Spettri beta da reattore in JUNO-TAO: ciclo di incontri...

- venerdì 21 maggio - ore 16-17

Spettri di antineutrini da rettore (Fabio Mantovani)

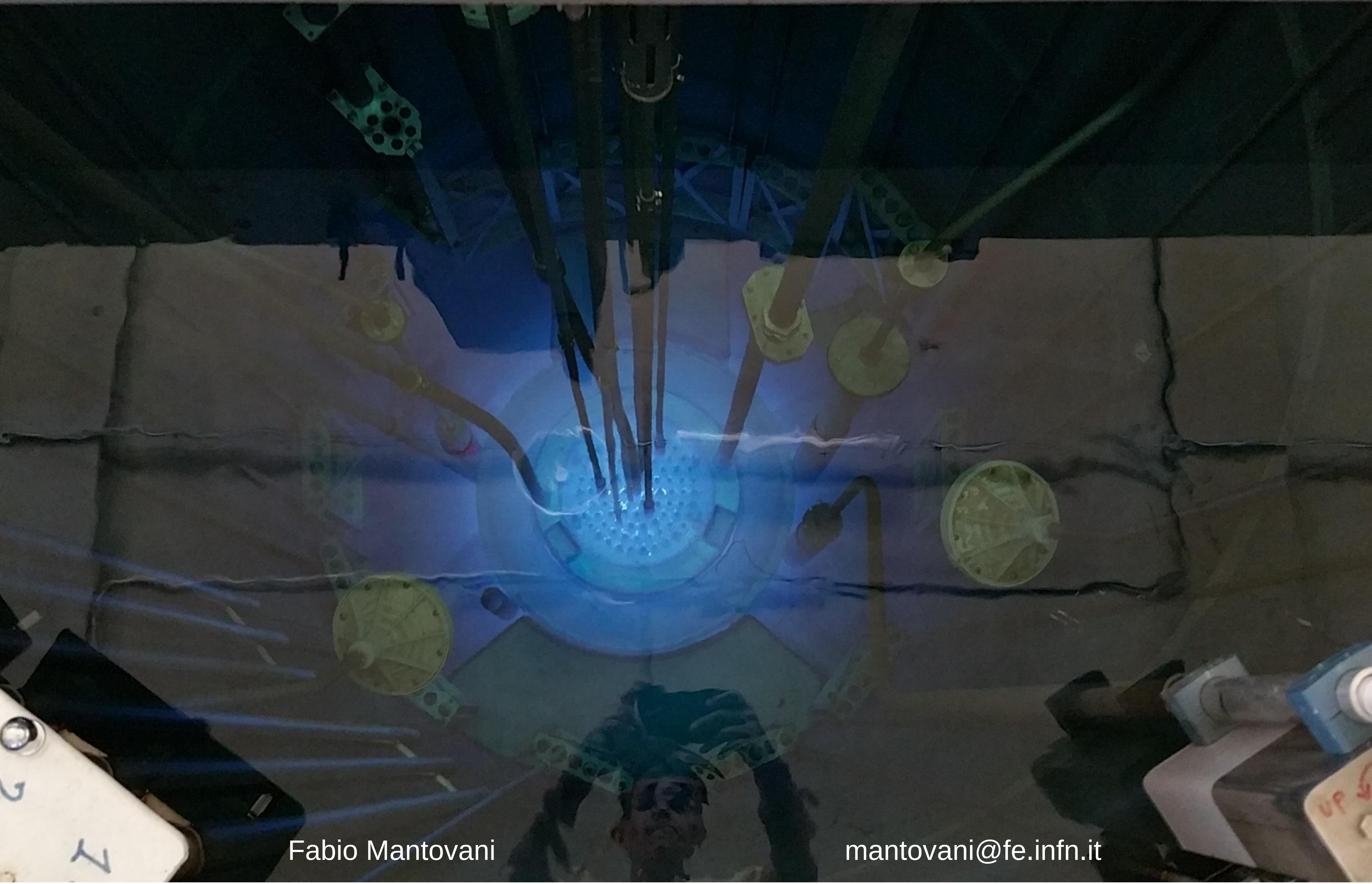
- giovedì 27 maggio - ore 16-17

Probabilità di oscillazione in JUNO (Eligio Lisi)

- giovedì 3 giugno - ore 16-17

Struttura fine dello spettro visibile in TAO (Eligio Lisi)

Spettri di antineutrini da rettore



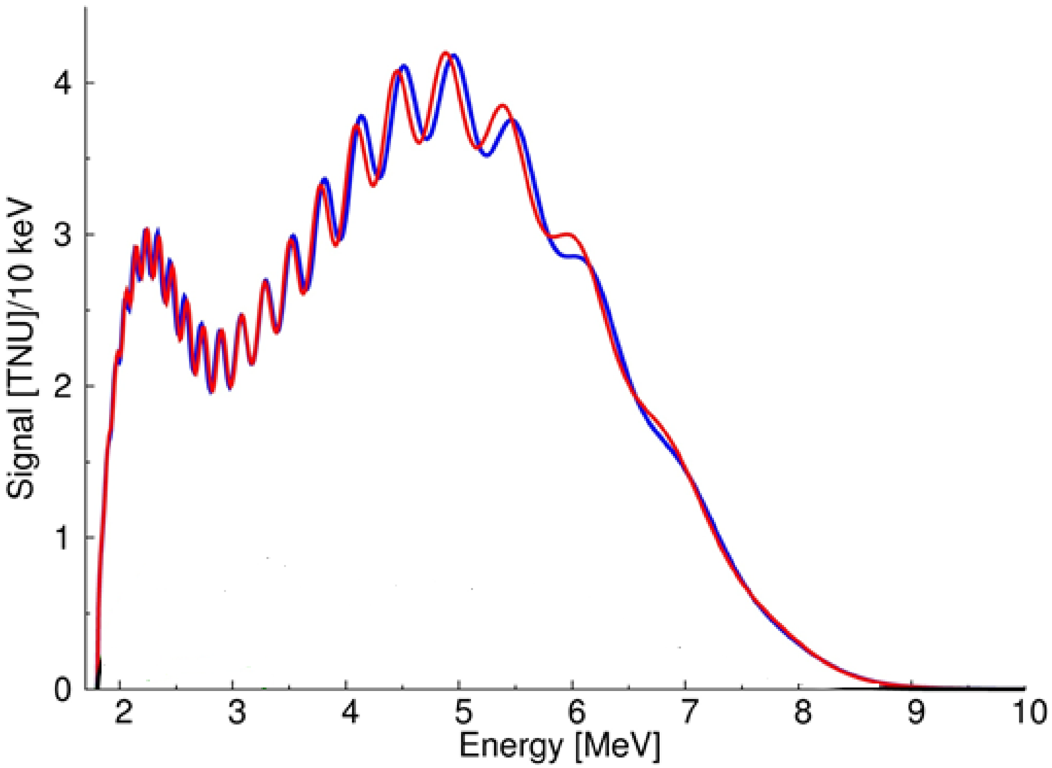
Fabio Mantovani mantovani@fe.infn.it


…guardiamoci dentro!

Orientiamoci...

R_{ON} **Normal Hierarchy**

R_{ON} **Inverse Hierarchy**



Reactor antineutrino signal calculation

The reactor antineutrino signal evaluation requires several ingredients for modeling the three antineutrino life stages:

- ✓ **production** at reactor cores
- ✓ **propagation** to the detector site
- ✓ **detection** in liquid scintillation detectors

DETECTOR

- ε = 100% efficiency
- τ = 1 year
- $N_p = 10^{32}$ free protons (~ 1kton liquid scintillator mass)

ν PHYSICS

- P_{ee} = ν_e oscillation survival probability
- $\sigma_{IBD}(E)$ = IBD cross section

$\bar{\nu}_e + p \rightarrow e^+ + n$ (E_{th} = 1.806 MeV)

$$N_{TOT} = \varepsilon N_p \tau \sum_{k=1}^{N_{reactor}} \frac{P_k}{4\pi d_k^2} \langle LF_k \rangle \int dE_\nu \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda_i(E_\nu)\, P_{ee}(E_\nu, d_k) \sigma_{IBD}(E_\nu)$$

[1 TNU = 1 event / 10^{32} free protons /year]

i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

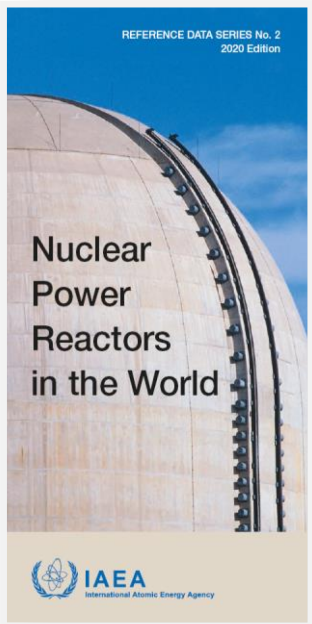
REACTOR

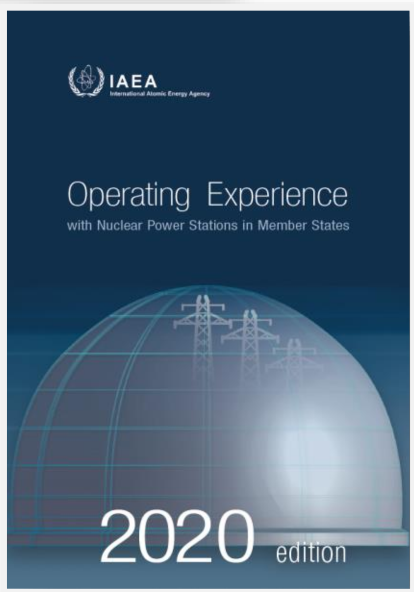
- d_k = reactor distance
- P_k = thermal power
- *LF* = Load Factor
- p_i = power fraction

NUCLEAR

- Q_i = energy released per fission
- λ_i = reactor antineutrino spectrum

Reattori nel mondo: fonti utili…





Laboratory for Nuclear Technologies
Applied to the Environment

HOME ACTIVITIES DOWNLOADS PUBLICATIONS PEOPLE JOIN US! NEWS

2003	2004	2005	2006
Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map
2007	**2008**	**2009**	**2010**
Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map
2011	**2012**	**2013**	**2014**
Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map
2015	**2016**	**2017 ***	**2018**
Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map	Input database Numerical map Map
2019			
Input database Numerical map Map			

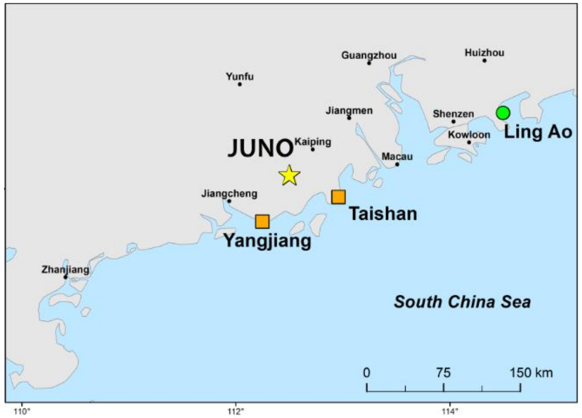
- ✓ **Global**: performance data of **all reactors in the world**
- ✓ **Monthly Load Factors** (%)
- ✓ **Public, official** and **free**
- ✓ **Latitude** and **longitude** of reactors
- ✓ **Multitemporal**: time lapse of **18 years** (2003 – 2021)
- ✓ **Direct implementation** thanks to standard file (ASCII, Excel)

https://www.fe.infn.it/radioactivity/antineutrino/

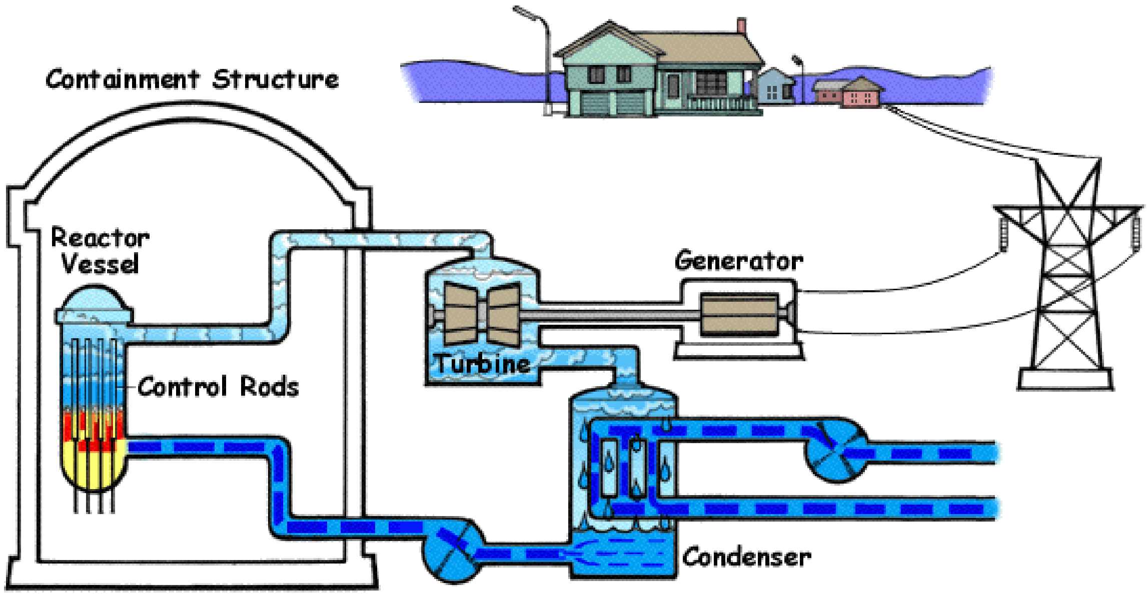
Taishan – Yangjiang – Operational 31 dec 2019

Country	Reactor Code	Reactor Name	Type	Model	Capacity (MW) Thermal	Gross	Net	Operator	NSSS supplier	Construction start	Grid connection	Commercial operation
CHINA	CN -6	LING AO-1	PWR	M310	2905	990	950	DNMC	FRAM	1997-5	2002-2	2002-5
	CN -7	LING AO-2	PWR	M310	2905	990	950	DNMC	FRAM	1997-11	2002-9	2003-1
	CN -12	LING AO-3	PWR	CPR-1000	2905	1086	1007	DNMC	DEC	2005-12	2010-7	2010-9
	CN -13	LING AO-4	PWR	CPR-1000	2905	1086	1007	DNMC	DEC	2006-6	2011-5	2011-8
	CN -18	NINGDE-1	PWR	CPR-1000	2905	1089	1018	NDNP	DEC	2008-2	2012-12	2013-4
	CN -19	NINGDE-2	PWR	CPR-1000	2905	1089	1018	NDNP	SHE	2008-11	2014-1	2014-5
	CN -34	NINGDE-3	PWR	CPR-1000	2905	1089	1018	NDNP	CFHI	2010-1	2015-3	2015-6
	CN -35	NINGDE-4	PWR	CPR-1000	2905	1089	1018	NDNP	CFHI	2010-9	2016-3	2016-7
	CN -4	QINSHAN 2-1	PWR	CNP-600	1930	650	610	NPQJVC	CNNC	1996-6	2002-2	2002-4
	CN -5	QINSHAN 2-2	PWR	CNP-600	1930	650	610	NPQJVC	CNNC	1997-4	2004-3	2004-5
	CN -14	QINSHAN 2-3	PWR	CNP-600	1930	660	619	NPQJVC	CNNC	2006-4	2010-8	2010-10
	CN -15	QINSHAN 2-4	PWR	CNP-600	1930	660	619	NPQJVC	CNNC	2007-1	2011-11	2011-12
	CN -8	QINSHAN 3-1	PHWR	CANDU 6	2064	728	677	TQNPC	AECL	1998-6	2002-11	2002-12
	CN -9	QINSHAN 3-2	PHWR	CANDU 6	2064	728	677	TQNPC	AECL	1998-9	2003-6	2003-7
	CN -1	QINSHAN-1	PWR	CNP-300	966	330	298	CNNO	CNNC	1985-3	1991-12	1994-4
	CN -28	SANMEN-1	PWR	AP-1000	3400	1251	1157	SMNPC	WH/MHI	2009-4	2018-6	2018-9
	CN -29	SANMEN-2	PWR	AP-1000	3400	1251	1157	SMNPC	WH/MHI	2009-12	2018-8	2018-11
	CN -32	TAISHAN-1	PWR	EPR-1750	4590	1750	1660	TNPJVC	AREVA	2009-11	2018-6	2018-12
	CN -33	TAISHAN-2	PWR	EPR-1750	4590	1750	1660	TNPJVC	AREVA	2010-4	2019-6	—
	CN -10	TIANWAN-1	PWR	VVER V-428	3000	1060	990	JNPC	IZ	1999-10	2006-5	2007-5
	CN -11	TIANWAN-2	PWR	VVER V-428	3000	1060	990	JNPC	IZ	2000-9	2007-5	2007-8
	CN -45	TIANWAN-3	PWR	VVER V-428M	3000	1126	1045	JNPC	IZ	2012-12	2017-12	2018-2
	CN -46	TIANWAN-4	PWR	VVER V-428M	3000	1126	1045	JNPC	IZ	2013-9	2018-10	2018-12
	CN -22	YANGJIANG-1	PWR	CPR-1000	2905	1086	1000	YJNPC	CFHI	2008-12	2013-12	2014-3
	CN -23	YANGJIANG-2	PWR	CPR-1000	2905	1086	1000	YJNPC	CFHI	2009-6	2015-3	2015-6
	CN -40	YANGJIANG-3	PWR	CPR-1000	2905	1086	1000	YJNPC	CFHI	2010-11	2015-10	2016-1
	CN -41	YANGJIANG-4	PWR	CPR-1000	2905	1086	1000	YJNPC	CFHI	2012-11	2017-1	2017-3
	CN -47	YANGJIANG-5	PWR	ACPR-1000	2905	1086	1000	YJNPC	CFHI	2013-9	2018-5	2018-7
	CN -48	YANGJIANG-6	PWR	ACPR-1000	2905	1086	1000	YJNPC	CFHI	2013-12	2019-6	2019-7

- EPR: European Pressurized Reactor - III gen. pressurised water reactor design – Framatome (Areva)
- CPR: Chinese Pressurized Reactor – Gen. II+ pressurized water reactor
- ACPR: Advanced Chinese Pressurised Reactor - Gen. II+ pressurized water reactor

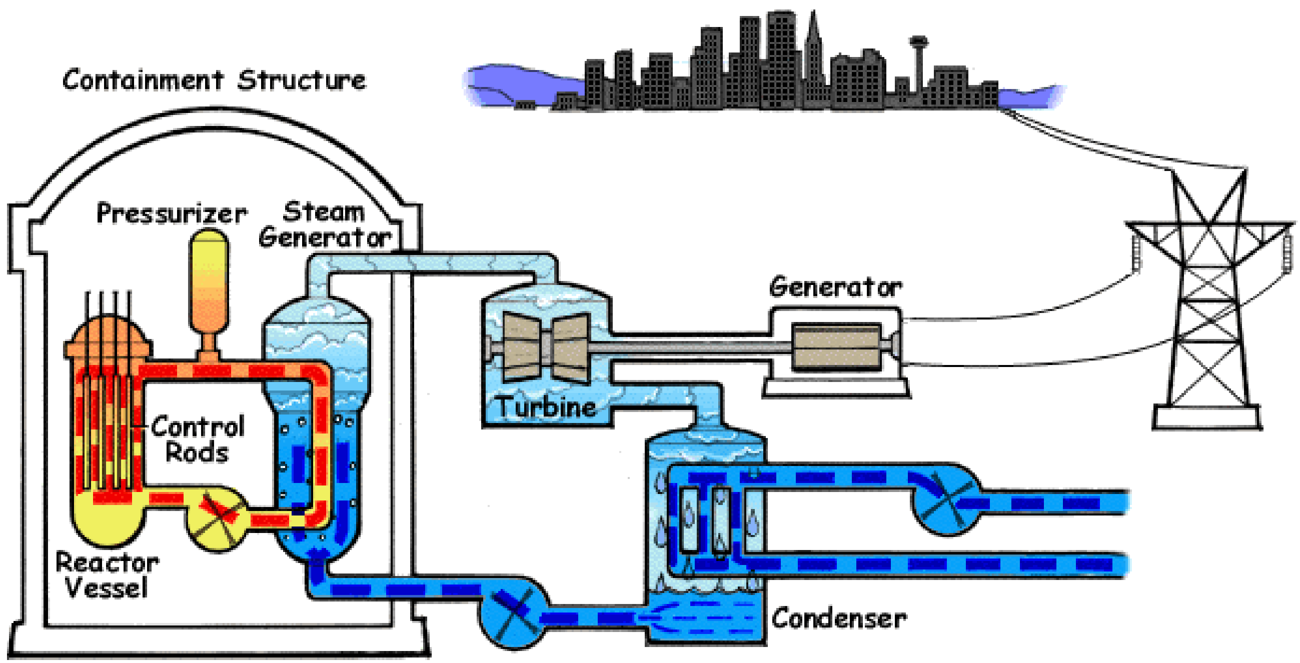


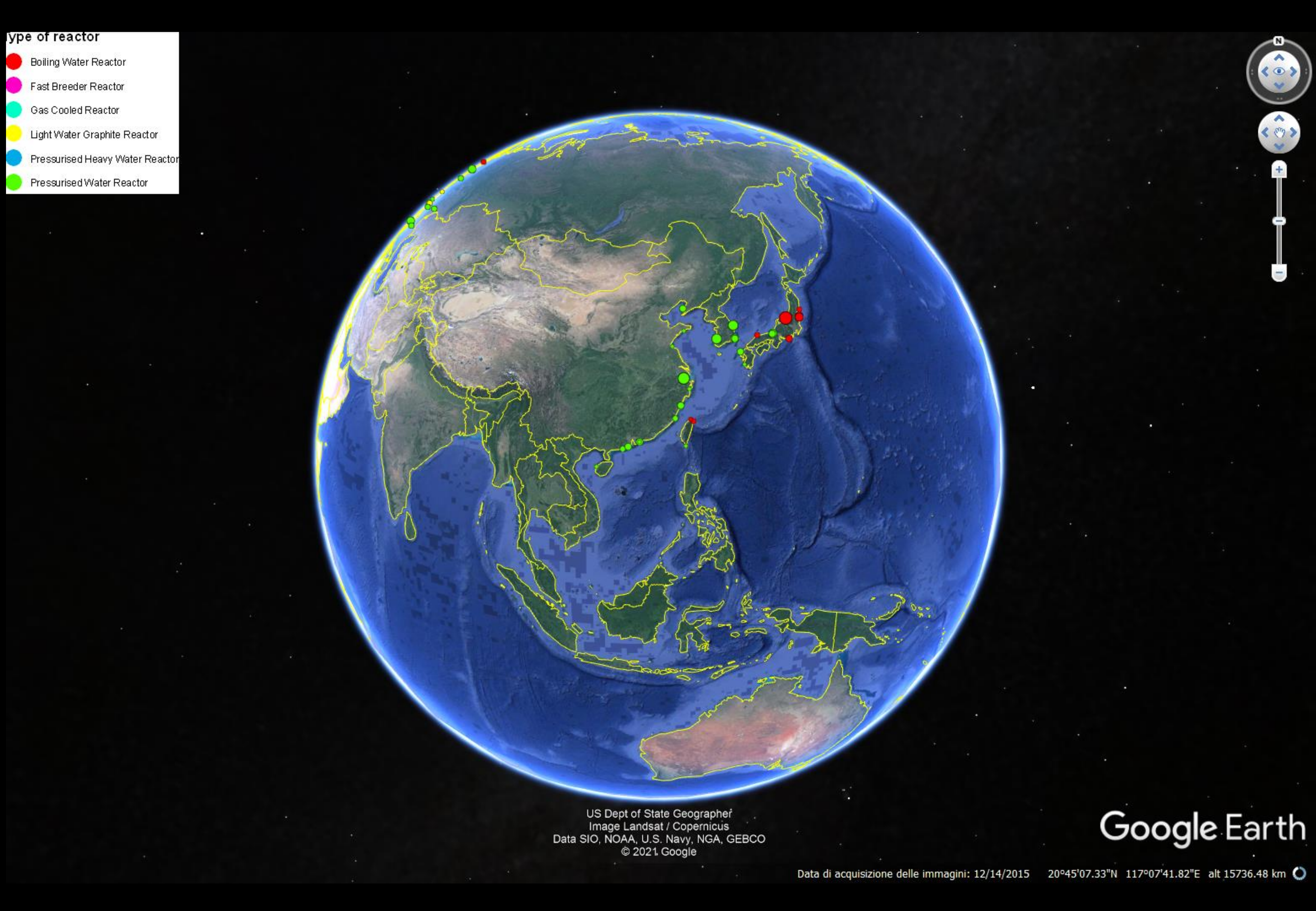
BWR and PWR



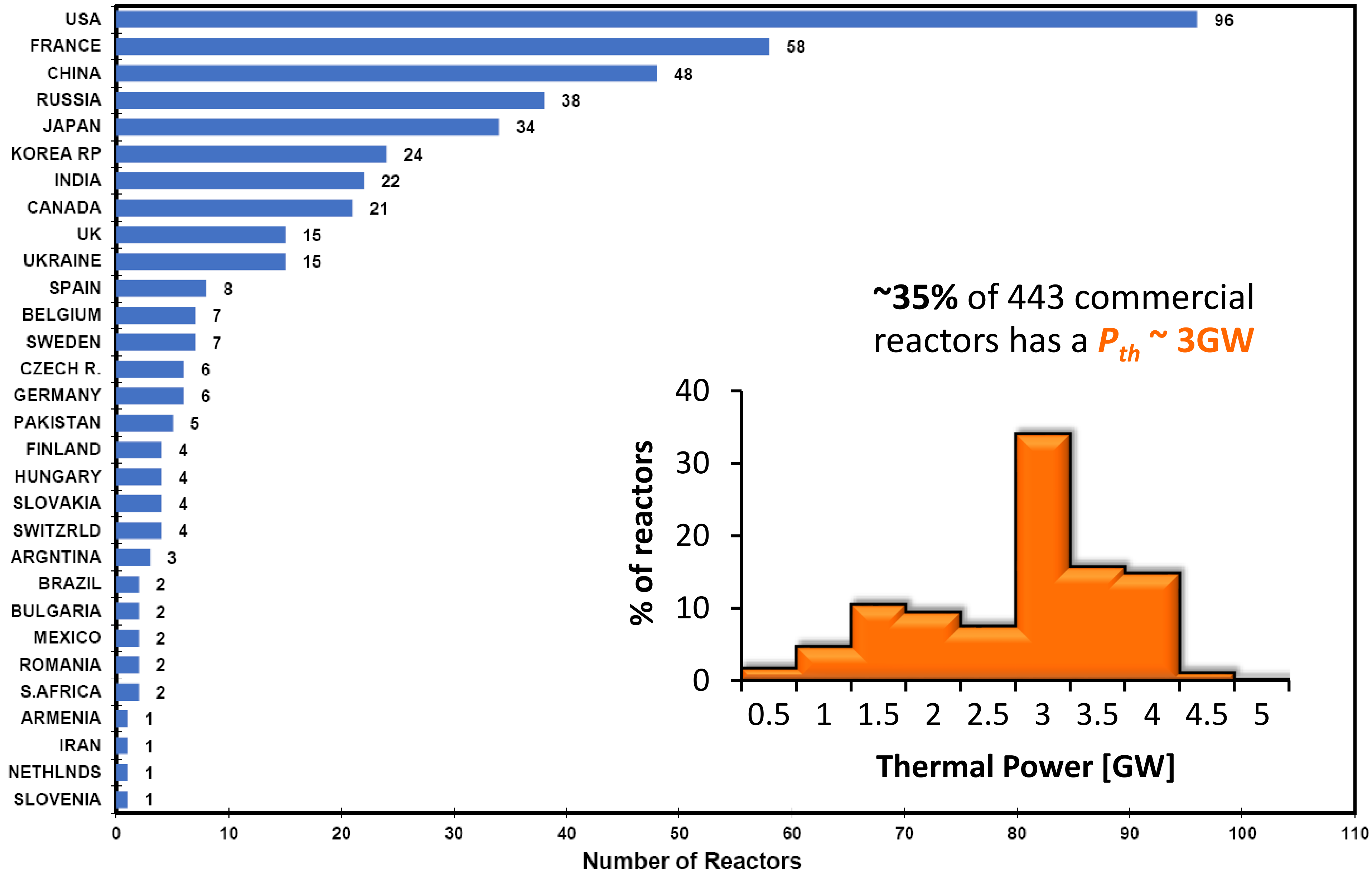
BWR
Boiling Water Reactor

PWR
Pressurized Water Reactor

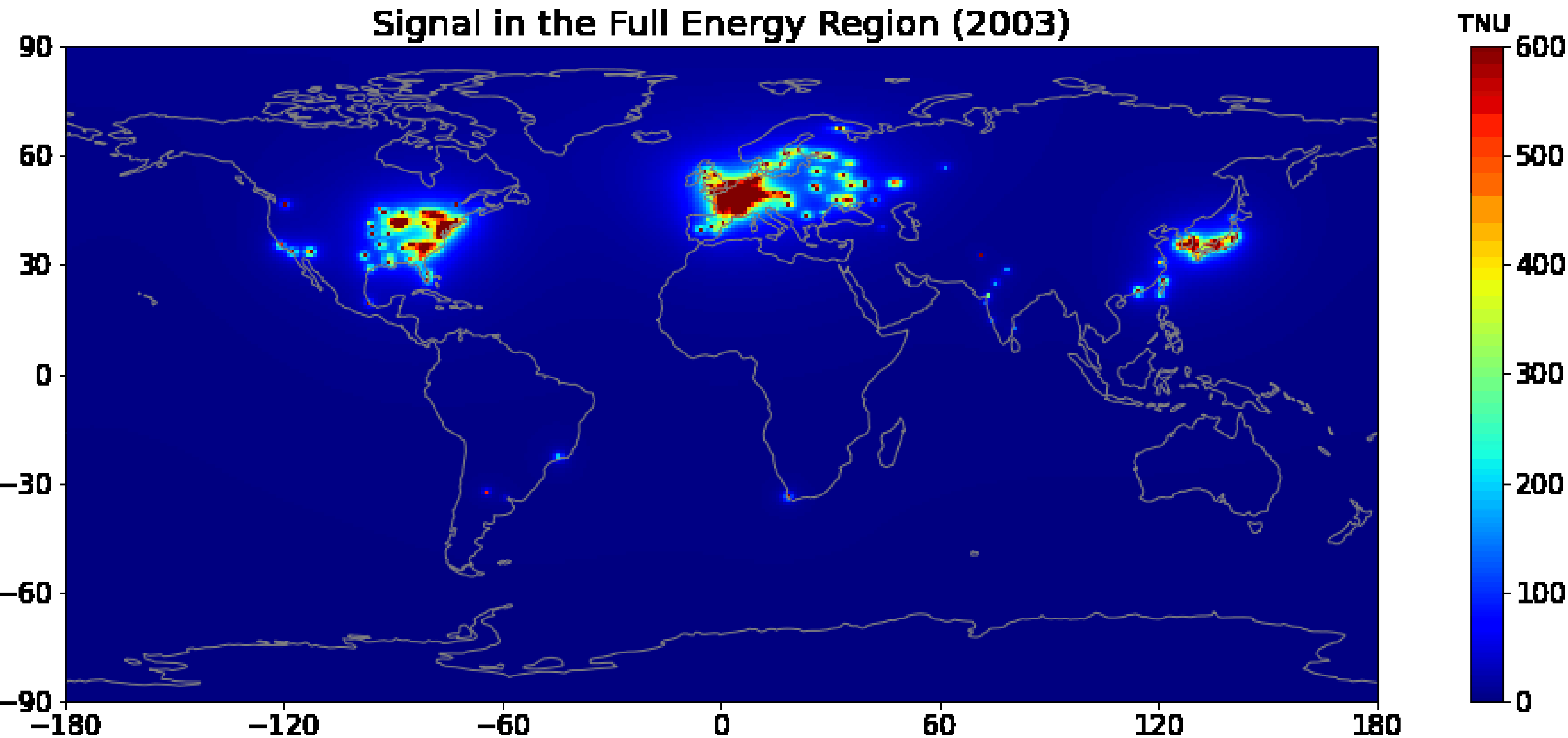



ype of reactor
Boiling Water Reactor
Fast Breeder Reactor
Gas Cooled Reactor
Light Water Graphite Reactor
Pressurised Heavy Water Reactor
Pressurised Water Reactor
US Dept of State Geographer
Image Landsat / Copernicus
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2021 Google
Google Earth
Data di acquisizione delle immagini: 12/14/2015
20°45'07.33"N 117°07'41.82"E alt 15736.48 km

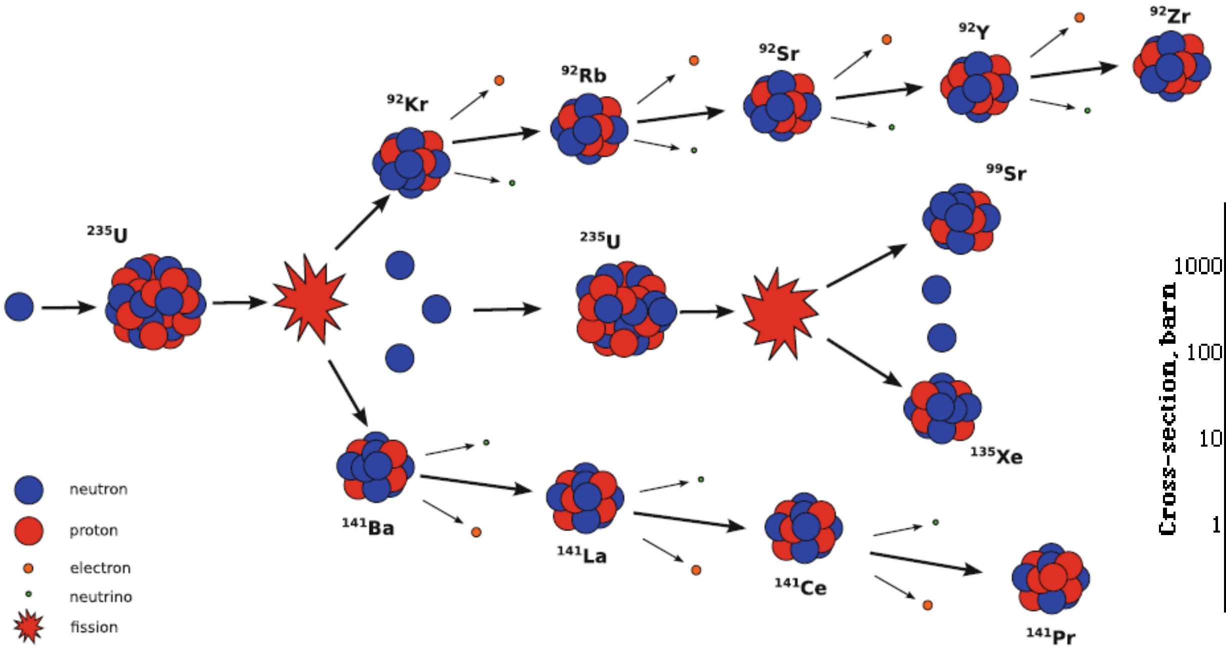
Number of Reactors in Operation (as of 1 January 2020)



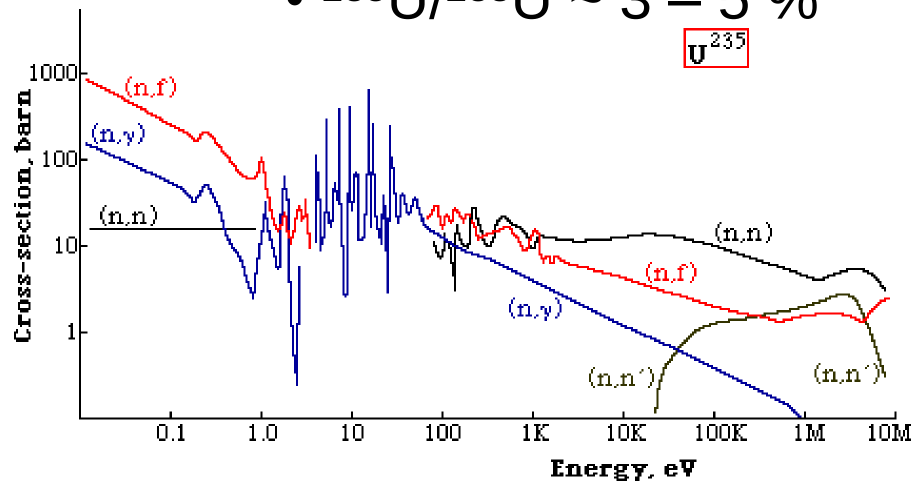
Reactor antineutrino signal: evolution over time



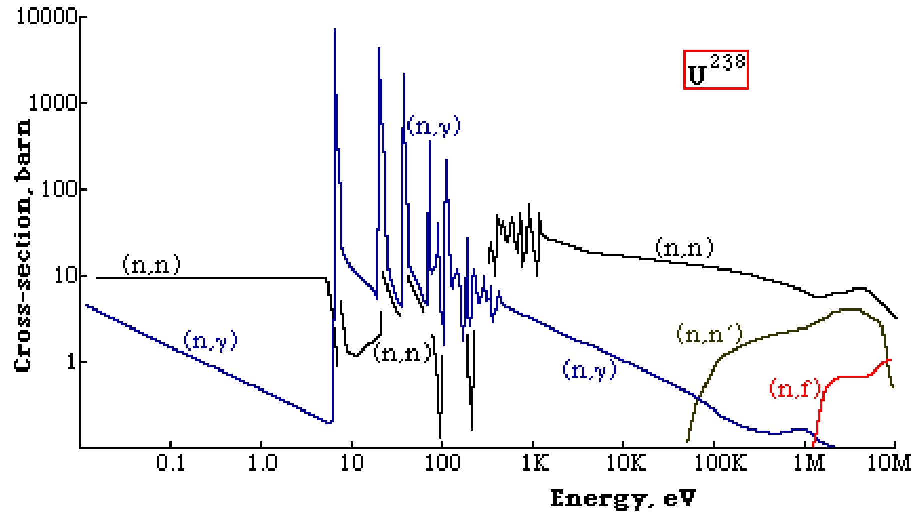
Nuclear physics in a reactor: few numbers



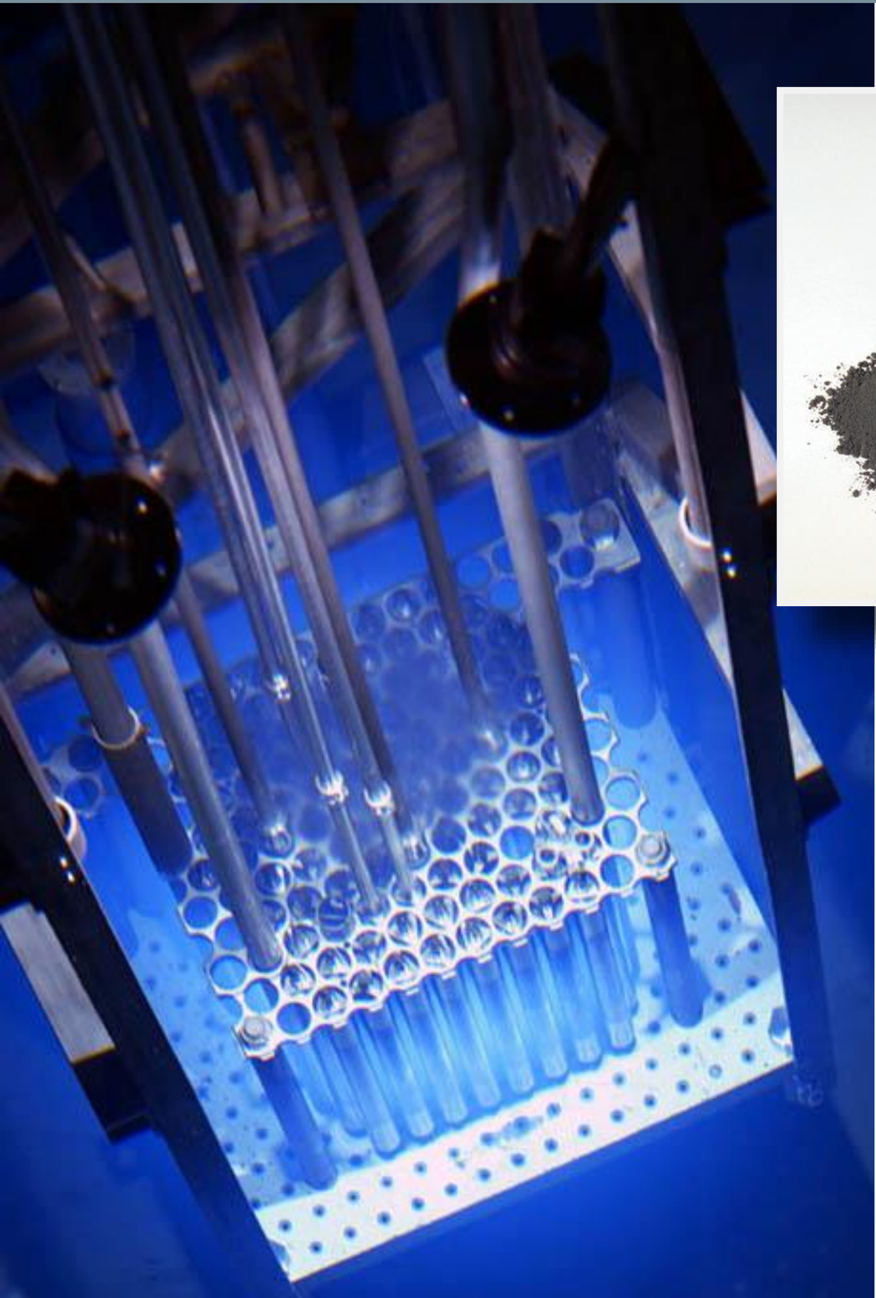
- $\langle P_{Th} \rangle \sim 3\ GW_{Th}$
- $\langle P_{El} \rangle \sim 1\ GW_{El}$
- $^{235}U/^{238}U \sim 3 - 5\ \%$

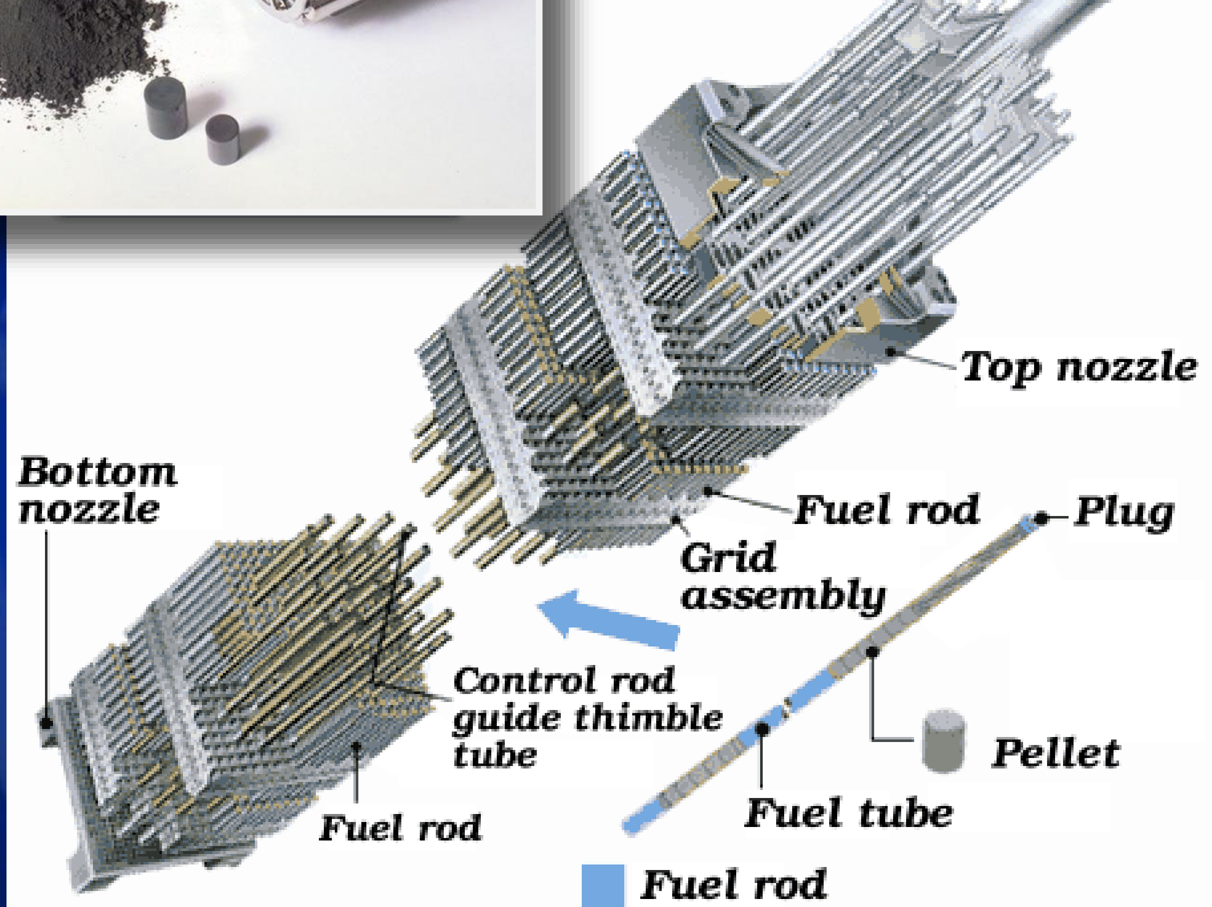


- Luminosity: $\sim 2\ 10^{20}$ anti-ν / s per 1 GW_{Th}
- $\langle E \rangle \sim 200$ MeV/fission
- $N_{neutron} \sim 3$ #/fission
- $N_{antin\ \nu} \sim 6$ #/fission
- Rate = ? Fission/s per 1 GW_{Th}



Nuclear reactor: some details…





The moderator

- Thermal reactors need a “moderator”, a component where neutrons are slowed down thus avoiding (or minimizing) losses due to capture in ^{238}U.
- The ideal moder has to be:
  - light (atomic mass comparable to neutron mass, for efficient slowing down)
  - Not neutron thirsty (i.e. does not capture neutrons)
  - cheap
  - not inflammable
- In practice, a compromise has to be obtained.
- Most common used materials are
  - light water (H_20)
  - heavy water (D_2O)
  - graphite

	H_20	D_2O	graphite
M_a/M_n	Ok	Ok	Accept.
σ_n	Accept.	small	small
Fire danger	NO	NO	YES
cost	cheap	Expens.	cheap

Andiamo a vedere da vicino YANGJIANG…

CN-22 **YANGJIANG-1** **CHINA**

Status at end of year	:	**Operational**
Operator	:	YJNPC (Yangjiang Nuclear Power Company)
Owner	:	YJNPC (Yangjiang Nuclear Power Company)
Reactor Supplier	:	CFHI (China First Heavy Industries)
Turbine Supplier	:	SEG (Shanghai Electric Group)

Reactor Unit Details

Reactor type and model	:	PWR / CPR-1000
Thermal power	:	2905 MWth
Gross electrical power	:	1086 MWe
Reference unit power (net)	:	1000 MWe

Key Dates

Construction Date	:	2008-12-16
Grid Date	:	2013-12-31
Commercial Date	:	2014-03-25
Age at end of year	:	6 years

Design Characteristics

Primary Systems		
Reactor vessel centreline orientation	:	Vertical
Fuel material	:	UO2
Refuelling type	:	OFF-line
Moderator material	:	H2O
Average fuel enrichment [% of U235]	:	4.45
Refuelling frequency [month]	:	18
Part of the core refuelled [%]	:	4.45
Average discharge burnup [MWd/t]	:	44000
Active core diameter [m]	:	3.04
Active core height/length [m]	:	3.66
Number of fissile fuel assemblies/bundles	:	157
Fuel linear heat generation rate [kW/m]	:	18.6
Number of control rod assemblies	:	61
Number of external reactor coolant loops	:	3
Coolant type	:	H2O
Operating coolant pressure [MPa]	:	15.5
Reactor outlet temperature [°C]	:	328.4
Number of SG	:	3
Containment type	:	Single
Containment design pressure [MPa]	:	0.52
Secondary systems		
Number of turbine-generators per unit/reactor	:	1
Turbine speed [rpm]	:	1500
Number of LP cylinders per turbine	:	2
HP cylinder inlet steam pressure [MPa]	:	6.43
Output voltage [kV]	:	24
Primary means of condenser cooling	:	Sea (once-through)
Number of main condensate pumps	:	3
Number of FW pumps for full power operation	:	2
Number of on-site safety related diesel generators	:	3
Non-electrical applications	:	none

Load factor

$$N_{TOT} = \varepsilon N_p \tau \sum_{k=1}^{N_{reactor}} \frac{P_k}{4\pi d_k^2} \langle LF_k \rangle \int dE_\nu \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda_i(E_\nu)\, P_{ee}(E_\nu, d_k) \sigma_{IBD}(E_\nu)$$

[1 TNU = 1 event / 10^{32} free protons /year]

$i = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$

REACTOR

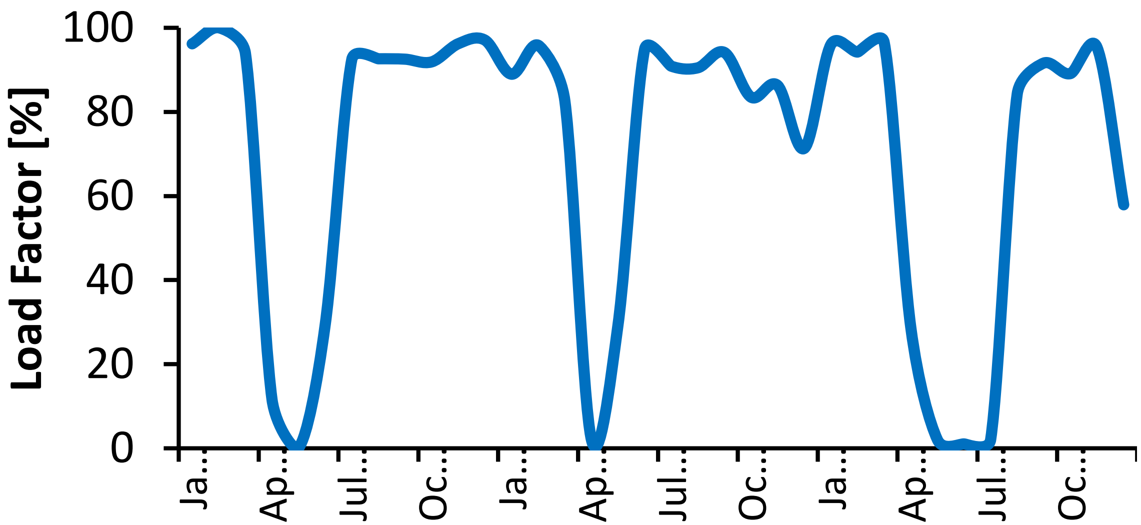
- d_k = reactor distance
- P_k = thermal power
- LF = Load Factor
- p_i = power fraction

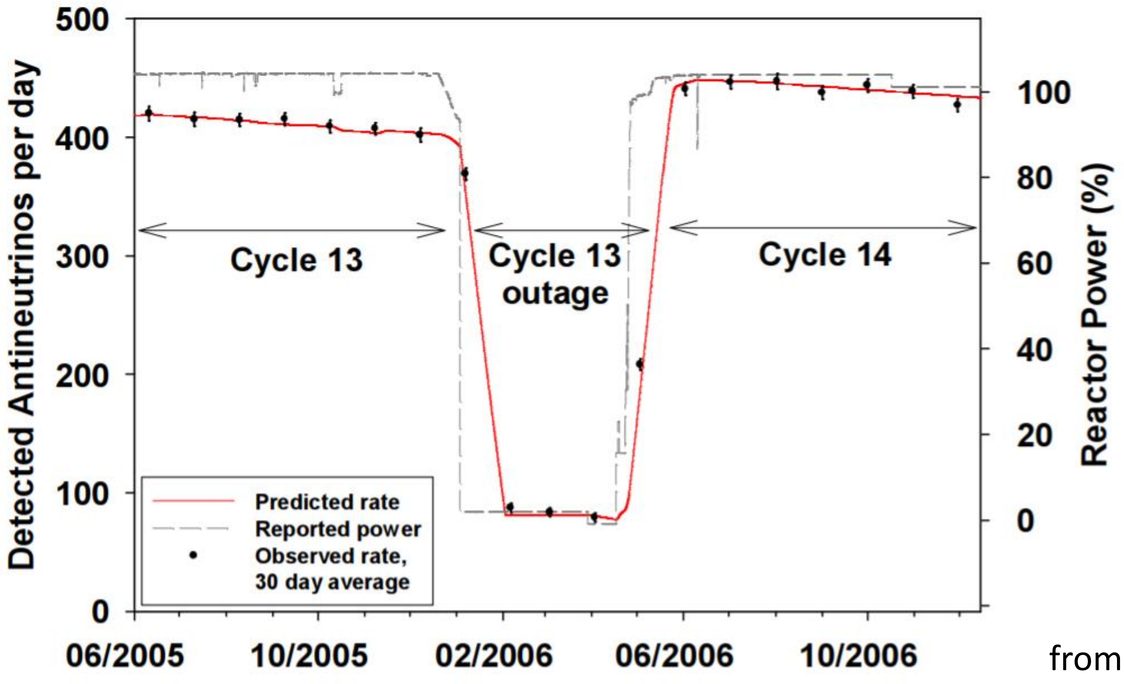
The load factor LF is the percentage quantity expressing the effective working condition of a core in a specific period of the operating cycle and is defined as the ratio:

$$\mathrm{LF} = 100 \text{ x } \frac{\mathrm{EG}}{\mathrm{REG}}$$

where EG is the net electrical energy produced during the reference period as measured at the unit outlet terminals, i.e., after subtracting the electrical energy taken by auxiliary units, while REG is the net electrical energy that would have been supplied to the grid if the unit were operated continuously at the reference power unit during the whole reference period.

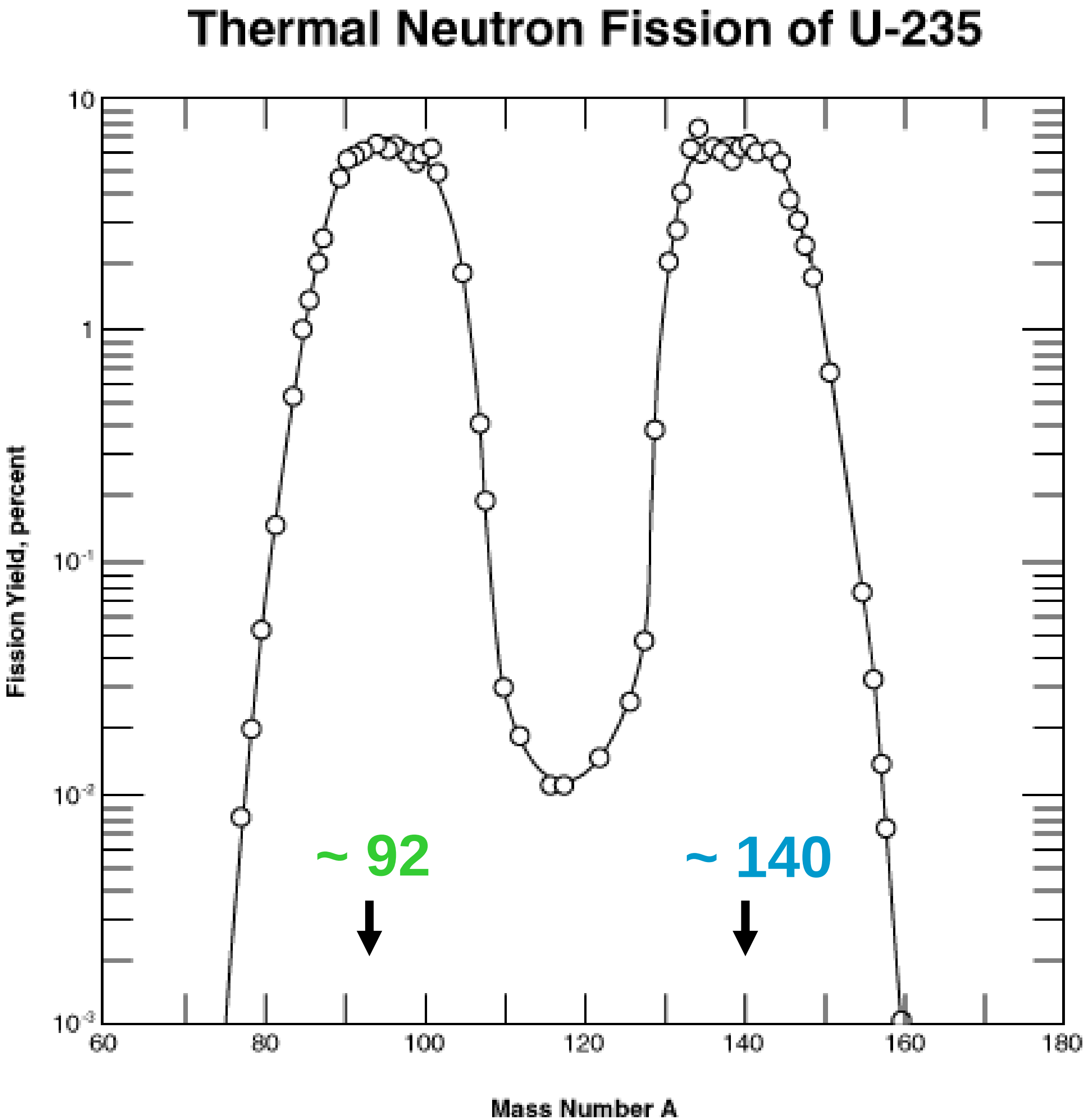
Load factor, reactor power and antineutrinos





from IAEA report, 2008

Fission fragments and (unpleasant) fruit salad



Spectrum of reactor antineutrinos

The reactor antineutrino signal evaluation requires several ingredients for modeling the three antineutrino life stages:

- ✓ **production** at reactor cores
- ✓ **propagation** to the detector site
- ✓ **detection** in liquid scintillation detectors

$$N_{TOT} = \varepsilon N_p \tau \sum_{k=1}^{N_{reactor}} \frac{P_k}{4\pi d_k^2} \langle LF_k \rangle \int dE_\nu \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda_i(E_\nu)\, P_{ee}(E_\nu, d_k) \sigma_{IBD}(E_\nu)$$

[1 TNU = 1 event / 10^{32} free protons /year]

The spectrum of reactor antineutrinos emitted by a reactor core having a thermal power P_{th} and operating with a load factor LF can be evaluated according to:

$$\mathrm{S}(E_\nu) = P_{th}\, \mathrm{LF} \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda(E_\nu)$$

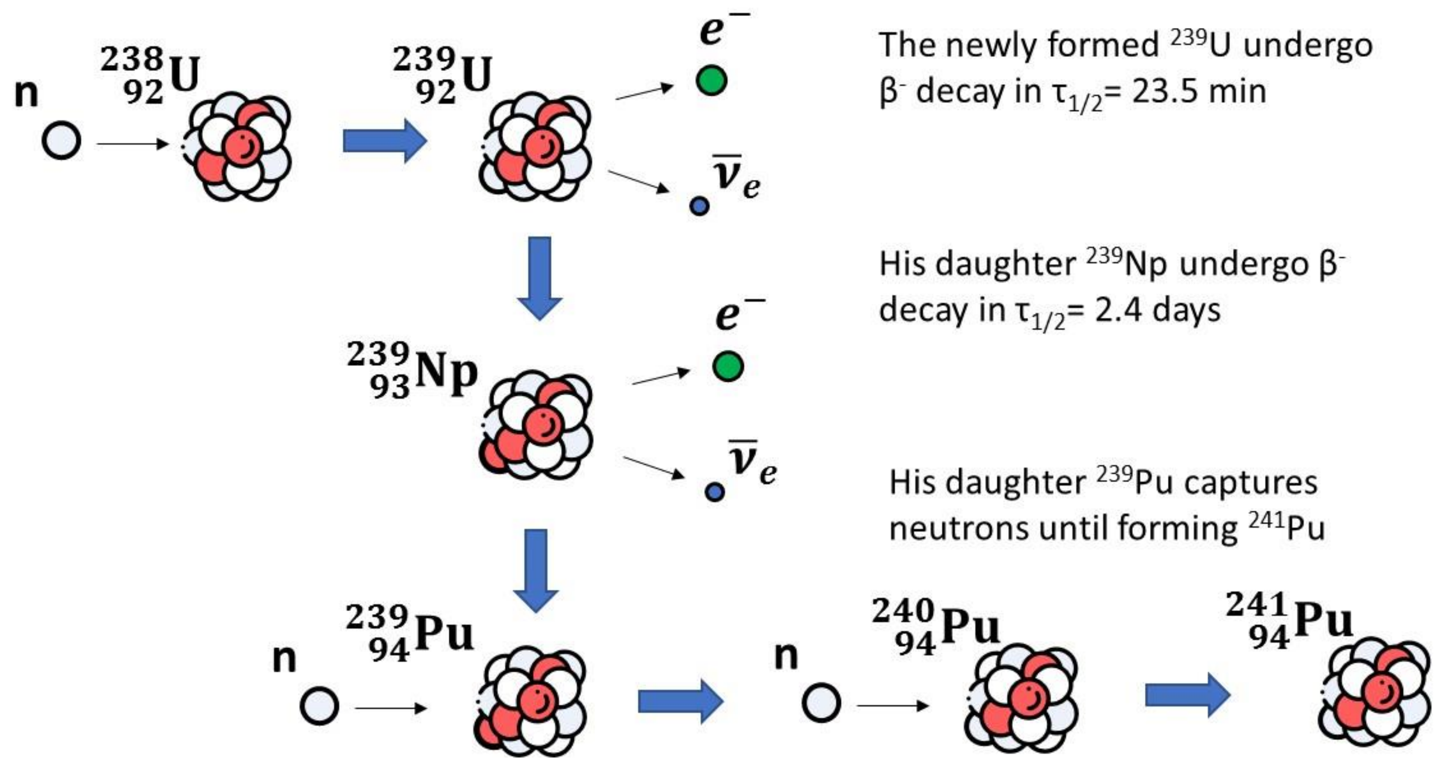
where p_i is power fraction, Q_i (i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) is the energy released per fission and λ_i is reactor antineutrino spectrum.

Energy released per fission and plutonium generation

TABLE II. Energy released per fission Q_i for ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu taken from Ma *et al.* [38].

Fissile isotope	Q_i (MeV)
^{235}U	202.36 ± 0.26
^{238}U	205.99 ± 0.52
^{239}Pu	211.12 ± 0.34
^{241}Pu	214.26 ± 0.33

Fresh fuel contains only U isotopes. The Pu isotopes are gradually generated through neutron captures on ^{238}U and β decays of its successor isotopes.



The newly formed ^{239}U undergo β^- decay in $\tau_{1/2}$= 23.5 min

His daughter ^{239}Np undergo β^- decay in $\tau_{1/2}$= 2.4 days

His daughter ^{239}Pu captures neutrons until forming ^{241}Pu

Fission fractions and power fractions collection

$$p_i = \frac{f_i Q_i}{\sum_{i=1}^{4} f_i Q_i}$$

p_i is the fraction of P_{th} produced by the fission of the *ith* isotope

$$\frac{dN_i^{fiss}}{dt} = LF \cdot P_{th} \frac{p_i}{Q_i}$$

Extensive collection of different sets of fission/power fractions from literature

Reactor Classes	Fractions	^{235}U	^{239}Pu	^{238}U	^{241}Pu	Reference
PWR BWR LWGR GCR	f_i	0.538	0.328	0.078	0.056	G. Mention et al. (2011)
		0.614	0.274	0.074	0.038	
		0.620	0.274	0.074	0.042	
		0.584	0.298	0.068	0.050	
		0.543	0.329	0.070	0.058	
		0.607	0.277	0.074	0.042	
		0.603	0.276	0.076	0.045	
		0.606	0.277	0.074	0.043	
		0.557	0.313	0.076	0.054	
		0.606	0.274	0.074	0.046	
		0.488	0.359	0.087	0.067	Y. Abe et al. (2012)
		0.580	0.292	0.074	0.054	Z. Djurcic et al. (2009)
		0.544	0.318	0.075	0.063	
		0.577	0.292	0.074	0.057	
		0.590	0.290	0.070	0.050	V. I. Kopeikin et al. (2004)
		0.570	0.295	0.078	0.057	S. Abe et al. (2008)
		0.568	0.297	0.078	0.057	K. Eguchi et al. (2003)
		0.563	0.301	0.079	0.057	T. Araki et al. (2005)
		0.650	0.240	0.070	0.040	V. I. Kopeikin (2012)
		0.560	0.310	0.070	0.060	
		0.480	0.370	0.070	0.080	
	p_i	0.560	0.300	0.060	0.080	G. Bellini et al. (2010)
MOX	p_i	0.000	0.708	0.080	0.212	G. Bellini et al. (2010)
PHWR	p_i	0.543	0.411	0.024	0.022	G. Bellini et al. (2013)

Enriched Uranium

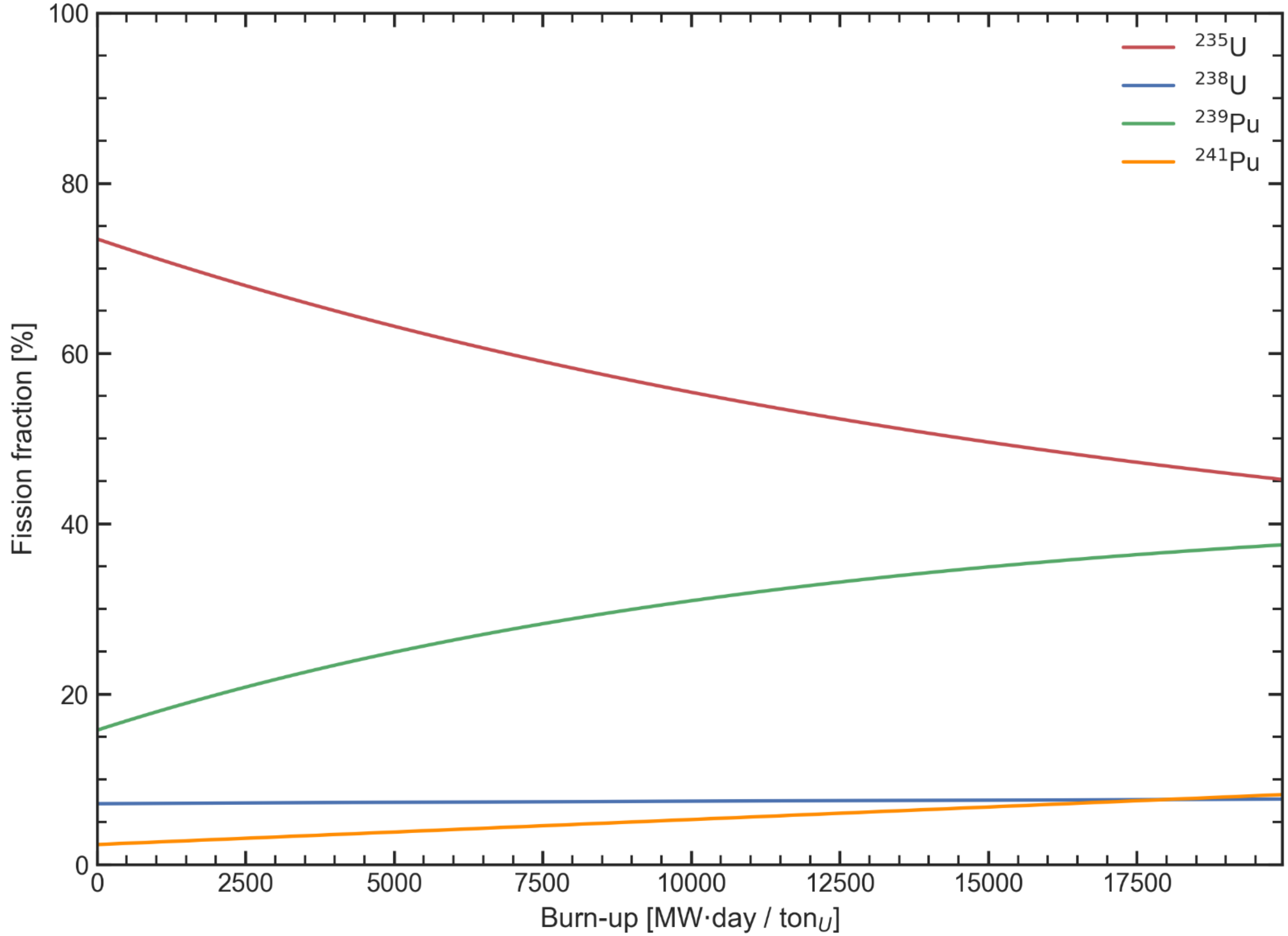
Mixed Oxide Fuel

Natural Uranium

Time variation of fission fractions

In reactors, electron antineutrinos are emitted primarily from the fissions of **four isotopes**: ^{235}**U**, ^{238}**U**, ^{239}**Pu**, and ^{241}**Pu**. Fissions of **other isotopes** contribute **less than 0.3%**.

Since U isotopes are burnt in fission or spent to generate Pu isotopes (that subsequently fission again), **fuel composition is not constant**.
As a result, **fission fractions** and the consequent antineutrino luminosity **change in time**.



*data from F. P. An et al., 2017

Facciamolo con le mani… ☺

The spectrum of reactor antineutrinos emitted by a reactor core having a thermal power P_{th} and operating with a load factor LF can thus be evaluated according to:

$$\mathrm{S}(E_\nu) = P_{th}\,\mathrm{LF}\sum_{i=1}^{4}\frac{p_i}{Q_i}\lambda(E_\nu)$$

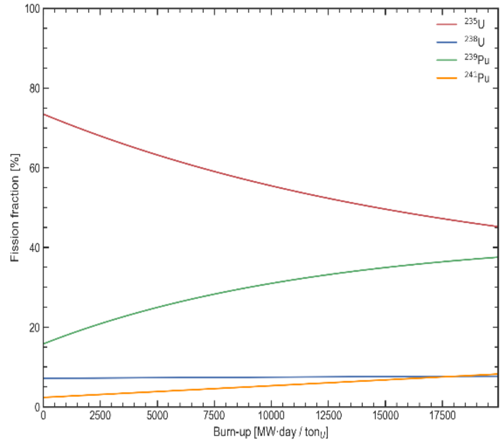
Power fraction

^{235}U = 55 %

^{238}U = 10 %

^{239}Pu = 30 %

^{241}Pu = 5 %



Fissile isotope	Q_i [MeV/fission]
^{235}U	202.36 ± 0.26
^{238}U	205.99 ± 0.52
^{239}Pu	211.12 ± 0.34
^{241}Pu	214.26 ± 0.33

Building reactor antineutrino spectrum

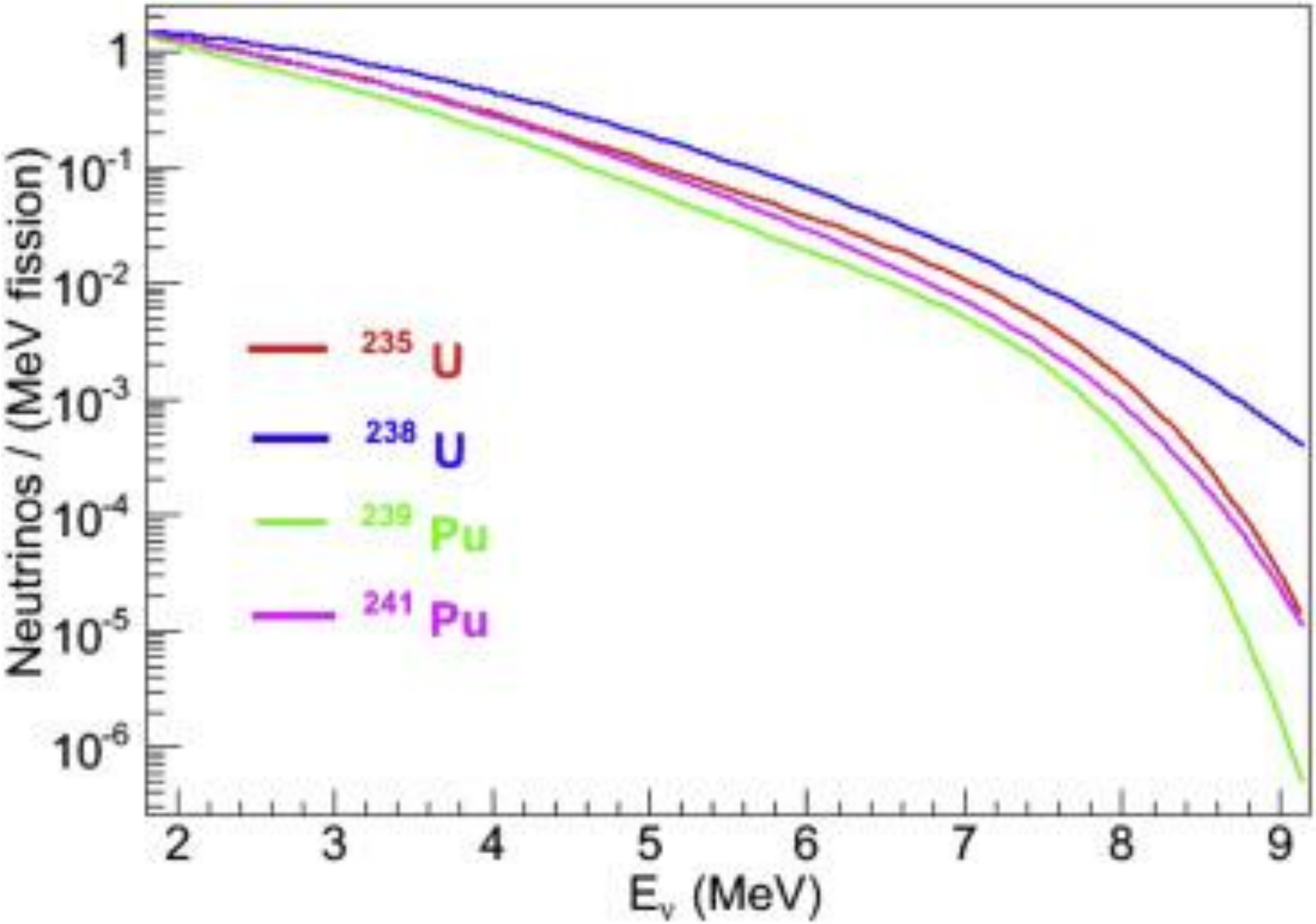
We can adopt as reference model the one published by Mueller et al., in which the spectra of all four contributing isotopes are consistently given in terms of the exponential of a polynomial of order 5, as stated in Eq. (8). Mueller et al. derive the ^{235}U, ^{239}Pu, and ^{241}Pu spectra based on a mixed approach that combines the accurate reference of the ILL electron spectra with the physical distribution of beta branches provided by the nuclear databases and calculates the ^{238}U spectrum via a pure summation method:

$$\lambda_i(E_{\bar{\nu}}) = \exp\left(\sum_{p=1}^{6} a_p^i E_{\bar{\nu}}^{p-1}\right)$$

TABLE III. Coefficients of the polynomial of order 5 used as argument of the exponential function for the analytical expression of the antineutrino spectra for ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu, taken from Mueller *et al.* [43].

Fissile isotope	a_1	a_2	a_3	a_4	a_5	a_6
^{235}U	3.217	−3.111	1.395	$-3.690\,(10^{-1})$	$4.445(10^{-2})$	$-2.053(10^{-3})$
^{238}U	$4.833(10^{-1})$	$1.927(10^{-1})$	$-1.283(10^{-1})$	$-6.762(10^{-3})$	$2.233(10^{-3})$	$-1.536(10^{-4})$
^{239}Pu	6.413	−7.432	3.535	$-8.820(10^{-1})$	$1.025(10^{-1})$	$-4.550(10^{-3})$
^{241}Pu	3.251	−3.204	1.428	$-3.675(10^{-1})$	$4.254(10^{-2})$	$-1.896(10^{-3})$

Reactor antineutrino spectra



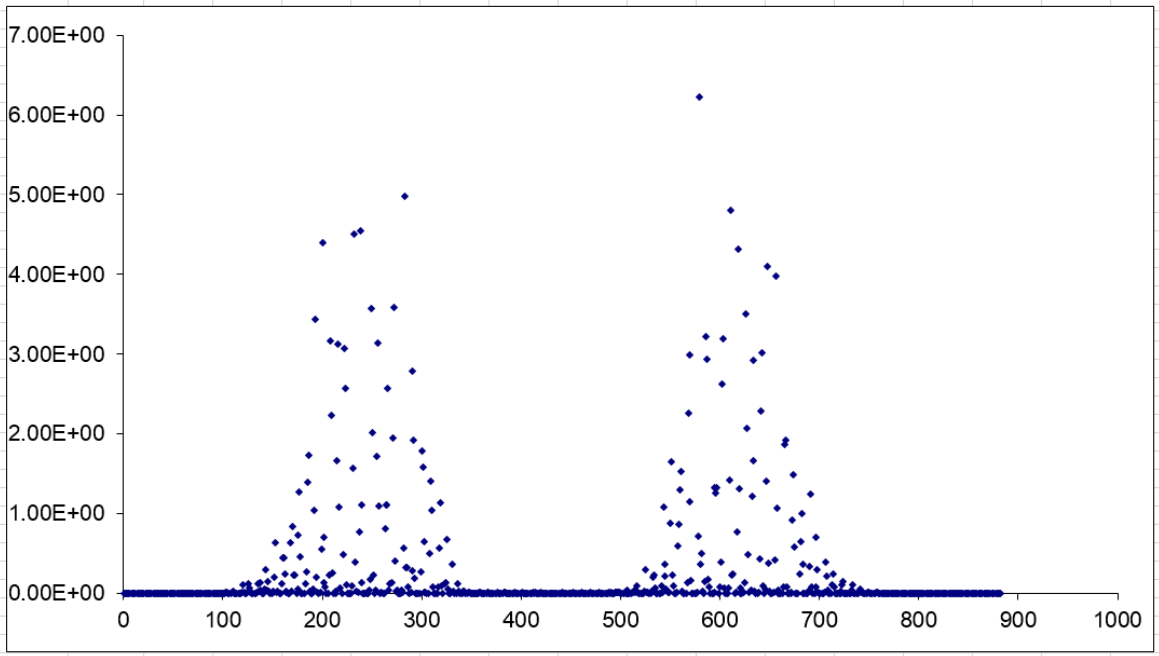
Kim Y., Detection of Antineutrinos for Reactor Monitoring - Nuclear Engineering and Technology - 2016

Fission products

fission_products.xls - Modalità compatibilità - Excel

	A	B	C	D	F	G	I	J	K
1									
2	66Cr		2.41E-12	2.41E-12	66	2.41E-12	66Cr	7.91E-08	66
3	66Mn		7.20E-10	7.22E-10	66	7.20E-10	66Mn	8.63E-06	66
4	66Fe		3.76E-08	3.83E-08	66	3.76E-08	66Fe	1.01E-04	66
5	66Co	0.23s	2.81E-08	6.64E-08	66	2.81E-08	66Co	1.49E-04	66
6	66Ni	54.6 h	5.78E-09	7.21E-08	66	5.78E-09	66Ni	2.84E-05	66
7	66Cu	5.10 m	1.43E-11	7.22E-08	66	1.43E-11	66Cu	6.41E-07	66
8							66Zn	1.39E-09	66
9	67Mn		5.38E-10	5.38E-10	67	5.38E-10			
10	67Fe		6.87E-08	6.92E-08	67	6.87E-08	67Cr	1.51E-08	67
11	67Co		2.00E-07	2.70E-07	67	2.00E-07	67Mn	3.98E-06	67
12	67Ni	21 s	9.04E-08	3.60E-07	67	9.04E-08	67Fe	1.07E-04	67
13	67Cu	2.580d	9.68E-10	3.61E-07	67	9.68E-10	67Co	3.42E-04	67
14							67Ni	1.43E-04	67
15	68Mn		6.66E-11	6.66E-11	68	6.66E-11	67Cu	7.23E-06	67
16	68Fe		3.92E-08	3.92E-08	68	3.92E-08	67Zn	3.62E-08	67
17	68Co		2.47E-07	2.86E-07	68	2.47E-07	67Ga	1.79E-11	67
18	68Ni	19 s	4.19E-07	7.05E-07	68	4.19E-07			
19	68Cu-m	3.79m	7.36E-09	7.36E-09	68	7.36E-09	68Cr	1.44E-09	68
20	68Cu	31 s	3.15E-09	7.12E-07	68	3.15E-09	68Mn	9.27E-07	68
21	68Zn	stable	4.74E-11	7.16E-07	68	4.74E-11	68Fe	5.84E-05	68
22							68Co	4.12E-04	68
23	69Mn		8.03E-12	8.03E-12	69	8.03E-12	68Ni	3.72E-04	68
24	69Fe		1.22E-08	1.22E-08	69	1.22E-08	68Cu-m	3.51E-05	68
25	69Co		3.25E-07	3.37E-07	69	3.25E-07	68Cu	7.70E-06	68
26	69Ni	10 s	1.12E-06	1.46E-06	69	1.12E-06	68Zn	5.41E-07	68
27	69Cu	2.8 m	1.14E-07	1.57E-06	69	1.14E-07	68Ga	6.64E-10	68
28	69Zn-m	13.76h	1.06E-09	1.06E-09	69	1.06E-09			
29	69Zn	56 m	2.48E-10	1.57E-06	69	2.48E-10	69Mn	1.56E-07	69
30							69Fe	2.35E-05	69
31	70Fe		3.24E-09	3.24E-09	70	3.24E-09	69Co	3.74E-04	69
32	70Co		2.09E-07	2.13E-07	70	2.09E-07	69Ni	7.31E-04	69
33	70Ni		2.78E-06	3.00E-06	70	2.78E-06	69Cu	1.86E-04	69
34	70Cu-m	47 s	4.46E-07	1.94E-06	70	4.46E-07	69Zn-m	4.94E-06	69
35	70Cu	5 s	1.49E-07	1.65E-06	70	1.49E-07	69Zn	6.10E-07	69
36	70Zn	stable	3.03E-08	3.62E-06	70	3.03E-08	69Ga	1.67E-08	69
37	70Ga	21.1 m	1.47E-11	1.47E-11	70	1.47E-11	69Ge	4.65E-12	69
38									
39	71Fe		4.92E-10	4.92E-10	71	4.92E-10	70Cr	5.68E-12	70
40	71Co		1.48E-07	1.49E-07	71	1.48E-07	70Mn	2.25E-08	70
41	71Ni		4.35E-06	4.50E-06	71	4.35E-06	70Fe	8.21E-06	70
42	71Cu	20 s	3.48E-06	7.97E-06	71	3.48E-06	70Co	3.02E-04	70
43	71Zn-m	3.97 h	3.29E-07	3.29E-07	71	3.29E-07	70Ni	1.29E-03	70
44	71Zn	2.4 m	7.71E-08	8.05E-06	71	7.71E-08	70Cu-m	6.08E-04	70
45	71Ga	stable	9.39E-10	8.38E-06	71	9.39E-10	70Cu	1.07E-04	70
46							70Zn	4.91E-05	70
47	72Fe		7.15E-11	7.15E-11	72	7.15E-11	70Ga	3.58E-07	70

	L	M	N	O	P	Q
3	Fiss fr	0.563	0.301	0.057	0.079	
4	Q	201.7	205	210	212.4	
5		113.5571	61.705	11.97	16.7796	204.0117
6	Power fr	0.557	0.302	0.059	0.082	



235ut_mod

Selezionare la destinazione quindi INVIO o scegliere Incolla.

...hai voglia a costruir spettri!

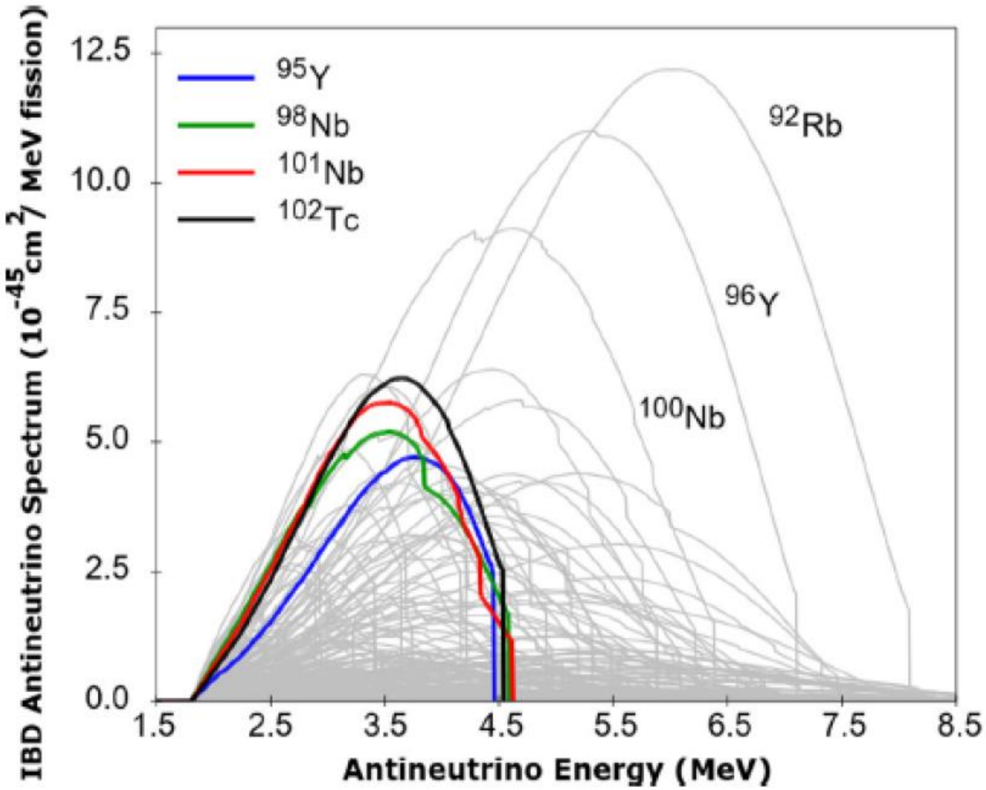


Figure 1-3: Calculated antineutrino energy spectra from many fission products in a commercial reactor. Figure is taken from Ref. [27].

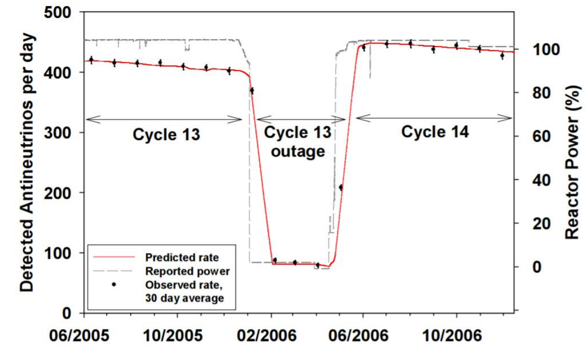
TAO Conceptual Design Report

A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution

Long Lived Isotopes (LLI)

Fission fragments produced by spent fuel have widespread half-lives (from fraction of seconds up to 10^{18} years).

Among these fission fragments, the β-decaying long-lived isotopes ($\tau_{1/2}$ > 10h) can produce spectral distortion in the resulting antineutrino spectrum (E < 4 MeV).



P	$\tau_{1/2}^{P}$	$E_{\bar{\nu}_e}^{max\,P}$ [MeV]	D	$\tau_{1/2}^{D}$	$E_{\bar{\nu}_e}^{max\,D}$ [MeV]	Y_{235} [%]	Y_{239} [%]
^{93}Y	10.18 h	2.895	^{93}Zr	$1.61 \cdot 10^{6}$ yr	0.091	6.35	3.79
^{97}Zr	16.75 h	1.916	^{97}Nb	72.1 m	1.277	5.92	5.27
^{112}Pd	21.03 h	0.27	^{112}Ag	3.13 h	3.956	0.013	0.13
^{131m}Te	33.25 h	/	^{131}Te	25.0 m	2.085	0.09	0.20
^{132}Te	3.204 d	0.24	^{132}I	2.295 h	2.141	4.31	5.39
^{140}Ba	12.753 d	1.02	^{140}La	1.679 d	3.762	6.22	5.36
^{144}Ce	284.9 d	0.319	^{144}Pr	17.28 m	2.998	4.58	3.11
^{106}Ru	371.8 d	0.039	^{106}Rh	30.07 s	3.541	0.30	3.24
^{90}Sr	28.79 yr	0.546	^{90}Y	64.0 h	2.280	0.27	0.10

Per chi vuole approfondire…

Reevaluating reactor antineutrino spectra with new measurements of the ratio between ^{235}U and ^{239}Pu β spectra

V. Kopeikin,[1] M. Skorokhvatov,[1,2] and O. Titov[1,*]

[1] *National Research Centre Kurchatov Institute, 123182, Moscow, Russia*

[2] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409, Moscow, Russia*

(Dated: March 3, 2021)

We report a reanalysis of the reactor antineutrino energy spectra based on the new relative measurements of the ratio $R =^e S_5/^e S_9$ between cumulative β spectra from ^{235}U and ^{239}Pu, performed at a research reactor in National Research Centre Kurchatov Institute (KI). A discrepancy with the β spectra measured at Institut Laue-Langevin (ILL) was observed, indicating a steady excess of the ILL ratio by the factor of 1.054 ± 0.002. We find a value of the ratio between inverse beta decay cross section per fission for ^{235}U and ^{239}Pu: $(^5\sigma_f/^9\sigma_f)_{KI} = 1.45 \pm 0.03$, and then we reevaluate the converted antineutrino spectra for ^{235}U and ^{238}U. We conclude that the new predictions are consistent with the results of Daya Bay and STEREO experiments.

Morale della storia...

$$N_{TOT} = \varepsilon N_p \tau \sum_{k=1}^{N_{reactor}} \frac{P_k}{4\pi d_k^2} \langle LF_k \rangle \int dE_\nu \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda_i(E_\nu)\, P_{ee}(E_\nu, d_k) \sigma_{IBD}(E_\nu)$$

[1 TNU = 1 event / 10^{32} free protons /year]

i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

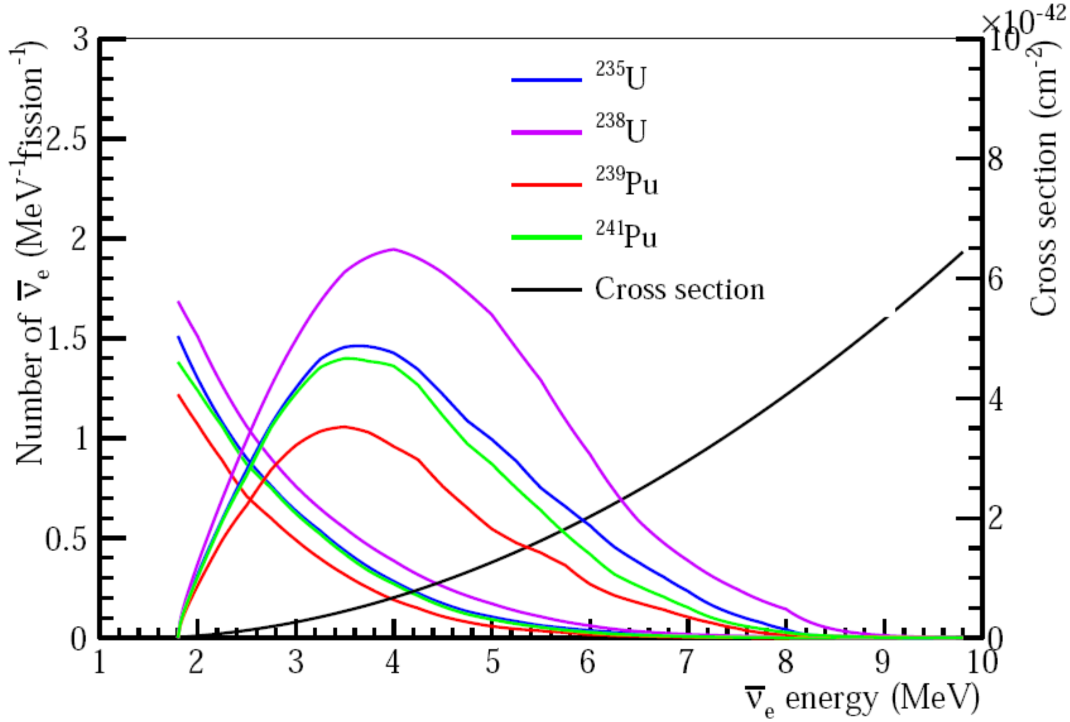
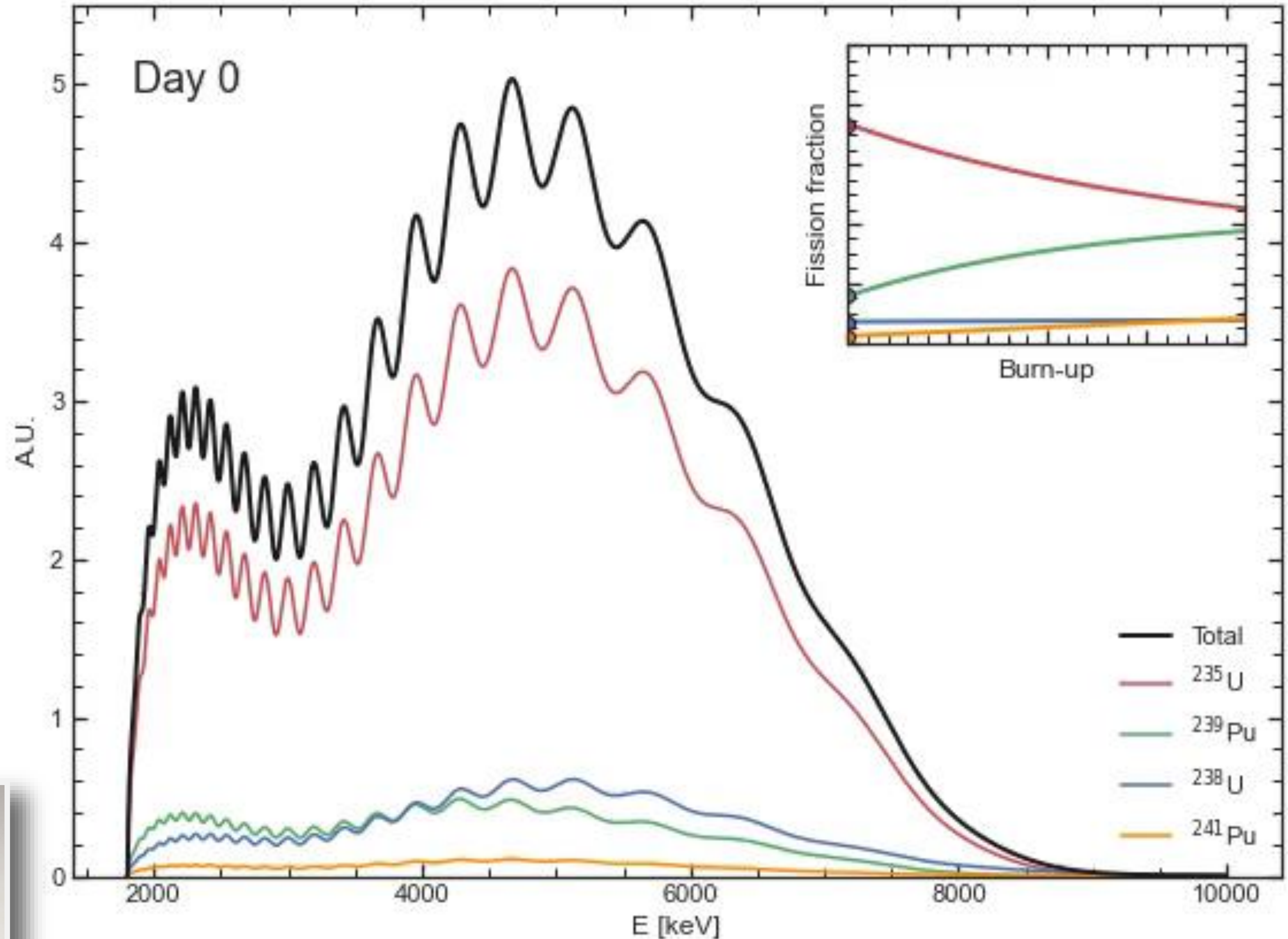
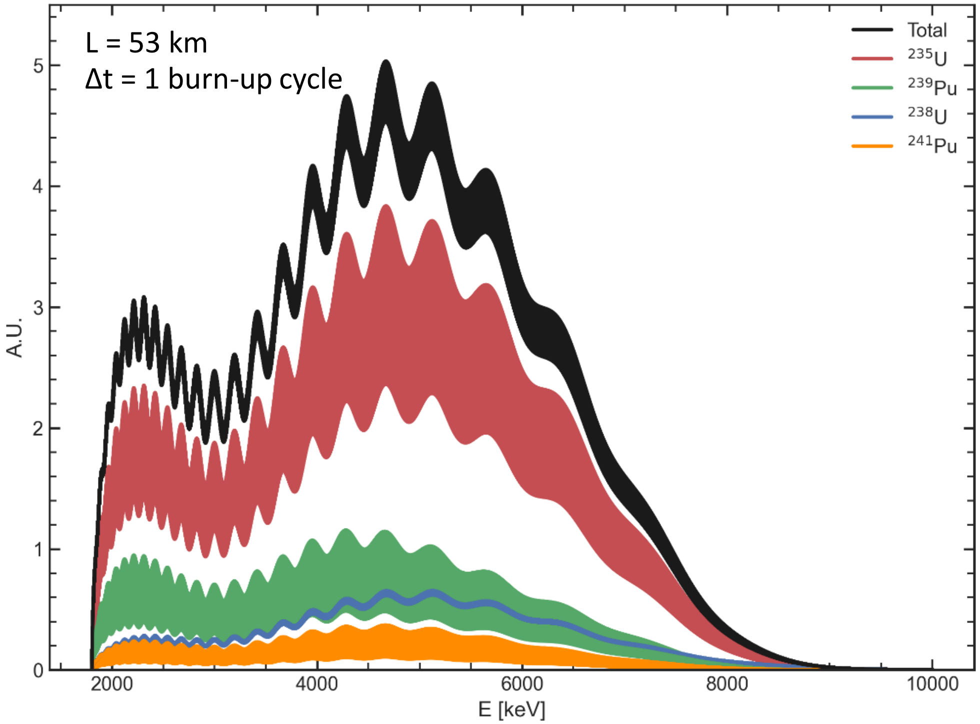


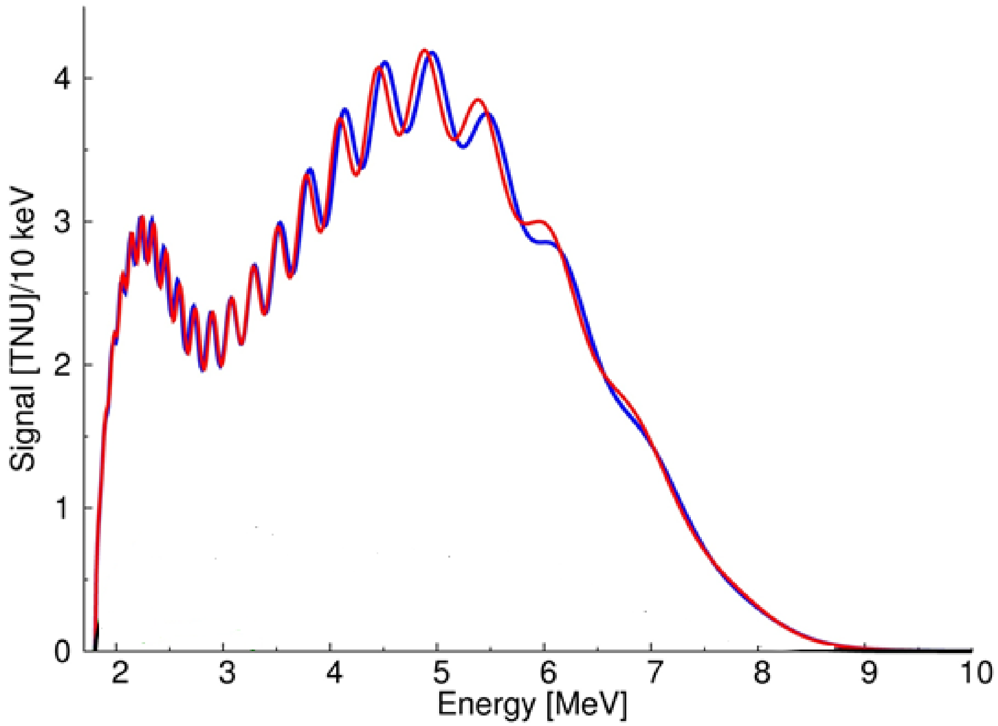
Figure 2-1: Antineutrino energy spectrum per fission in a commercial reactor weighted by the inverse beta decay cross section, from Ref. [9].

Ecco cosa succede nel tempo…



Ecco perchè (ma non solo) è stato proposto TAO...





Ci vediamo giovedì prossimo!

The reactor antineutrino signal evaluation requires several ingredients for modeling the three antineutrino life stages:

- ✓ **production** at reactor cores
- ✓ **propagation** to the detector site
- ✓ **detection** in liquid scintillation detectors

$$N_{TOT} = \varepsilon N_p \tau \sum_{k=1}^{N_{reactor}} \frac{P_k}{4\pi d_k^2} \langle LF_k \rangle \int dE_\nu \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda_i(E_\nu)\, P_{ee}(E_\nu, d_k) \sigma_{IBD}(E_\nu)$$

[1 TNU = 1 event / 10^{32} free protons /year]

i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

The spectrum of reactor antineutrinos emitted by a reactor core having a thermal power P_{th} and operating with a load factor LF can thus be evaluated according to:

$$S(E_\nu) = P_{th}\, \mathrm{LF} \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda(E_\nu)$$

Signal increase due to the Spent Nuclear Fuels (SNFs)

- A maintenance is typically scheduled **once a year** to **substitute 1/3 of the burnt fuel**
- SNFs are typically stored for **10 years** in **water pools** close to the reactor for cooling and shielding
- On the base of ^{235}U e ^{239}Pu normalized yields the mean life of SNFs is τ_{SNF} ***= 2.8 yr***
- Assuming that all SNF is accumulated for 10 years in the water pool close to each core the enhancement of the **antineutrino event rate** is **2.4%** in the **LER**