Power Production and ADS

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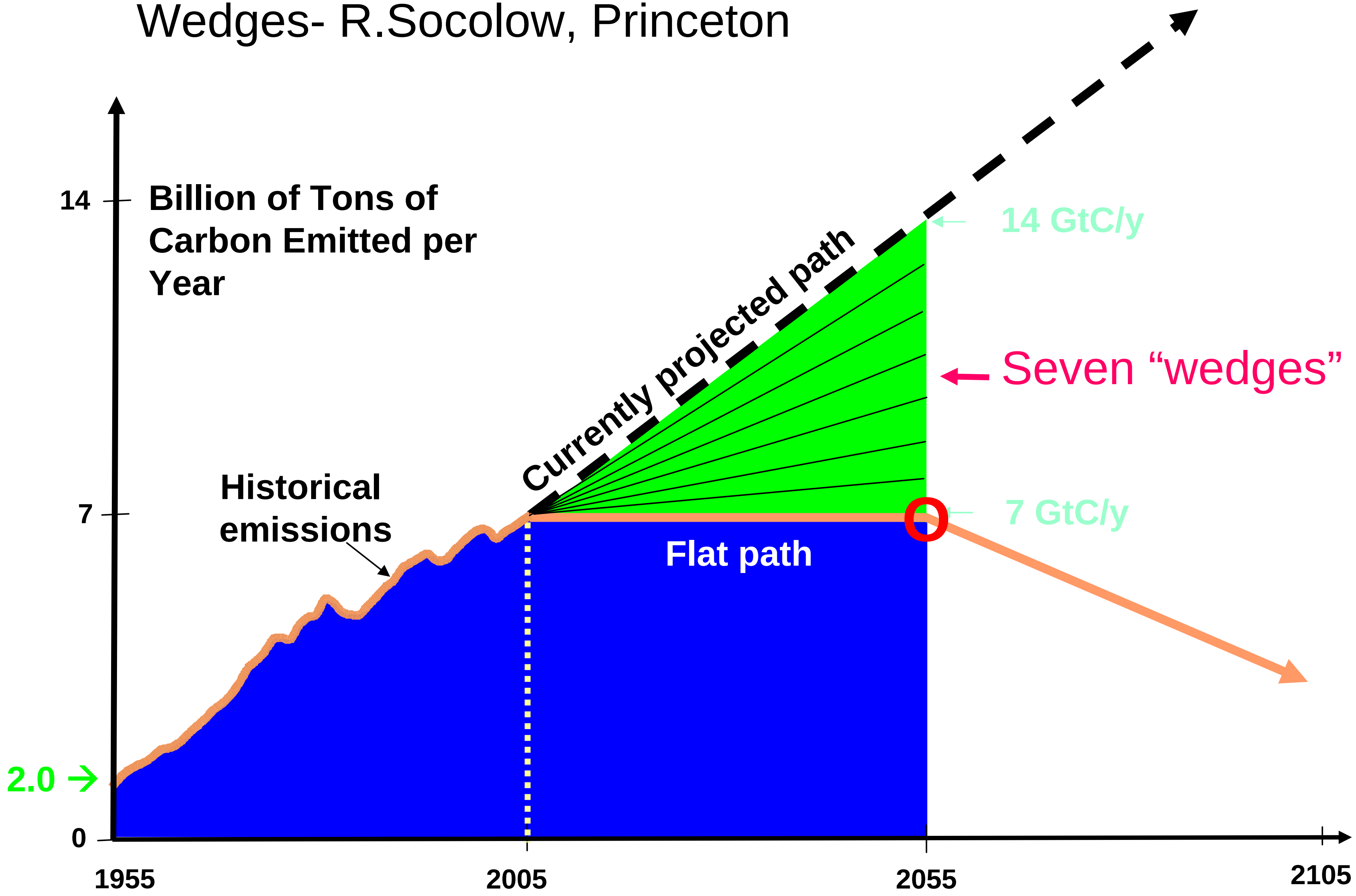
Fermilab

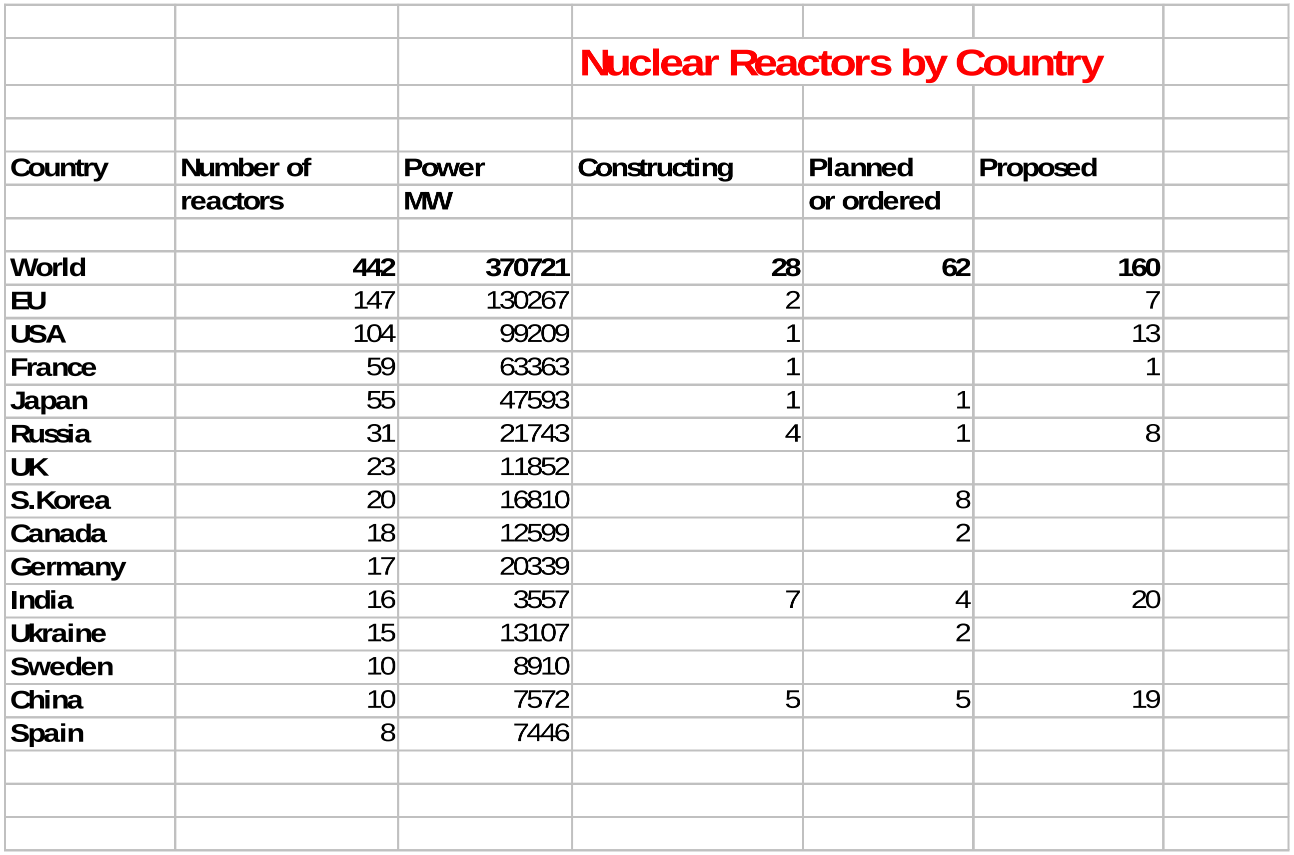
- Discuss basic ideas
- Compare ADS systems with Pressurized water reactors in power production efficiency
- Compare Rubbia parameters with OECD report assumptions

Wedges- R.Socolow, Princeton



1 Wedge needs 700 GW (2 current capacity) from nuclear energy by 2055.

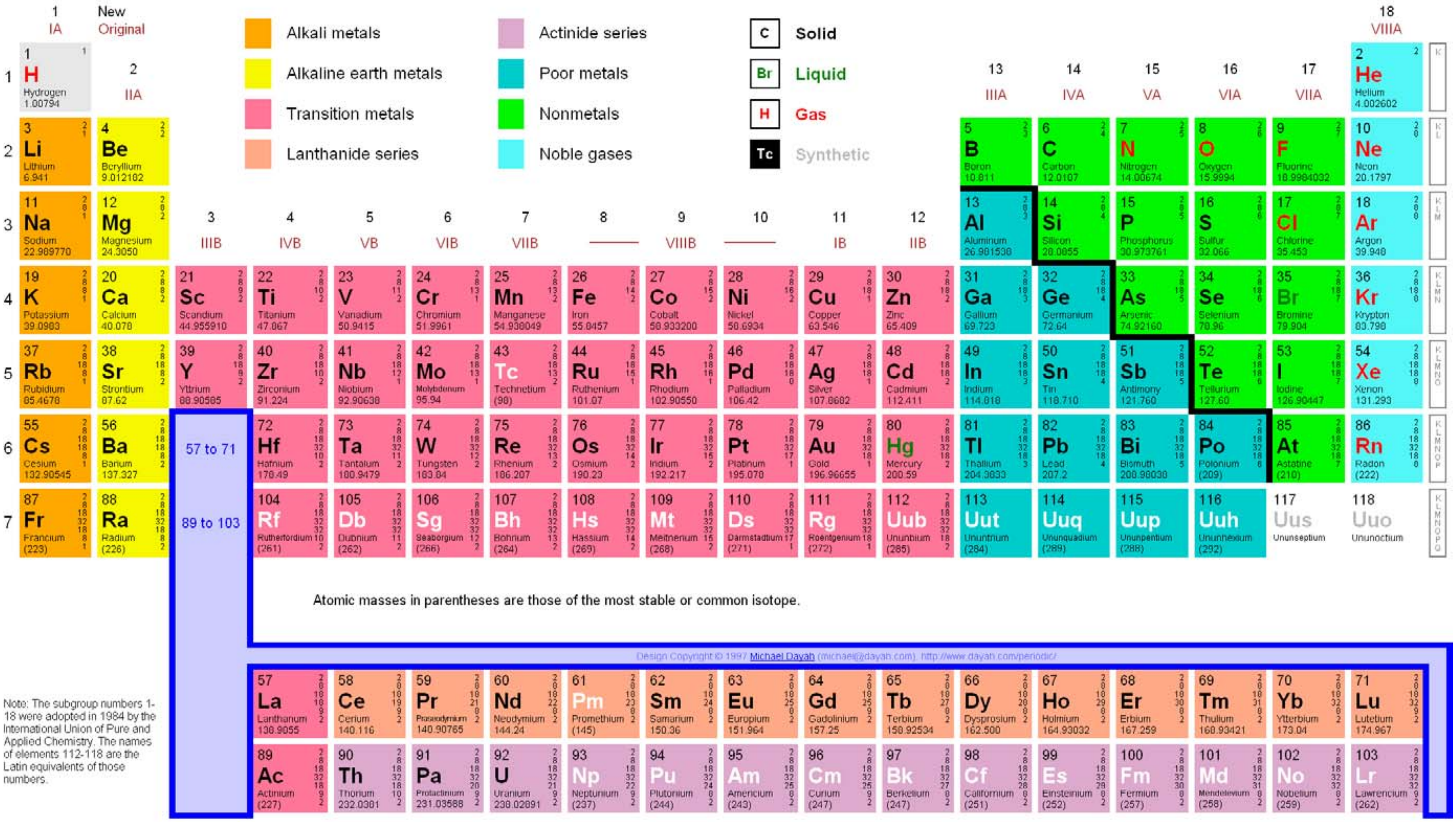
Nuclear Reactors by Country



Nuclear Reactors by Country

Country	Number of reactors	Power MW	Constructing	Planned or ordered	Proposed
World	**442**	**370721**	**28**	**62**	**160**
EU	147	130267	2		7
USA	104	99209	1		13
France	59	63363	1		1
Japan	55	47593	1	1	
Russia	31	21743	4	1	8
UK	23	11852			
S.Korea	20	16810		8	
Canada	18	12599		2	
Germany	17	20339			
India	16	3557	7	4	20
Ukraine	15	13107		2	
Sweden	10	8910			
China	10	7572	5	5	19
Spain	8	7446			

Periodic Table of the Elements



- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanide series
- Actinide series
- Poor metals
- Nonmetals
- Noble gases

- C Solid
- Br Liquid
- H Gas
- Tc Synthetic

New Original	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 H Hydrogen 1.00794																	2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.8457	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.409	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 to 71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
7	87 Fr Francium (223)	88 Ra Radium (226)	89 to 103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium

Atomic masses in parentheses are those of the most stable or common isotope.

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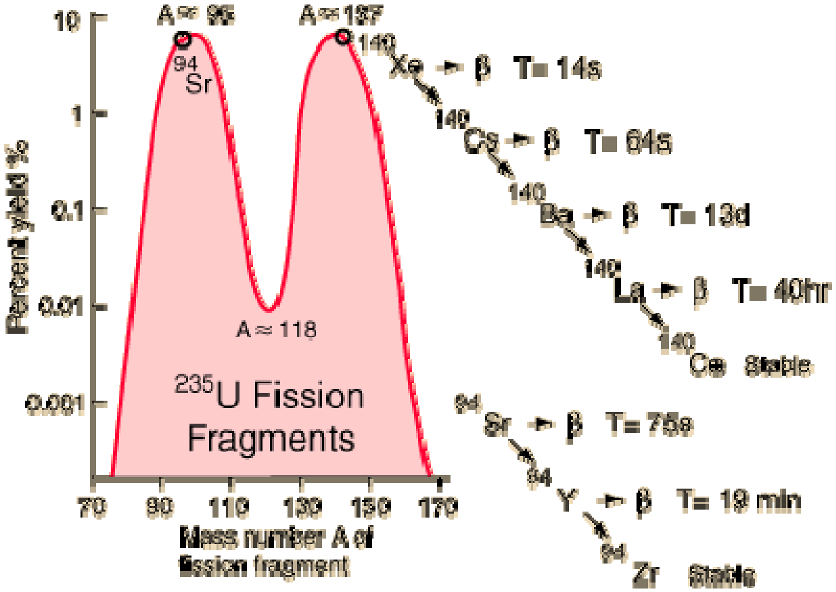
57 La Lanthanum 138.9055	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
89 Ac Actinium (227)	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

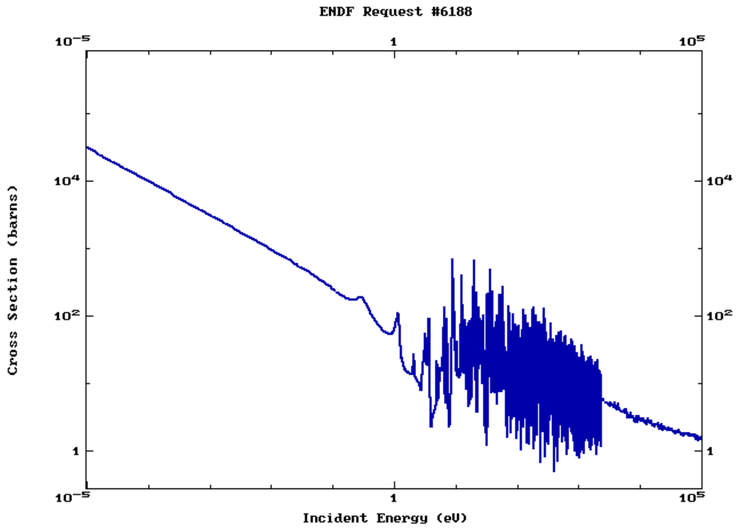
Reactors 101--Fissile and Fertile Nuclei

- In the actinides, nuclei with odd Atomic Weight (U^{235}, U^{233}, Pu^{239}) are fissile nuclei. They absorb slow thermal neutrons and undergo fission with the release of more neutrons and energy.
- Those with even Atomic Weight (Th^{232}, U^{238} etc) are Fertile nuclei. They can absorb "Fast neutrons" and will produce fissile nuclei. This is the basis of "fast breeders" and also the "energy amplifier", the subject of this talk.

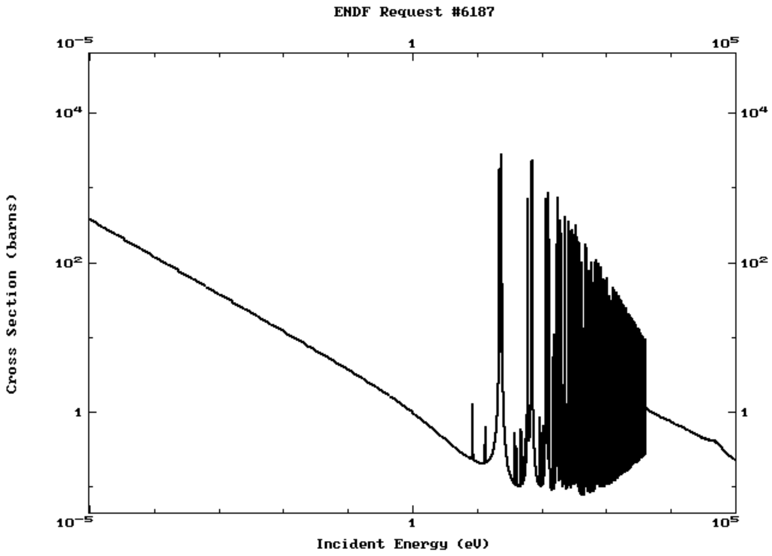


Mean energy released per fission ~200 MeV

Fission and breeding cross sections.



Cross section in barns for U^{235}+n→Fission vs incident neutron energy (eV).

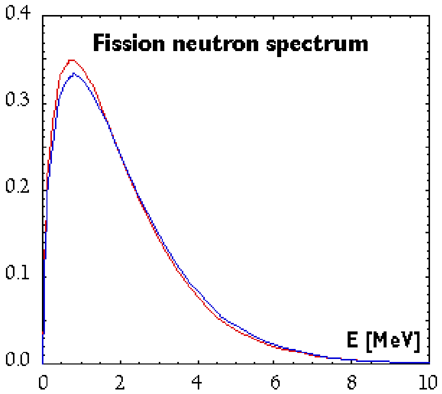


Cross section in barns for Th^{232}+n →Th^{233}+γ. This is a breeding cross section. Another is

$$U^{238} + n \to U^{239} + \gamma$$

$$U^{239} \to Np^{239} + \beta^{-} \text{ (23.4m)}$$

$$Np^{239} \to Pu^{239} + \beta^{-} \text{ (2.35d)}$$



Drawbacks of Fission reactors

- Enrichment needed for both PWR and FBR.
  - Proliferation worries
- Waste storage is a worry for PWR's and PHWR's.
  - Fission products are highly toxic, but are shortlived (Max ~30yrs halflife). However, higher actinide waste products take ~10^5 years storage to get rid of.
- All reactors operate at criticality. So are potentially unsafe.
- Economics of pre-processing fuel and post-processing the waste must be taken into account in costing the reactor kiloWatt hour.
- Uranium 235 is not that plentiful.
- Fast reactors need enriched Pu^{239} or U^{235} and do not compete economically (currently) with conventional fission reactors. French reactor Superphenix (1.2 GWe Commissioned 1984) was shut down in 1997 due to political and other problems.
- Fast Breeders have not caught on. At present BN-600 (Russia), Monju (Japan) FBTR (India) comprise most of the list.

Criticality factor k

- Let number of neutron at the first step of spallation =N_1. After these interact in the fuel once, they produce kN_1 neutrons. After the second level of interactions, this will produce N_1k^2 neutrons and so on. So in total there will be

$$N_{tot} = N_1(1 + k + k^2 + k^3 \ldots) = \frac{N_1}{1-k}$$

neutrons.

k has to be less than 1 or we have a runaway situation.

Uranium supply and demand

- Currently, Uranium supplies are expected to last 50- 100 years due to the projected use by existing and future planned conventional nuclear reactors.
- DoE Energy Information Administration Report #:DOE/EIA-0484(2008) states that

"Uranium Supplies Are Sufficient To Power Reactors Worldwide Through 2030 "

It further states

"Also, the uranium supply can be extended further by worldwide recycling of spent fuel and the use of breeder reactors. "

We MUST breed if we want to use nuclear energy long term.

Accelerator Driven Energy Amplifier

- Idea due to C.Rubbia et al (*An Energy Amplifier for cleaner and inexhaustible Nuclear energy production driven by a particle beam accelerator, F.Carminati et al, CERN/AT/93-47(ET).).* Waste transmutation using accelerator driven systems goes back even further.(*C.Bowman et al, Nucl. Inst. Methods A320,336 (1992))*
- *Conceptual Design Report of a Fast Neutron Operated High Power Energy amplifier (C.Rubbia et al, CERN/AT/95-44(ET)).*
- *Experimental Determination of the Energy Generated in Nuclear Cascaded by a High Energy beam (S.Andriamonje et al) CERN/AT/94-45(ET)*
- *A Physicist's view of the energy problem, lecture given at Energy and Electrical Systems Institute,J-P Revol,Yverdon-les-bains, Switzerland,2002*
- *Advantages-*
  - » *Sub-Critical*
  - » *Use Thorium- More plentiful than* U^{238}
  - » *Breed more fuel*
  - » *Can burn waste*
- *Disadvantages-*
  - » *Needs 10 MW proton accelerator- Does not exist as yet*

Rubbia Energy Amplifier (EA)

- EA operates indefinitely in a closed cycle
  - Discharge fission fragments
  - Replace spent fuel by adding natural Thorium
- After many cycles, equilibrium is reached for all the component actinides of the fuel.
- Fuel is used much more efficiently
  - 780 kg of Thorium is equivalent to 200 Tons of native Uranium in a PWR
  - Rubbia et al estimate that there is enough Thorium to last ~ 10,000 years.
- Probability of a critical accident is suppressed because the device operates in a sub-critical regime. Spontanous convective cooling by surrounding air makes a "melt-down" leak impossible.
- Delivered power is controlled by the power of the accelerator.
- After ~ 70 years, the radio-toxicity left is ~ 20,000 times smaller than one of a PWR of the same output. Toxicity can be further reduced by "incineration"

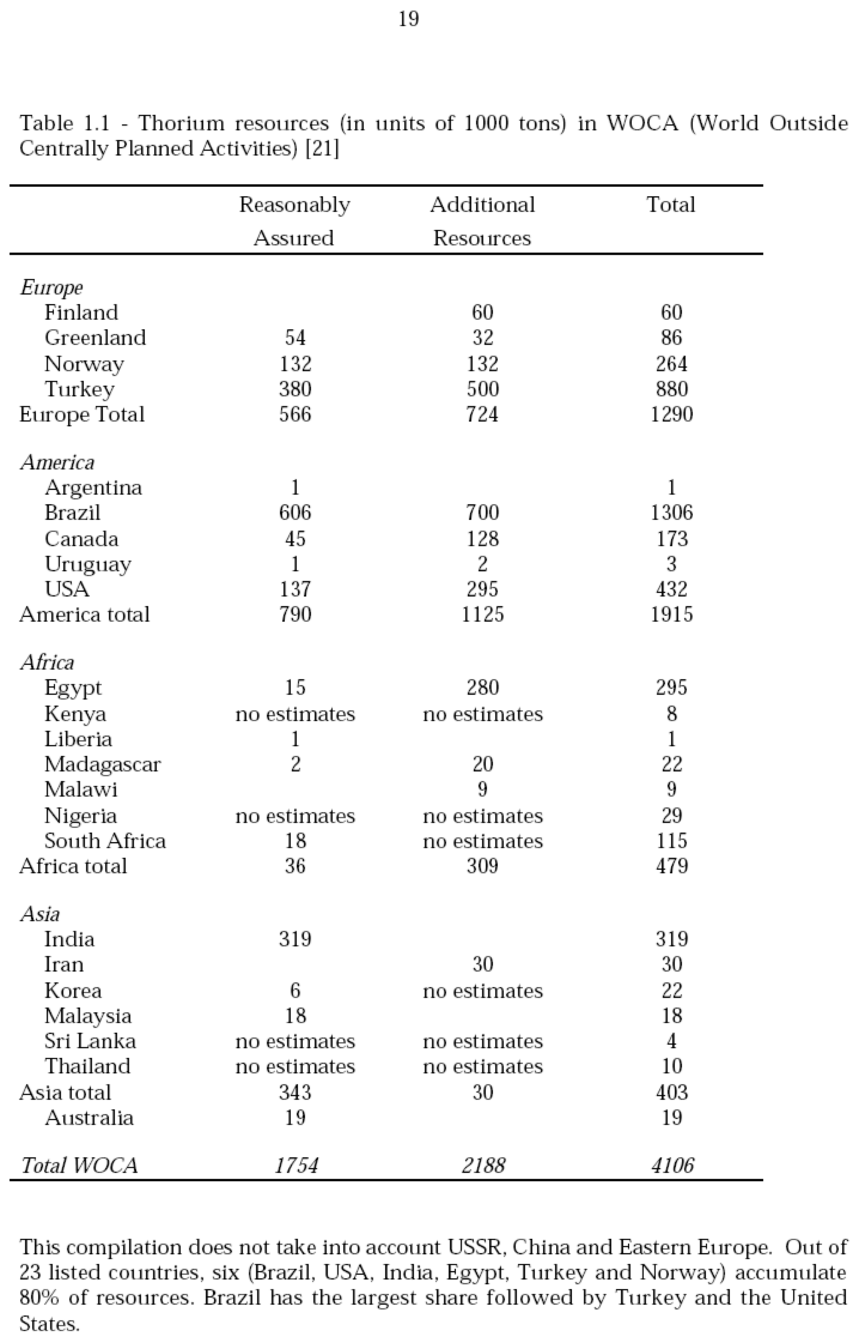


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Table 1.1 - Thorium resources (in units of 1000 tons) in WOCA (World Outside Centrally Planned Activities) [21]

	Reasonably Assured	Additional Resources	Total
Europe			
Finland		60	60
Greenland	54	32	86
Norway	132	132	264
Turkey	380	500	880
Europe Total	566	724	1290
America			
Argentina	1		1
Brazil	606	700	1306
Canada	45	128	173
Uruguay	1	2	3
USA	137	295	432
America total	790	1125	1915
Africa			
Egypt	15	280	295
Kenya	no estimates	no estimates	8
Liberia	1		1
Madagascar	2	20	22
Malawi		9	9
Nigeria	no estimates	no estimates	29
South Africa	18	no estimates	115
Africa total	36	309	479
Asia			
India	319		319
Iran		30	30
Korea	6	no estimates	22
Malaysia	18		18
Sri Lanka	no estimates	no estimates	4
Thailand	no estimates	no estimates	10
Asia total	343	30	403
Australia	19		19
Total WOCA	*1754*	*2188*	*4106*

This compilation does not take into account USSR, China and Eastern Europe. Out of 23 listed countries, six (Brazil, USA, India, Egypt, Turkey and Norway) accumulate 80% of resources. Brazil has the largest share followed by Turkey and the United States.

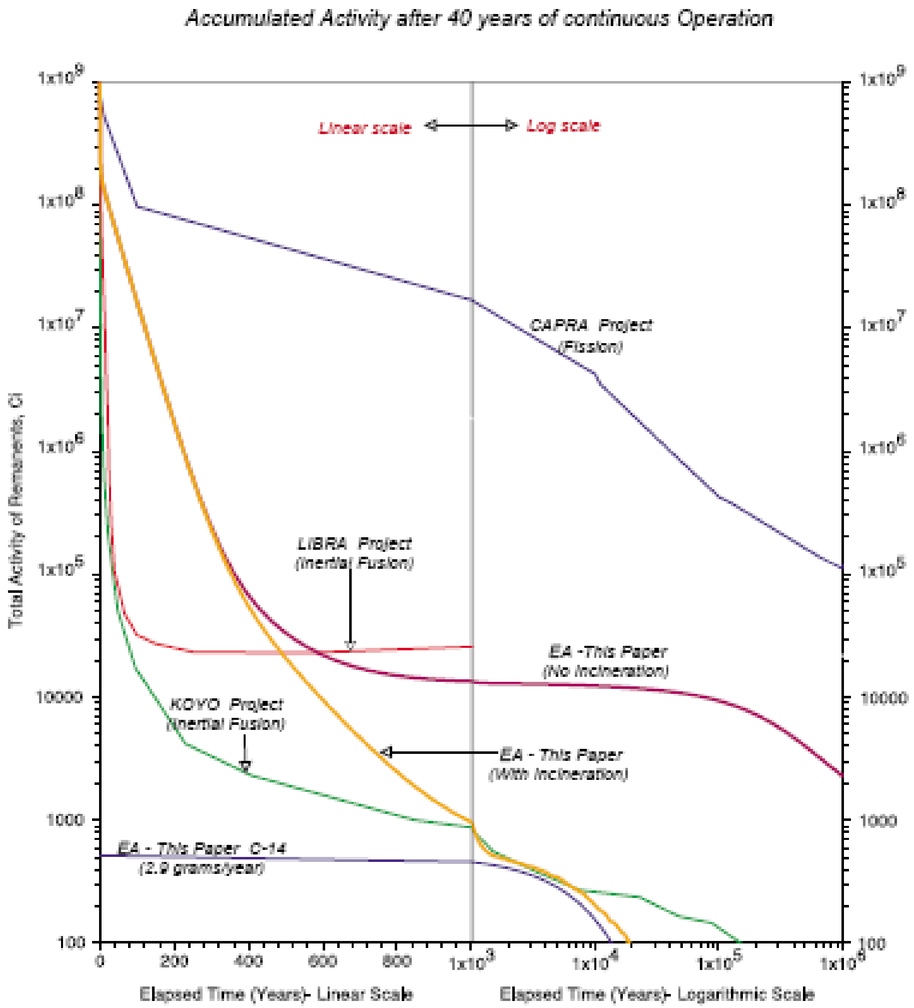
Worldwide distribution of Thorium

Geothermal energy is 38 Terawatts. Due to mostly decay of Th^{232} (predominant), U^{238} and Potassium 40.

Th^{232} has halflife of 14 billion years, U^{238}(4.5 billion years) and K^{40} (1.3billion years). Th^{232} is roughly 4-5 times more abundant than $U^{238.}$ May be enough Thorium to last $2.2x10^5$ years using the energy amplifier method.

Waste Storage Times

- Fission Products are shorter lived (~30 years half life) than actinides(~10^5 years). So actinide wastes need storage for geological periods of time – Yucca mountain solution. EA produces less actinide waste so the storage time is reduced.



The basic idea of the Energy Amplifier

- In order to keep the protactinium (It can capture neutrons as well) around for beta decay to ^{233}U, one needs to limit neutron fluxes to ~10^{14} cm^{-2} sec^{-1}. Provide this by an accelerator.

$$^{232}Th + n \Rightarrow {}^{233}Th + \gamma \xRightarrow{(22m)} {}^{233}Pa + \beta^- \xRightarrow{(27d)} {}^{233}U + \beta^-$$

- Let σ_i be the capture cross section of neutrons and σ_f be the fission cross section.

$$\frac{^{232}Th}{(1)} \Rightarrow \frac{^{233}Pa}{(2)} \Rightarrow \frac{^{233}U}{(3)} \qquad \frac{dn_1}{dt} = -\lambda_1 n_1(t)\,; \frac{dn_2}{dt} = \lambda_1 n_1(t) - \lambda_2 n_2(t)\,; \frac{dn_3}{dt} = \lambda_2 n_2(t) - \lambda_3 n_3(t)$$

- Where Φ is the neutron flux and τ_2 is the lifetime of Pa

$$\lambda_1 = \sigma_i^{\,1}\Phi;\ \lambda_2 = \frac{1}{\tau_2};\ \lambda_3 = (\sigma_i^{\,3} + \sigma_f^{\,3})\Phi$$

Thin slab of Thorium solution

- In the limit $\lambda_1 \ll \lambda_2$ and $\lambda_1 \ll \lambda_3$, one finds

$$n_1(t) = n_1(0)e^{-\lambda_1 t};\ n_2(t) = n_1(t)\frac{\lambda_1}{\lambda_2}(1-e^{-\lambda_2 t})$$

$$n_3(t) = n_1(t)\frac{\lambda_1}{\lambda_3}\left(1-\frac{1}{\lambda_3-\lambda_2}(\lambda_3 e^{-\lambda_2 t}-\lambda_2 e^{-\lambda_3 t})\right)$$

- In stationary conditions

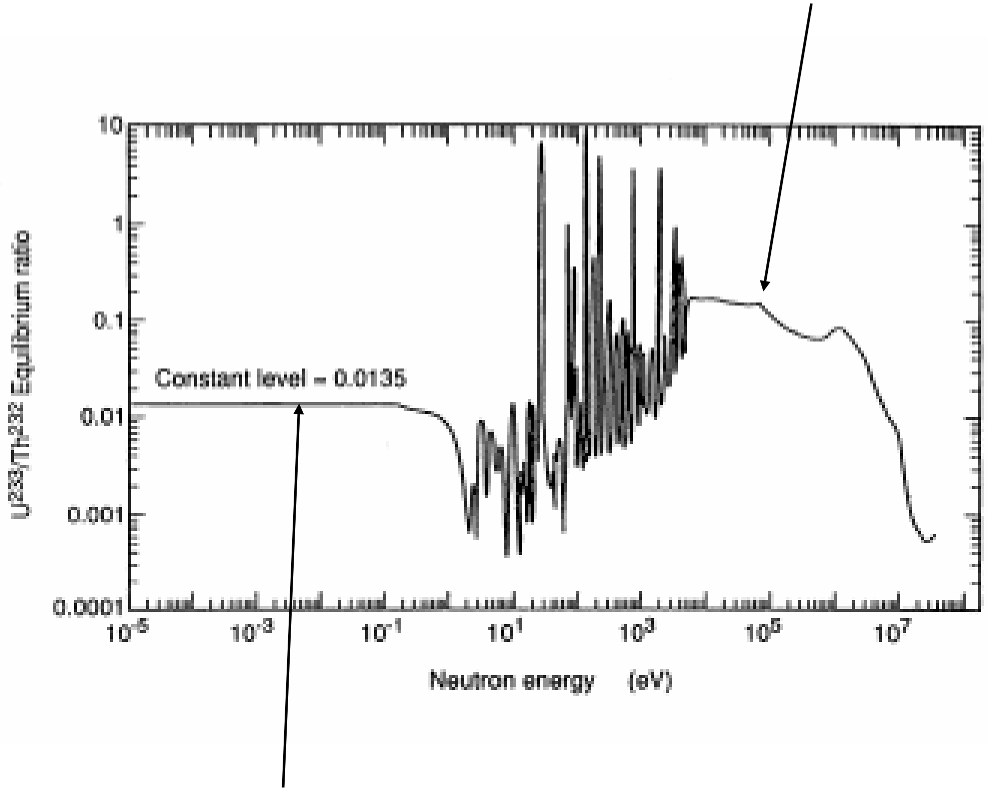
$$\frac{n_3}{n_1} = \frac{\sigma^1{}_i}{(\sigma^3{}_i + \sigma^3{}_f)}$$

- Independent of neutron flux Φ
- Power of reactor is given by (hidden k factor)

$$P = 55.3\left(\frac{M}{1\,\mathrm{Ton}}\right)\left(\frac{\Phi_{ave}}{10^{14}\,cm^{-2}s^{-1}}\right)\left(\frac{300^o K}{T^o K}\right)^{1/2}\ \mathrm{MWatt}$$

Thin Slab solution

- Operate above the resonance region where $n_3/n_1=0.1$ a factor 7 larger than thermal neutron regime.



Operate with fast neutrons here

Thermal neutron regime

Pure thorium initial state.

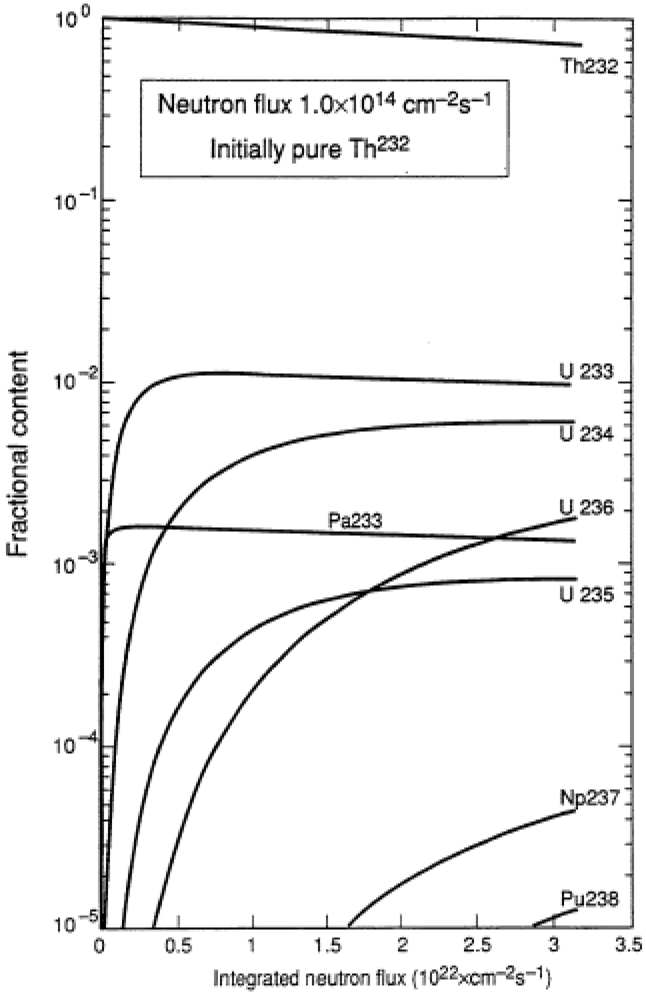


Figure 4

Thorium with initial ^{233}U as fuel

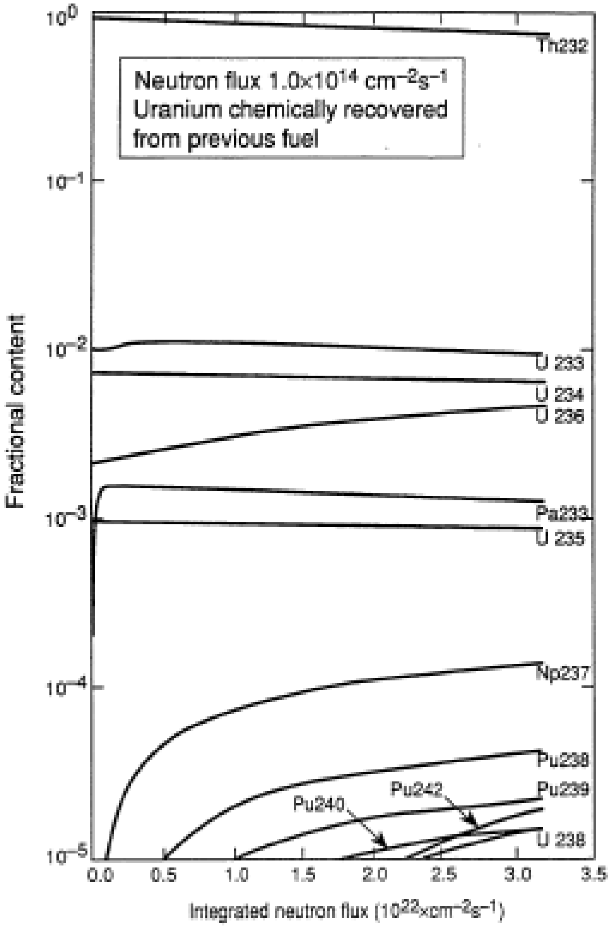
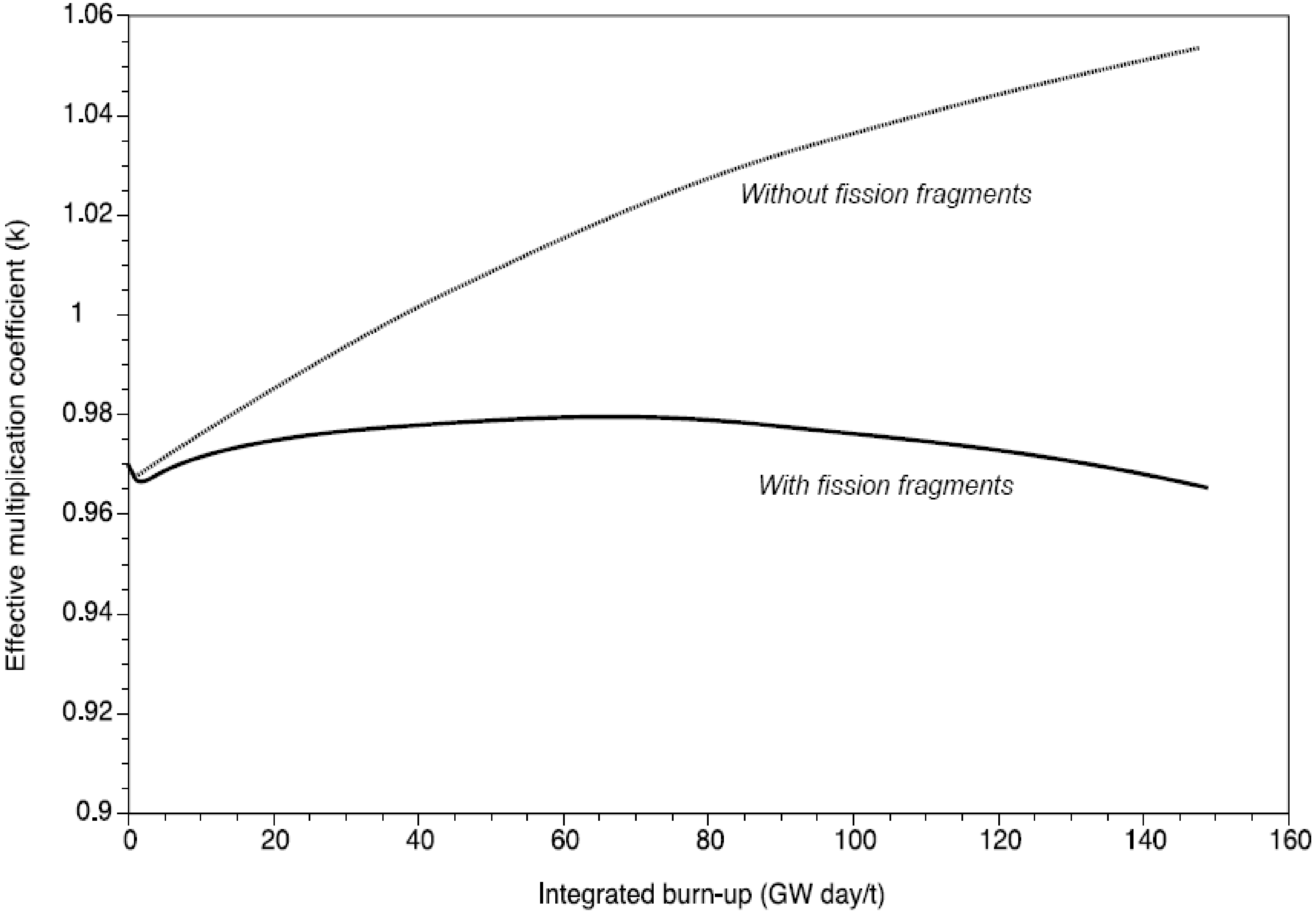
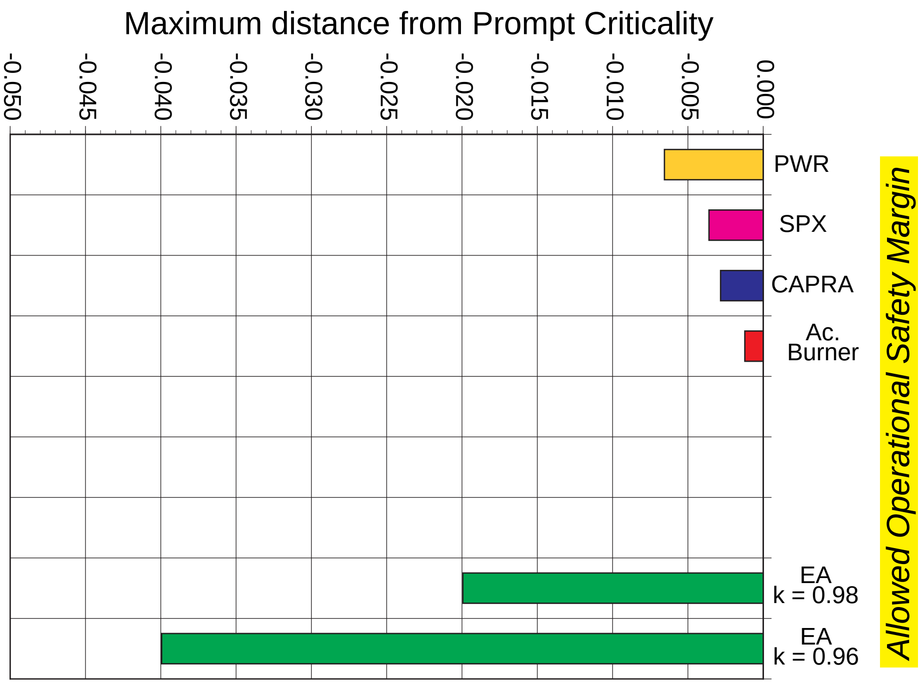


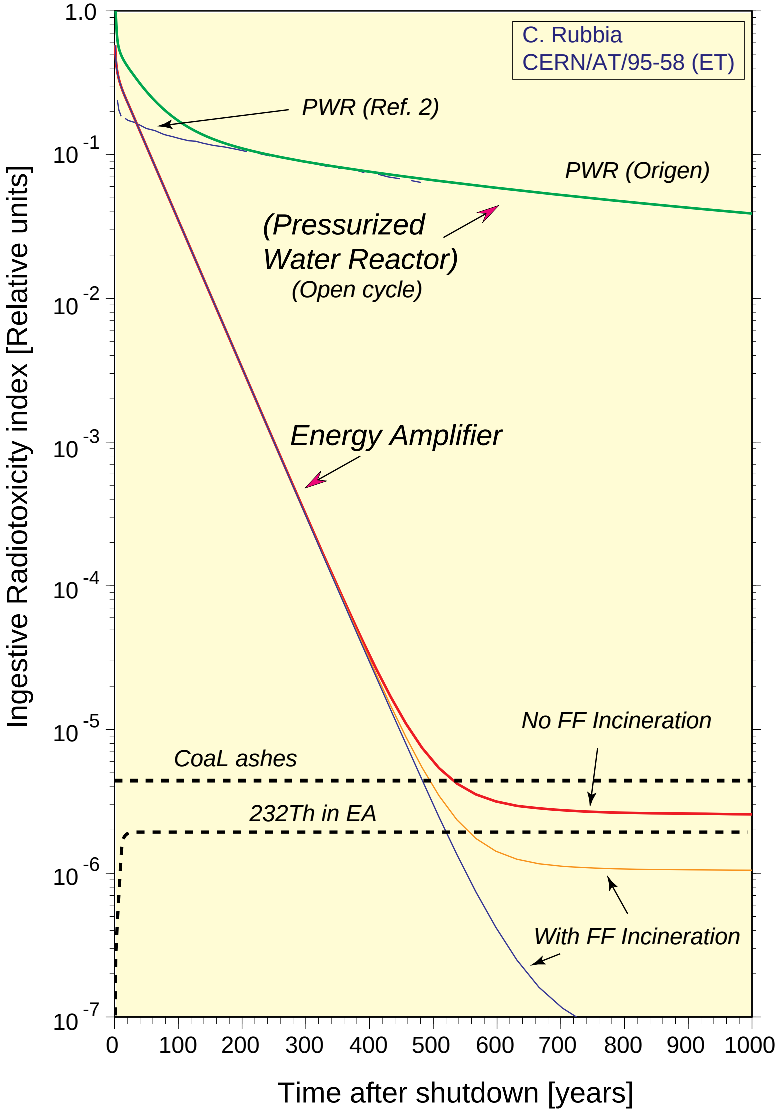
Figure 5

Variation of k with time for EA



Advantages of the EA:





Safety margin with different systems
(fraction of delayed neutrons)
as compared with that of an Energy Amplifier

The Conceptual design

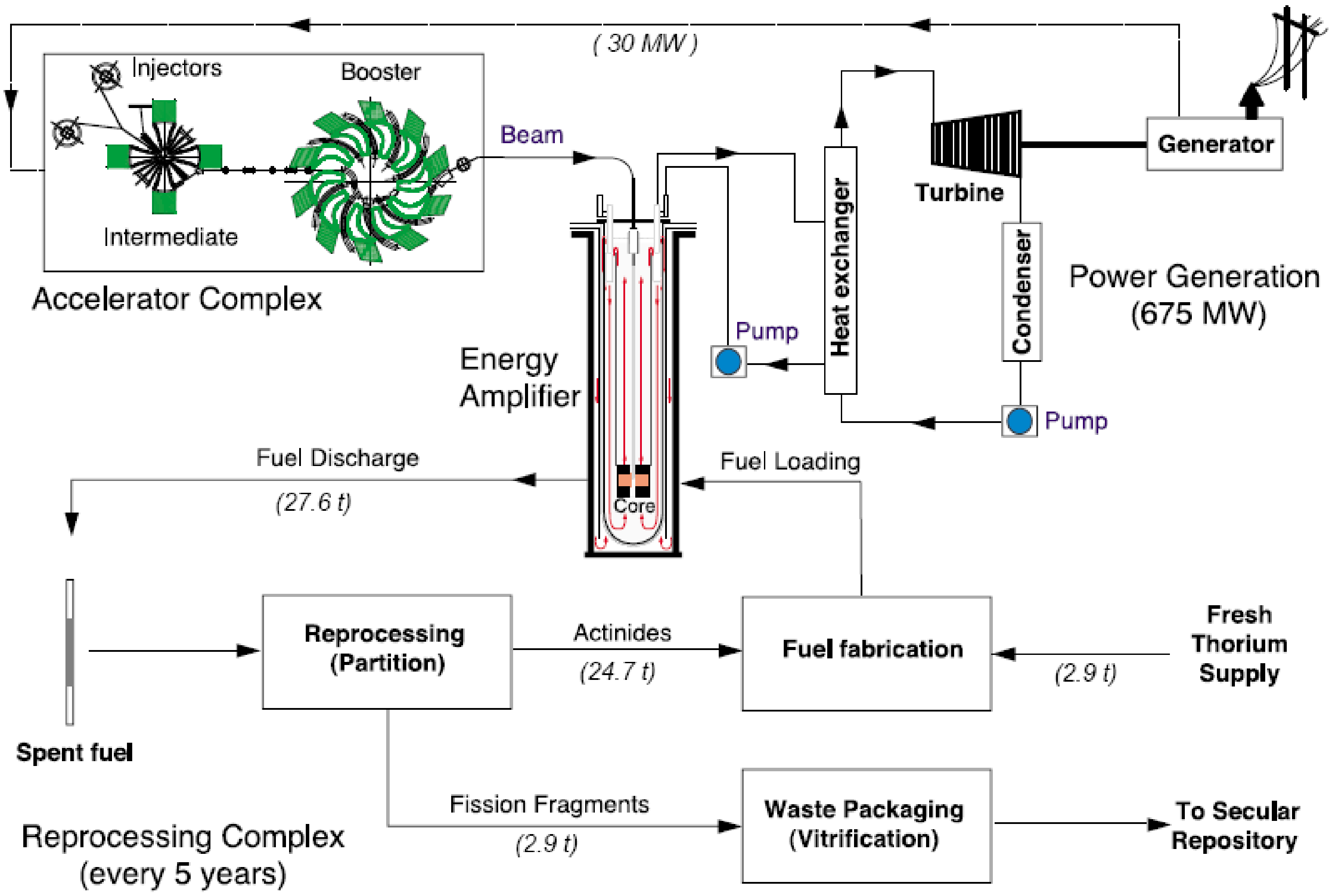


Figure 1.1

Rubbia assumptions

- 30 MW of wall power produces 10MW beam
- This serves to produce 1500 MW_{th}
- This produces 675MW_e corresponding to an efficiency of ~45%, This is better than a PWR because ADS operates at a higher temperature 600-700 degrees C.

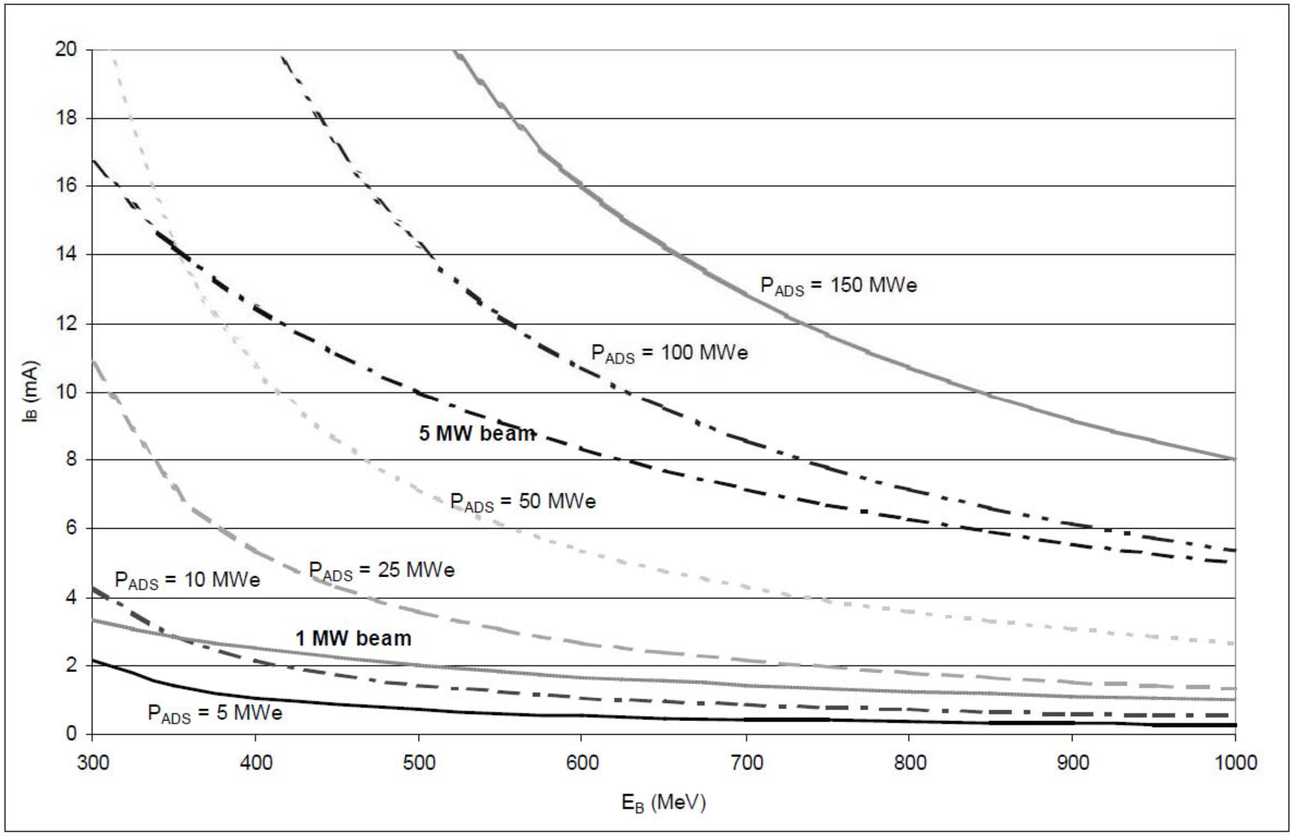
$$G = \frac{G_0}{1-k} = \frac{2G_0}{2-\eta(1-L)}$$

- Where G is the Gain of the ADS. G_0 is ~ 2.4, k is the effective criticality factor,η is the spectrum averaged number of fission neutrons produced by a neutron absorbed in the fissile isotope and L is the sum of fractional losses of neutrons absorbed by things other than fission.

Rubbia Assumptions

- In order to achieve criticality, $\eta=2/(1-L)$
- More precisely criticality is achieved when neutron losses are reduced to the value $L_{crit} = 1-2/\eta$. Since $L_{crit}>0$, $\eta>2$ for criticality. One neutron is required to maintain chain reaction and the second to be absorbed in the fertile material.
- Fast ADS has advantage over thermal breeding since it operates in a regime where η is significantly larger.

ADS and Fast Reactors a Comparative Study in Advanced Fuel Cycles (Nuclear Energy Agency and OECD 2002 report



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Rubbia and OECD Comparisons

- Rubbia ADS (10MW in, 675 MW_e) has G=120 corresponding to k=0.98. Nominal beam current for 1500MW_{th} is set to 12.5mAxGeV. Practice we may need 20 mAxGeV to allow for fission product buildup etc and loss of k factor.
- OECD assumes k=0.97
- A 10MW 1 GeV accelerator here only produces 100MW_e.
- All things being equal (Thermal efficiency), Rubbia has an equivalent k factor 0.9995!
- So clearly the two designs are NOT equivalent.
- Note that the OECD plot clearly shows that power production for a given accelerator power is optimize at ~ 1 GeV energy not lower.

Comparison of thermal efficiencies

Reactor type		Temperature		Temperature		Carnot Eff.		Actual
		Deg C		Deg K				
PWR		375		648		0.543		0.330
EA		700		973		0.696		0.423
Coal with water below critical point								0.36-0.40
Room		23		296				

A preliminary Estimate of the Economic Impact of the Energy Amplifier-CERN/LH/96-01(EET)

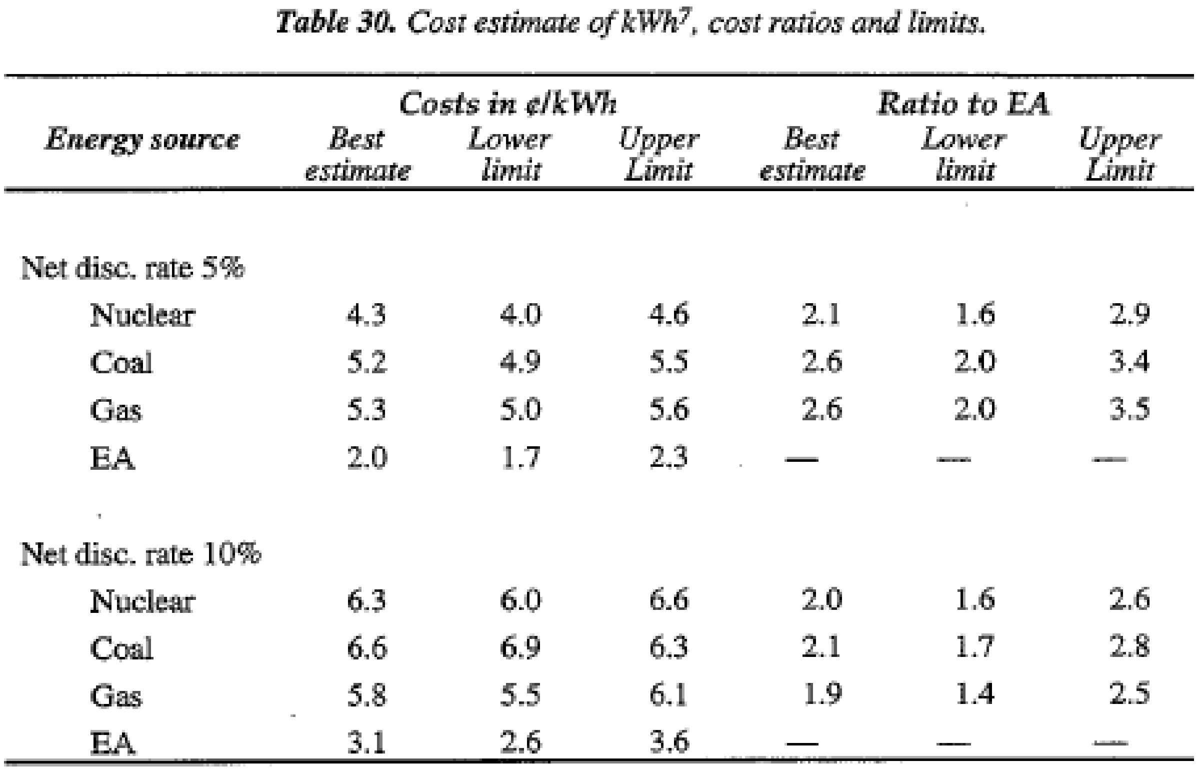
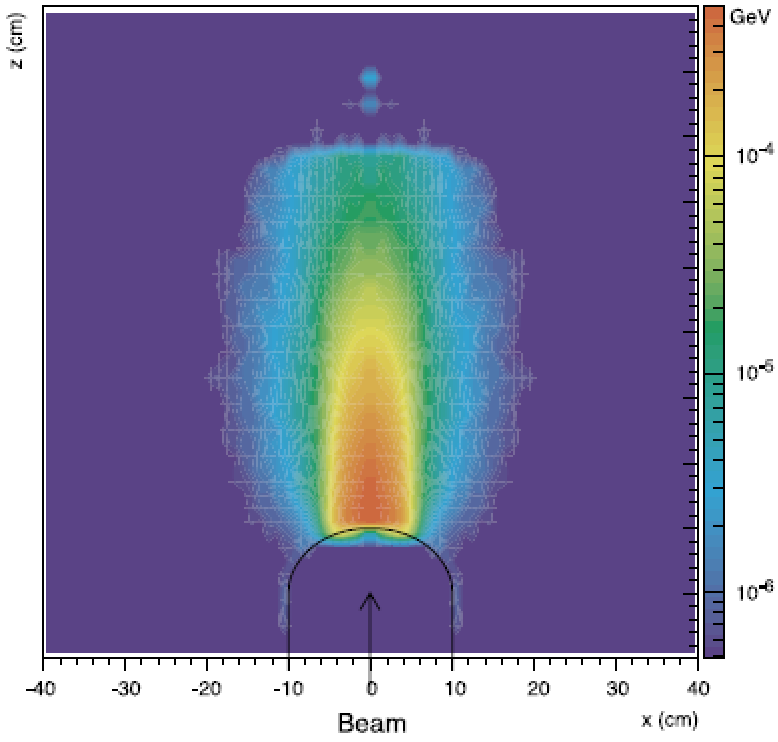


***Table 30.** Cost estimate of kWh[7], cost ratios and limits.*

Energy source	*Costs in ¢/kWh* *Best estimate*	 *Lower limit*	 *Upper Limit*	*Ratio to EA* *Best estimate*	 *Lower limit*	 *Upper Limit*
Net disc. rate 5%						
Nuclear	4.3	4.0	4.6	2.1	1.6	2.9
Coal	5.2	4.9	5.5	2.6	2.0	3.4
Gas	5.3	5.0	5.6	2.6	2.0	3.5
EA	2.0	1.7	2.3	—	—	—
Net disc. rate 10%						
Nuclear	6.3	6.0	6.6	2.0	1.6	2.6
Coal	6.6	6.9	6.3	2.1	1.7	2.8
Gas	5.8	5.5	6.1	1.9	1.4	2.5
EA	3.1	2.6	3.6	—	—	—

Map of the energy deposit of a 1 GeV proton into the FEA target



- Will multiple beams into a reactor make for a more uniform neutron distribution?
- Window stress will clearly be eased.
- Lead spallation produces ~30 neutrons for every 1 GeV proton.
- Lead has a negative void coefficient (i.e reactor power decreases if local voids form). So may be possible to run it higher temperatures still. Boiling point of lead is 1743°C.
- Much R&D needed here.

SCRF Q factor vs normal rf Q factor

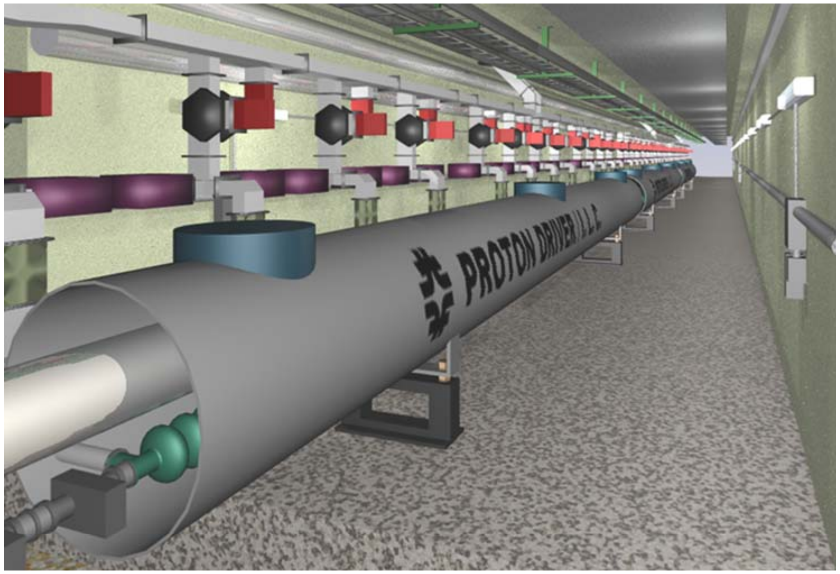
- Q factor of an oscillating system is defined as

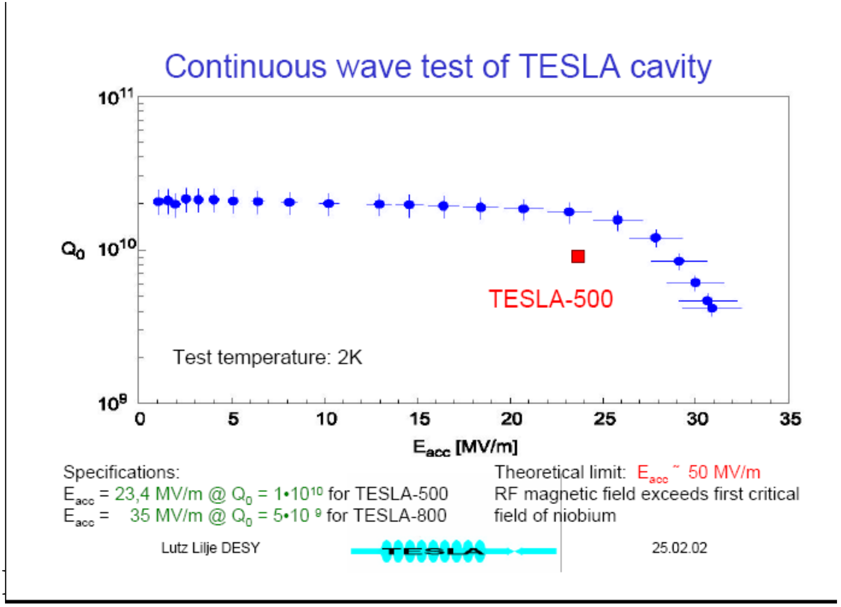
$$Q = \omega \frac{\text{Energy stored in cavity}}{\text{Power lost in cavity}}$$

$$\text{eg } Q = \frac{1}{R}\sqrt{\frac{L}{C}} \text{ for a resonant tuned circuit}$$

- SCRF Q factors ~2.0E10
- Normal rf Q factors are of order 3E5, 5E5.

- So SCRF has an advantage of ~1E5 in terms of energy dissipated in the rf itself. However, one needs to factor in cryogenics, klystron losses etc.




Continuous wave test of TESLA cavity

Specifications:
E_{acc} = 23,4 MV/m @ $Q_0 = 1\cdot10^{10}$ for TESLA-500
E_{acc} = 35 MV/m @ $Q_0 = 5\cdot10^{9}$ for TESLA-800

Theoretical limit: E_{acc} ~ 50 MV/m
RF magnetic field exceeds first critical field of niobium

Lutz Lilje DESY

25.02.02

AC Power requirements for a Superconducting 1 GeV 10 MW Linac/Al Moretti– Preliminary

There are 87 Superconducting cavities at 4 K and 18 cavities at room temperature plus Rt. RFQ at 325 MHz and 50 ILC superconducting cavities at 1.8 K to reach 1 GeV. I have used data from reports of the PD, XFEL and Cryo group to derive this AC Power Table below. All Cavities and RFQ are made superconducting in this case.

klystron	*Eff = 64 %*	Power to Beam 10 MW	Mains Power 15.6 MW
Water tower cooling	Eff=80 %	15.6 MW/.80	7 MW
4 Deg Load	6100 W	AC Power ratio 200/1	1.2 MW
2 K Load	1250	AC Power ratio 800/1	1 MW
70 K load	5580	AC Power ratio 20/1	0.1 MW
HOM 2 K load	116	AC Power ratio 800/1	0.1 MW
		TOTAL	25 MW

Conclusions and questions

- We need to demonstrate that we can build a 10 MW 1GeV proton accelerator.
- How reliable does it need to be made?
- What is the Wall power/beam power ratio for a SRF Linac with 20mAxGeV power built along the lines of Project-X?
- Can we design better reactors that remove the stringent requirement of a few pulses lost every month? Or do we have to design in redundancy?
- Will a smart grid and energy storage systems (needed for wind and solar) ameliorate the accelerator reliability requirements?
- Perhaps this workshop can help answer some of these questions.