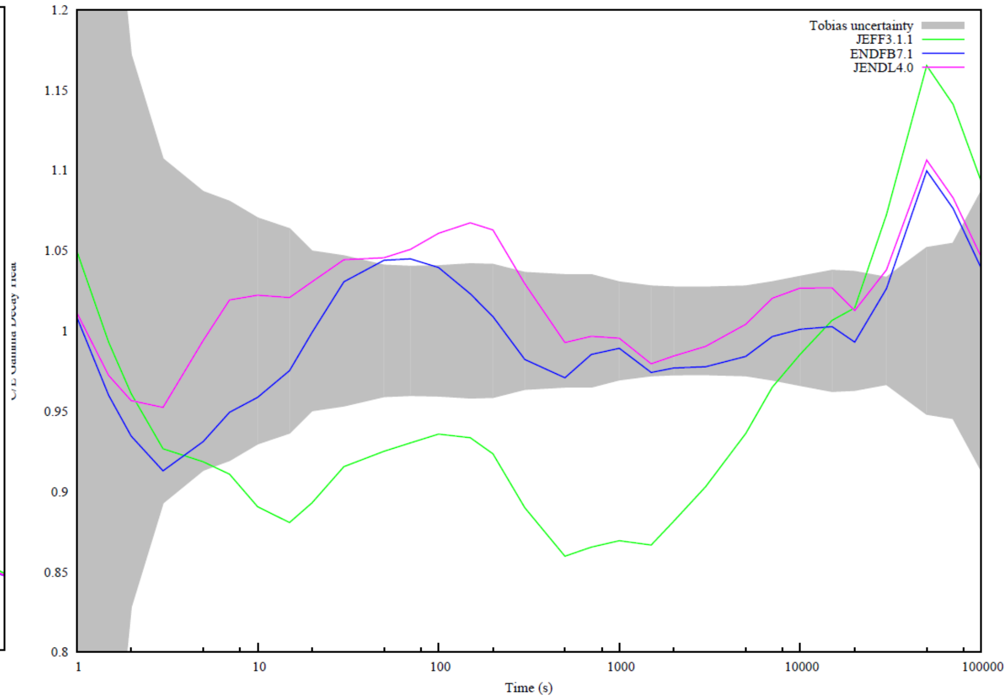
- Below are the dominant nuclides and their ***beta*** heat contribution at 4s after pulse for $^{235}U_{th}$ in kW
- JENDL: Y96 reallocated to gamma and Nb102(m) switch
- Rb94 differences but suspiciously little Rb92 difference

Nuclide	ENDF/B-VII.1	Nuclide	JENDL-4.0	Nuclide	JEFF3.2/3.1.1
Y96	**116**	**Rb92**	**109**	**Y96**	**118**
Rb92	**107**	**Y96**	**95.8**	**Rb92**	**107**
Zr99	89.2	Zr99	93.8	Zr99	84.6
Nb100	84.9	Nb100	82.8	Nb100	82.9
Cs142	71.0	**Nb102m**	**71.4**	Cs142	70.6
Zr101	61.5	Cs142	70.6	Zr101	61.5
⋮	⋮	Zr101	62.5	**Nb102**	**60.6**
Nb102	**45.0**	⋮	⋮	⋮	⋮
Rb94	**26.1**	**Rb94**	**35.0**	**Rb94**	**40.0**
Nb102m	**14.6**	**Nb102**	**18.3**	**Nb102m**	**18.3**

Pu239 thermal gamma C/E vs Tobias

- Comparison with gamma shows clear discrepancies
- ***Nota bene*** again no Lowell data included in Tobias
- Better simulation with TAGS results, recently added in JENDL 4.0 and ENDF/B-VII.1, not JEFF-3.1.1 decay files !!





Dominant nuclide heat production for $^{239}Pu_{th}$

- Below are the dominant nuclides and their ***gamma*** heat contribution at 800s after pulse for $^{239}Pu_{th}$ in kW
- Again Tc 104/5 different feeding for JEFF-3.1.1
- Sr93 jumps by 30% between ENDF and JENDL

Nuclide	ENDF/B-VII.1	Nuclide	JENDL-4.0	Nuclide	JEFF3.2/3.1.1
Tc104	**93.8**	**Tc104**	**93.8**	**Tc104**	**54.9**
Tc105	**59.5**	**Tc105**	**59.6**	**Sr93**	**44.6**
Mo101	44.5	Mo101	45.9	Mo101	44.5
Sr93	**53.6**	**Sr93**	**40.6**	Y95	29.5
Y95	33.1	Y95	30.0	Xe138	28.7
Xe138	28.8	Xe138	28.8	Cs138	26.9
Cs138	27.0	Cs138	27.0	Ba142	26.7
Ba142	26.7	Ba142	26.5	**Tc105**	**21.8**

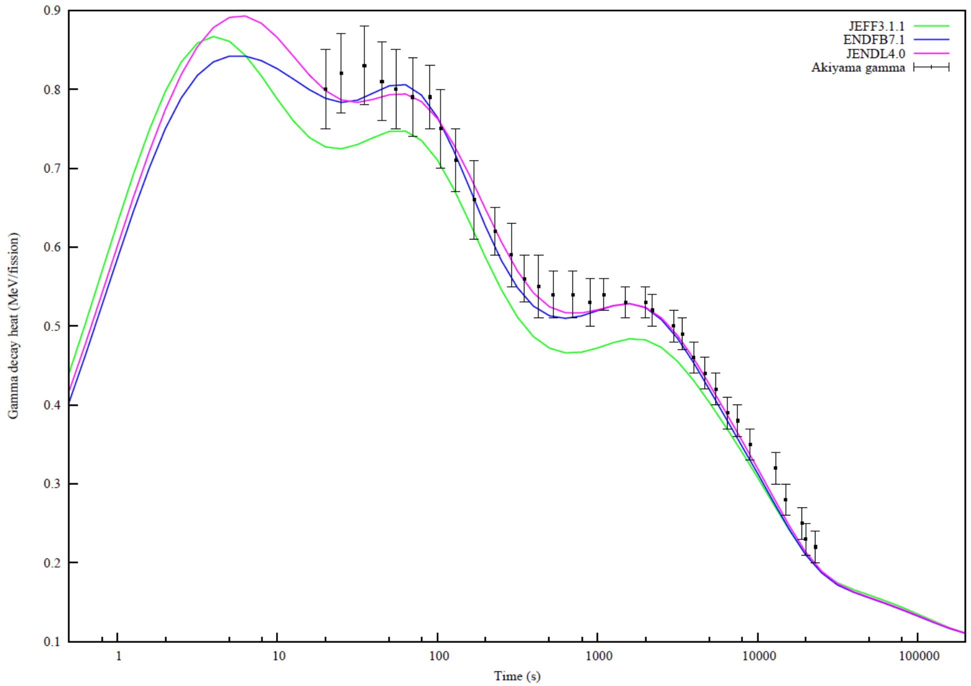
Dominant nuclide heat production for $^{239}Pu_{th}$

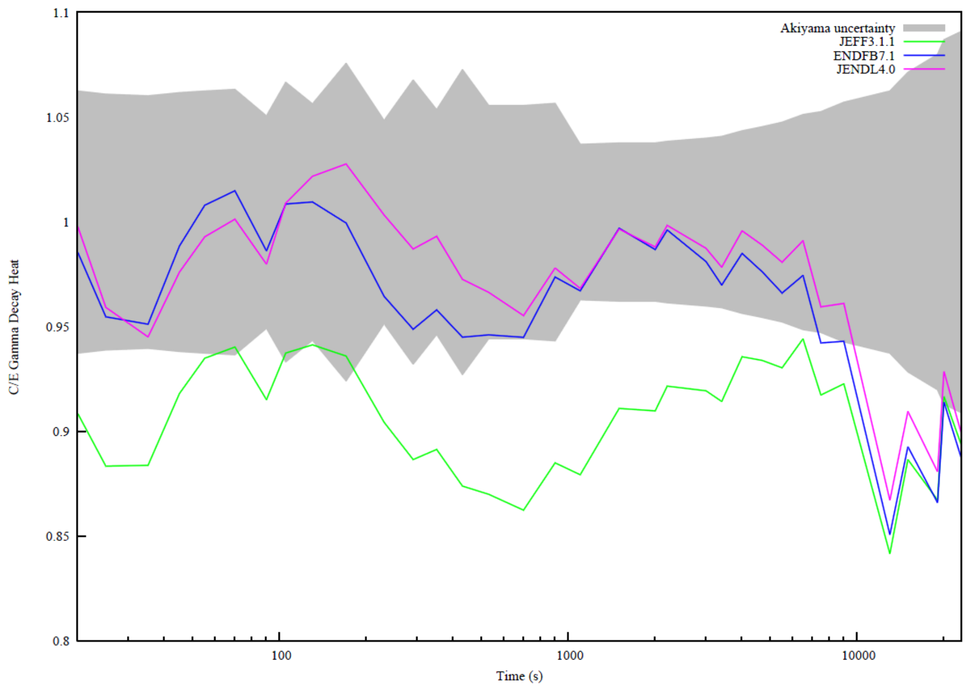
- Below are the dominant nuclides nuclides and their ***beta*** heat contribution at 800s after pulse for $^{239}Pu_{th}$ in kW
- Tc differences reflected in beta
- Suspiciously little difference in Sr93 beta, given gamma

Nuclide	ENDF/B-VII.1	Nuclide	JENDL-4.0	Nuclide	JEFF3.2/3.1.1
Tc102	64.3	Tc102	63.8	Tc102	64.2
Cs139	54.8	Cs139	54.6	Cs139	55.0
Y95	37.4	Y95	38.9	**Tc104**	**46.3**
Y94	37.2	Y94	37.1	**Tc105**	**42.6**
Tc104	**27.0**	**Tc104**	**24.7**	Y95	38.9
Tc105	**24.9**	**Tc105**	**23.3**	Y94	37.2
⋮	⋮	⋮	⋮	⋮	⋮
Sr93	**15.9**	**Sr93**	**15.5**	**Sr93**	**16.0**

Decay heat following a pulse of fast neutrons

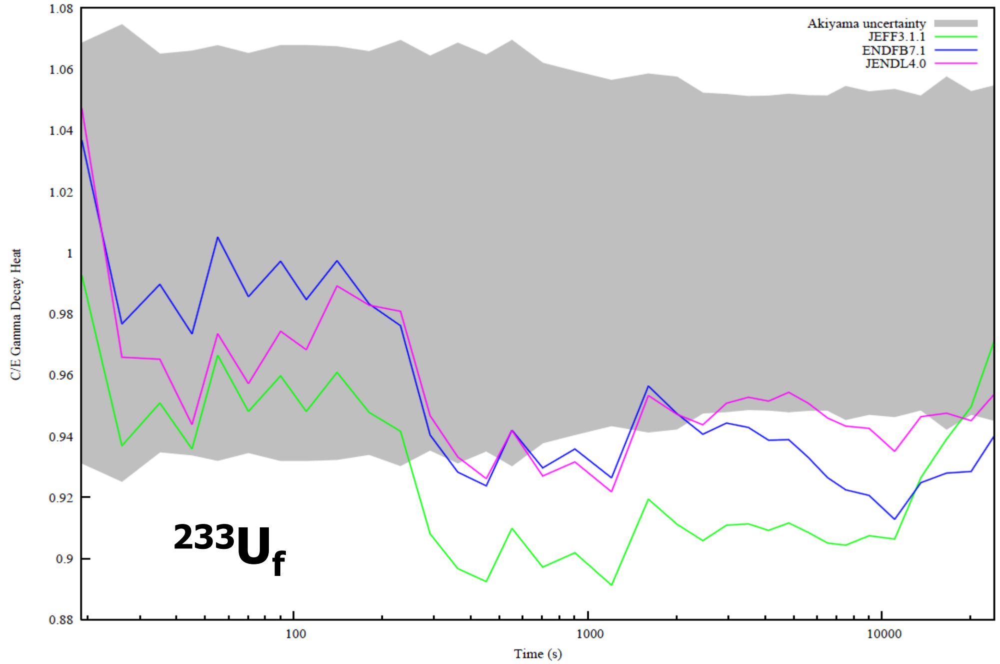
- All fast fission results from YAYOI reactor by Akiyama *et al*
- Simulation using 400 keV pulse to access fast fission nFY
- Below are MeV/fission of $^{238}U_f$ **pulse gamma** and C/E
- Discrepancies after ~2 hours (~1E4s) may be outside error?
  - No TAGS made for this time-period

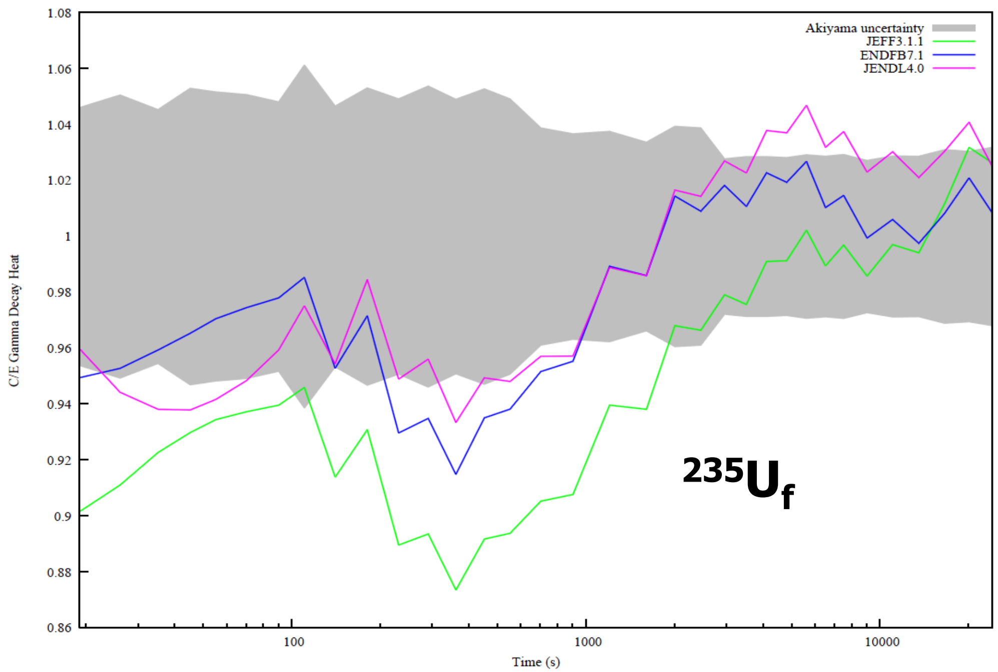


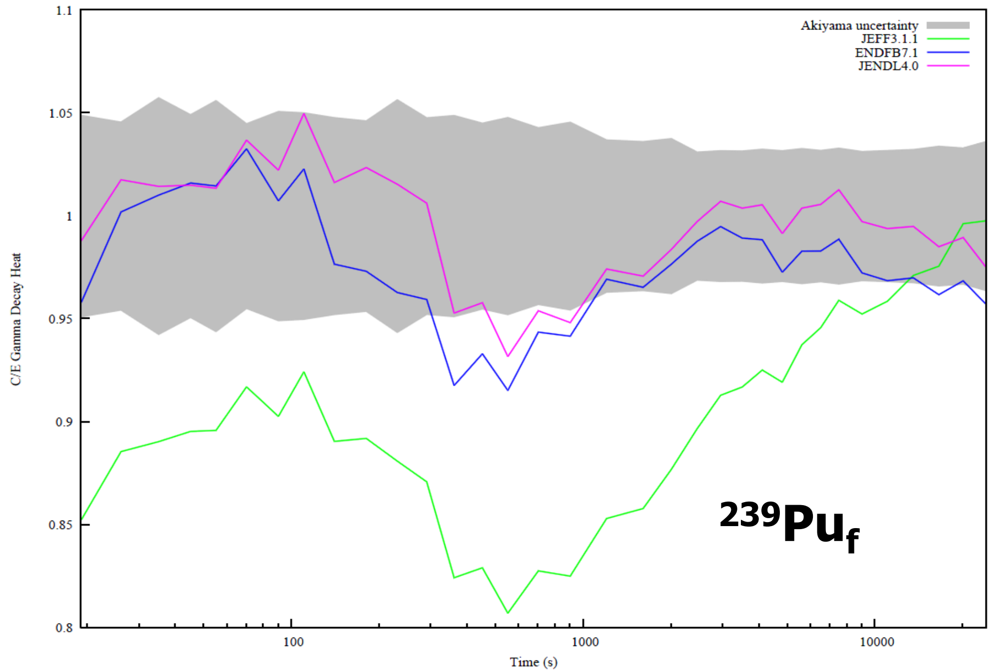


Gamma discrepancies in fast fission vs Akiyama

- These are **gamma** C/E
- Other fast fission data shows similar disagreements
- Mainly due to beta/gamma (mis)allocation
- JEFF-3.1.1dd missing TAGS







Comments on fission decay heat

- Decay data application (nuclear fuel) responsible for purposeful and systematic overestimation in *e.g.* ANSI/ ANS-5.1
- Discrepancies between simulations with different dd show data is not accurate enough for sophisticated applications
- Uncanny agreement in γ, β and total heat values where individual nuclide contributions are substantially different
- Cumulative nFY should be re-examined to ensure no contamination with incomplete decay data
- Decay heat experiments are filled with complexity and care must be taken when making comparisons with simulations

EASY-II enhanced physics

- FISPACT-II capabilities:
  - Can calculate based on arbitrary pulses and longer irradiations
  - Any ENDF-6 formatted library can be used for calculations
  - Full uncertainty treatment – if given by the data
  - Handles arbitrary combination of nFY and sFY, DD
  - Tracking heat contributions and pathways for nuclide production
- EASY-II with TENDL (or other capable library) has the ability to use fission yields of arbitrary incident neutron energy
  - Potentially required for correct beta feeding (and emitted neutrino spectrum)

Questions

- Are decay files ‘evaluated’ averages or are the averages calculated from the decay schemes??

- Appropriate decay scheme
- How to account and compensate for missing levels
- Decay data for isomers?

- High energy gamma lines transport further
- Low energy beta equates high energy anti-neutrino
- Missing gamma lines impact on doses

EASY-II platform

21st century multi-particle/system inventory code package for stockpile, fuel cycle stewardship, source terms, materials characterization and life cycle management for:

- Magnetic and inertial confinement fusion
- Fission Gen II, III+, IV plants and piles
- High energy and accelerator physics
- Medical applications, isotope production
- Earth exploration, Astrophysics
- Homeland security, material sciences
- ….
- Able to access rich, multifaceted nuclear data forms and their uncertainties.

http://www.ccfe.ac.uk/EASY.aspx