Accelerator Driven Nuclear Energy- An Introduction

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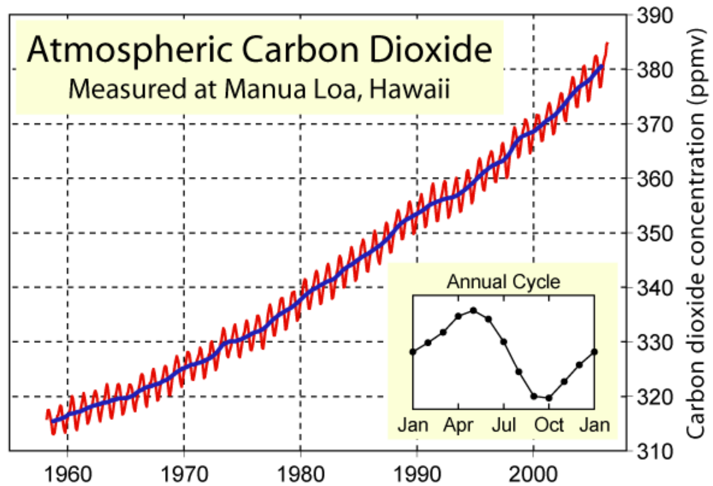
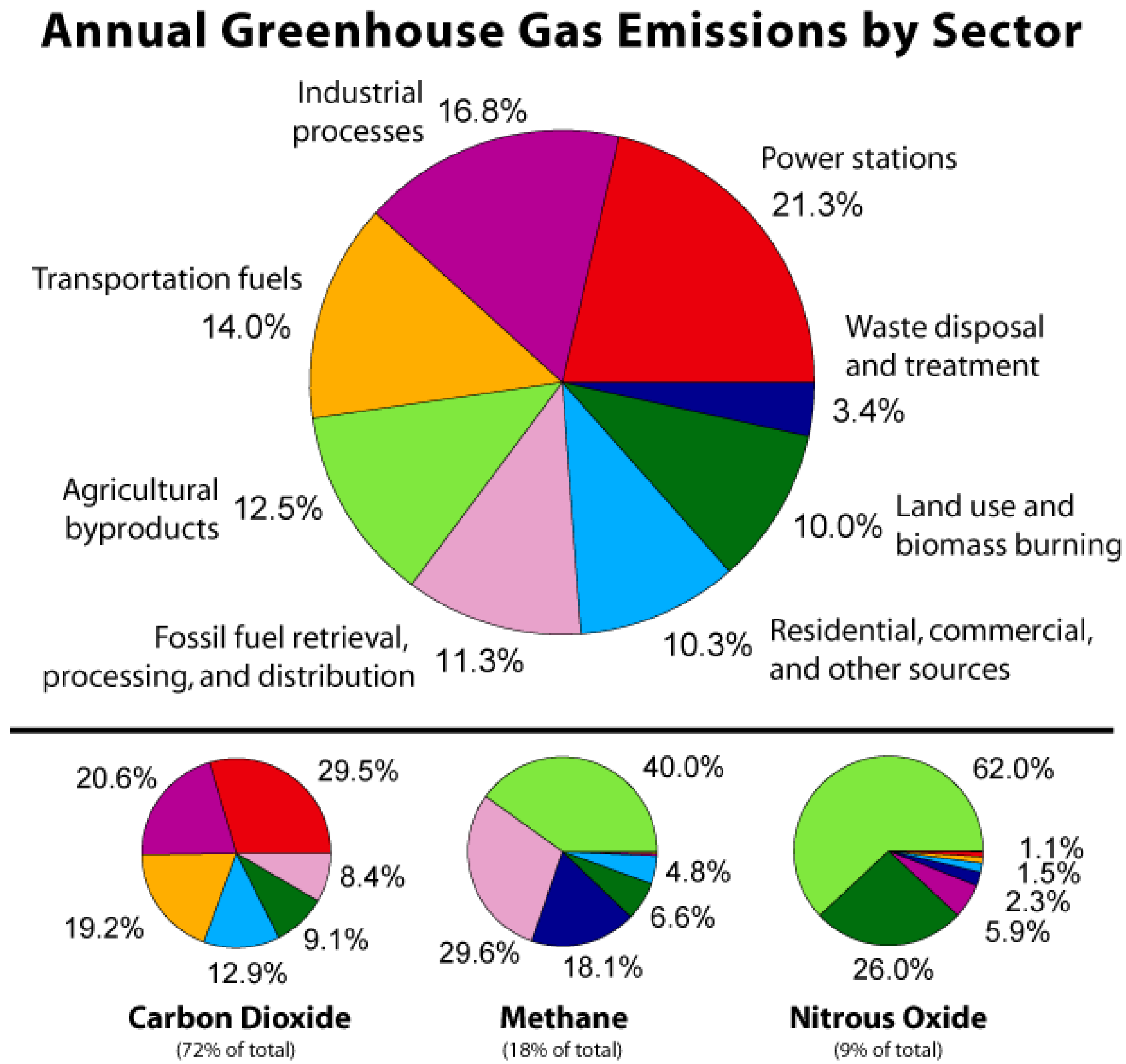
- Global Warming has to be taken seriously.
- 6% of world's energy from Nuclear, Oil, coal and Natural gas (85%)!
- There is widespread consensus in many countries with nuclear energy experience that ADS (Accelerator Driven Sub-critical systems) need to be developed.

Format of talk

- Will briefly review the world energy situation and projections
- Nuclear reactors –review various types
  - » Uranium 235 Fission reactors
    - Pressurised water reactors
    - CANDU Heavy water reactors
  - » Fast Breeder Reactors
  - » Problems-
    - Fuel enrichment
    - Nuclear Waste Storage
- Accelerator supplying neutrons is an old idea. 1948 fear of uranium shortage- MTA accelerator project started to produce fissile material from U238 (0.25Amps of deuterons).
- R.R. Wilson Fermilab note FN-298
- Accelerator Driven Breeder reactors (C.Rubbia et al-1993-1997)
  - » Thorium option
  - » Uranium 238 Option
  - » Advantages in fuel availability, efficiency and waste storage
- Needs a 1 GeV 10-20 MegaWatt accelerator
  - » May be doable with SCRF and/or FFAG
  - » Challenging accelerator R&D.
- .

Global Warming-GASES





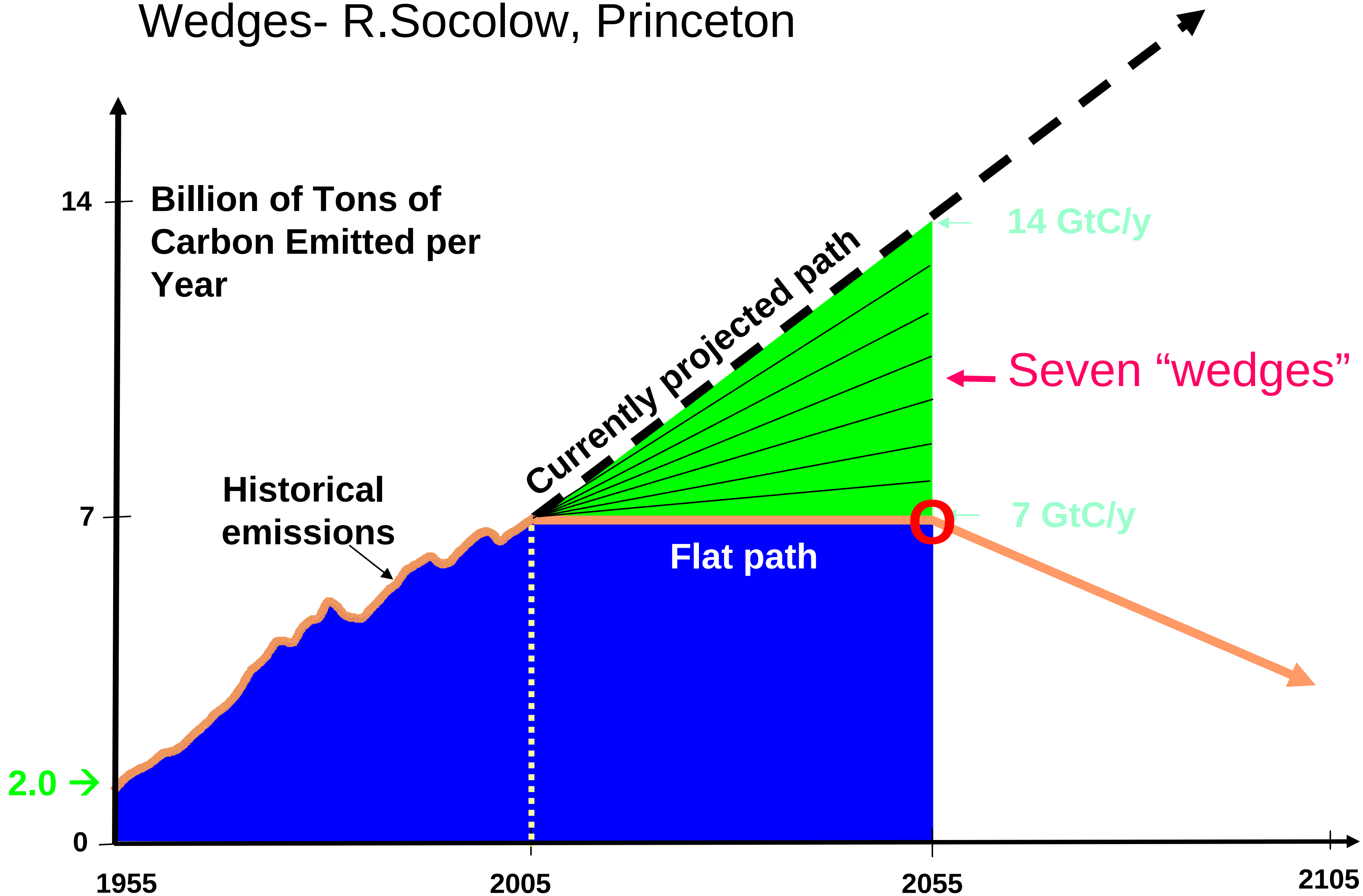
Predicted effects of global warming

- **Top Scientists Warn of Water Shortages and Disease Linked to Global Warming**
- By THE ASSOCIATED PRESS
- Published: March 12, 2007
- WASHINGTON, March 11 (AP) — The harmful effects of global warming on daily life are already showing up, and within a couple of decades hundreds of millions of people will not have enough water, top scientists are likely to say next month at a meeting in Belgium.
- At the same time, tens of millions of others will be flooded out of their homes each year as the earth reels from rising temperatures and sea levels, according to portions of a draft of an international scientific report by the authoritative Intergovernmental Panel on Climate Change.
- Tropical diseases like malaria will spread, the draft says. By 2050, polar bears will mostly be found in zoos, their habitats gone. Pests like fire ants will thrive.
- For a time, food will be plentiful because of the longer growing season in northern regions. But by 2080, hundreds of millions of people could face starvation, according to the report, which is still being revised.
- Loss of coastal cities in 100 years?

How do we combat global warming?

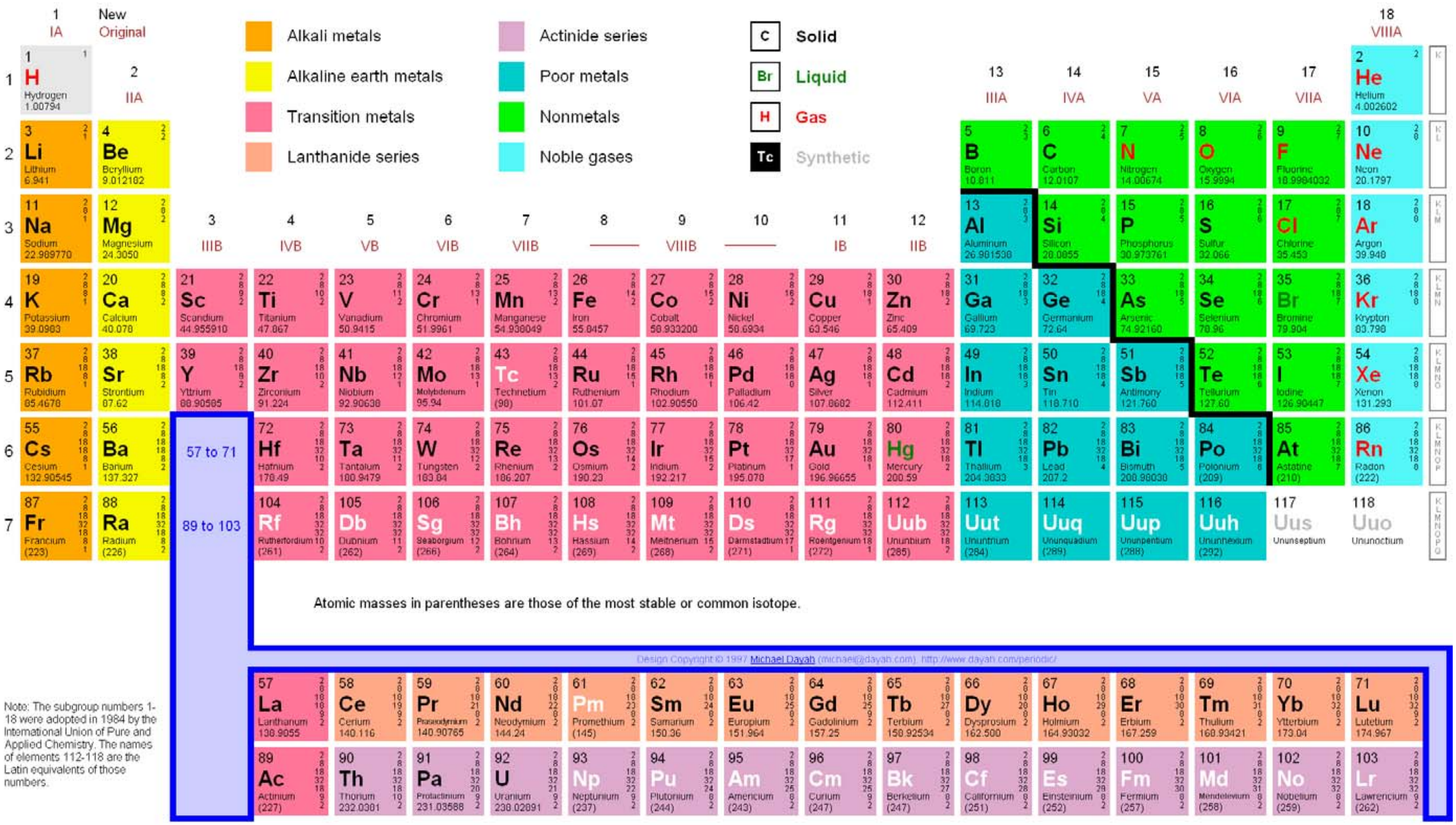
- Conservation
- Cleaner burning of coal, oil, natural gas
- More solar, wind, geothermal—Need Scale up by factor of 10—Unforeseen problems. Transmission grid, storage of power could be such issues.
- Nuclear energy---Fission, Fusion
- Which one shall we choose?
- Answer all of the above.
- Nuclear energy currently has problems-
  - » Current sources of Uranium will run out in 50-100 years if conventional nuclear power is used.
  - » Nuclear Waste—long term storage, use only 0.7% of natural Uranium (^{235}U). If more fuel needed, will have to breed.
  - » Fast breeder reactors are inherently critical. Need plutonium core-not economically competitive with Light Water Reactors (LWR) at present
  - » Try a new tack– breed using accelerators.

Wedges- R.Socolow, Princeton



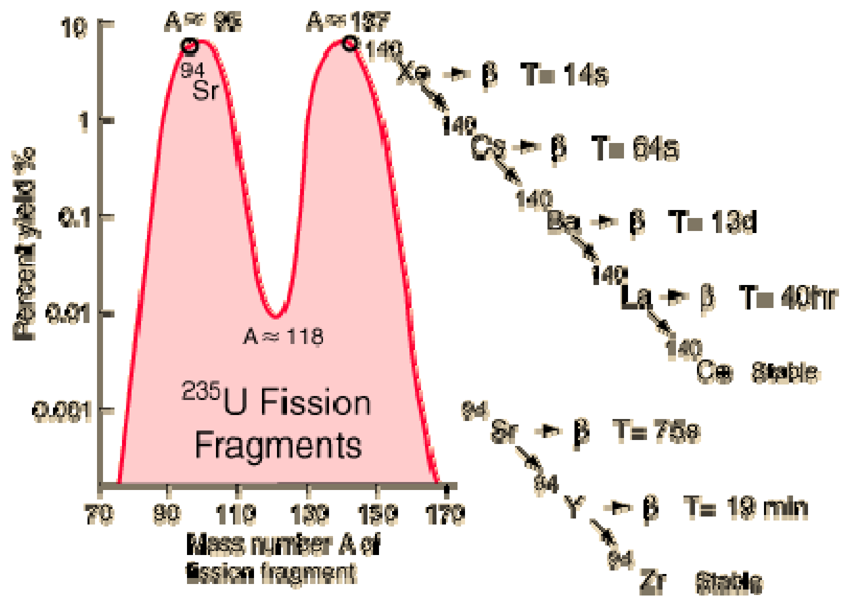
1 Wedge needs 700 GW (2 current capacity) from nuclear energy by 2055.

Periodic Table of the Elements



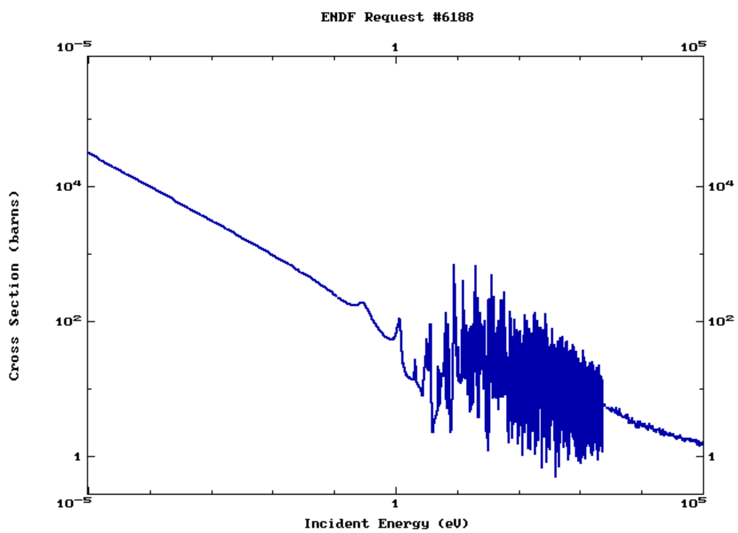
Reactors 101--Fissile and Fertile Nuclei

- 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.

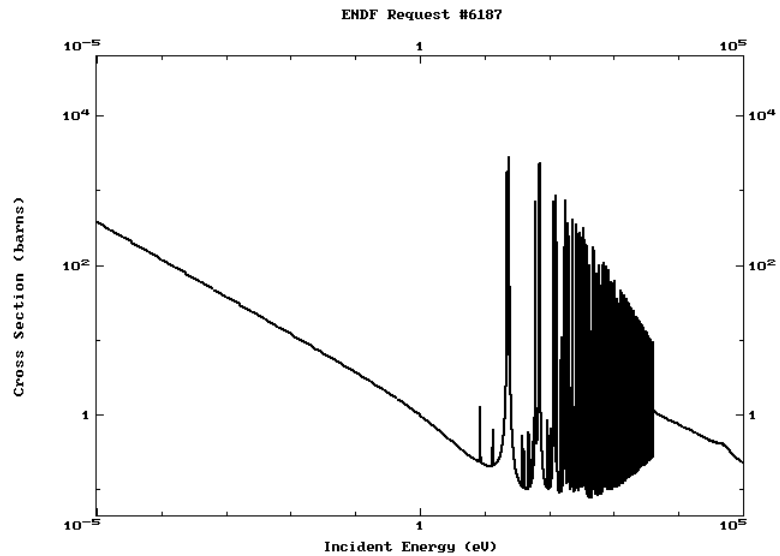


Mean energy released per fission ~200 MeV

Fission and breeding cross sections.



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

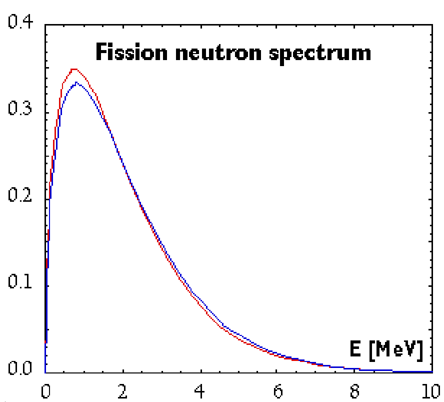


Cross section in barns for Th^{232}+n →Th^{233}+γ. This is a breeding cross section. Another is

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

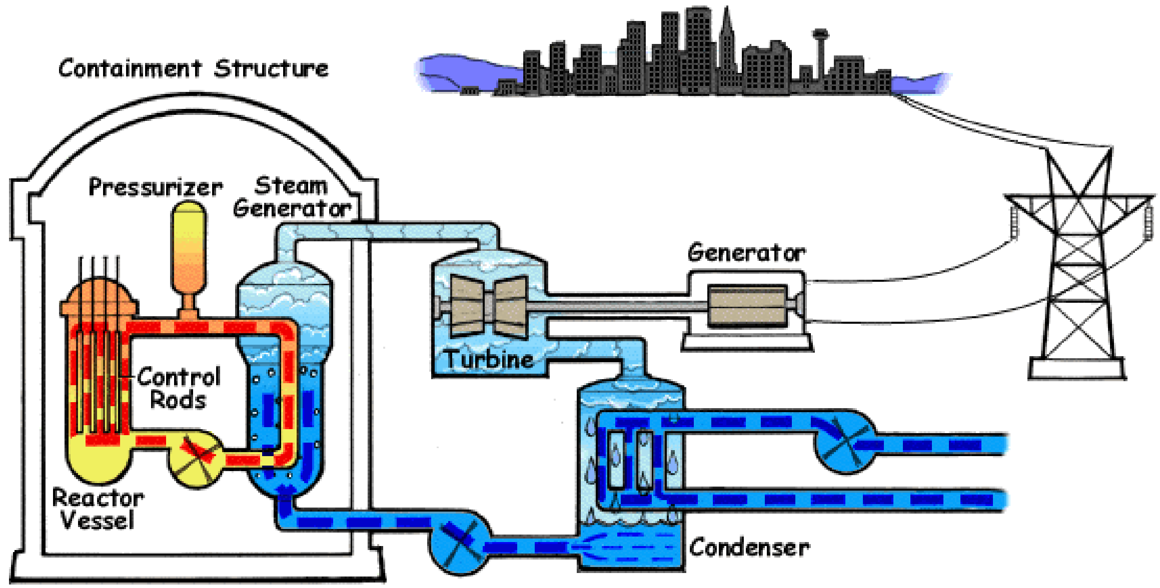
$$U^{239} \to Np^{239} + \beta^- \text{ (23.4m)}$$

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

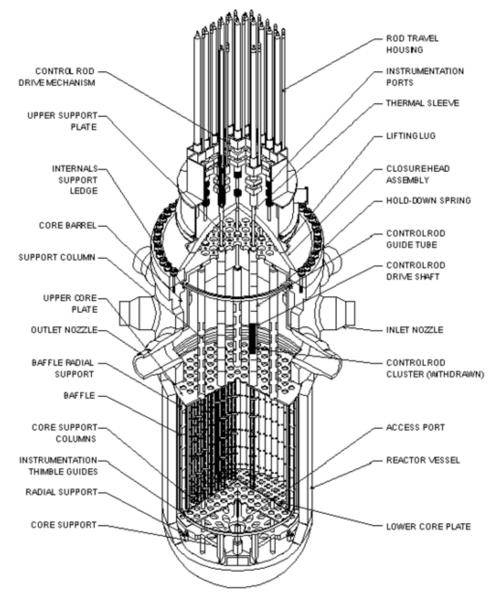


Fission Reactors-Pressurised Water reactors (PWR)

- Moderation using boric acid in pressurised water (150atm). Too much heat will produce steam, will reduce moderation. Safety feedback loop
- Uranium is enriched to ~4% U^{235}, Natural 0.7%
- Delayed neutrons from decay of isotopes make the reactor just critical.

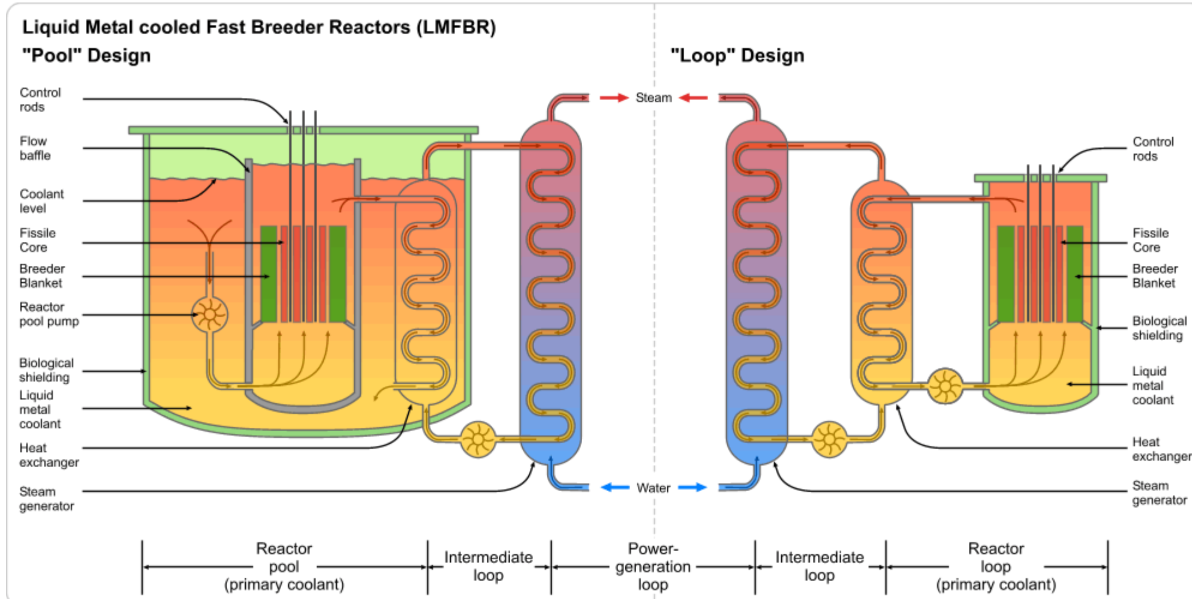


Control rods used for starting and stopping the reactor.



Fast Breeder Reactors

- Neutrons not moderated.
- Use the neutrons to breed fissile material using fertile nuclei (U^{238}, Th^{232}).
- Coolant is usually liquid sodium. Cannot use Water!
- Fissile core eg ($20\%PuO_2+80\%UO_2$)
- Breeds more fuel in the blanket and also in the fissile fuel.
- Control is more complicated than conventional reactors.



Two common designs shown= Pool type and loop type.

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

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

neutrons.

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

Criticality is a property of the pile.

Criticality issues

- In both conventional and fast reactors, criticality is achieved by carefully balancing the neutron budget.
- Delayed neutrons from decay of unstable nuclei have time constants of up to 30 secs and ameliorate the job of controlling the reactor.
- Indeed Fermi declared that " without delayed neutrons we could not have a nuclear power program".
- In a critical reactor, any random increase in power generation must be controlled by a rapid feedback mechanism through mechanical control of neutron absorbing rods. In an ADS, this is done by control of accelerator power. Neutrons from Plutonium cannot be switched off!
- Richard Wilson adds to this " without delayed neutrons, we would have to have an accelerator driven sub-critical assembly".
- Both fast and conventional reactors rely on delayed neutrons for control. In conventional reactors, there is the additional mechanism of "doppler control". If the temperature rises, the fission cross section by thermal neutrons drops.

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.

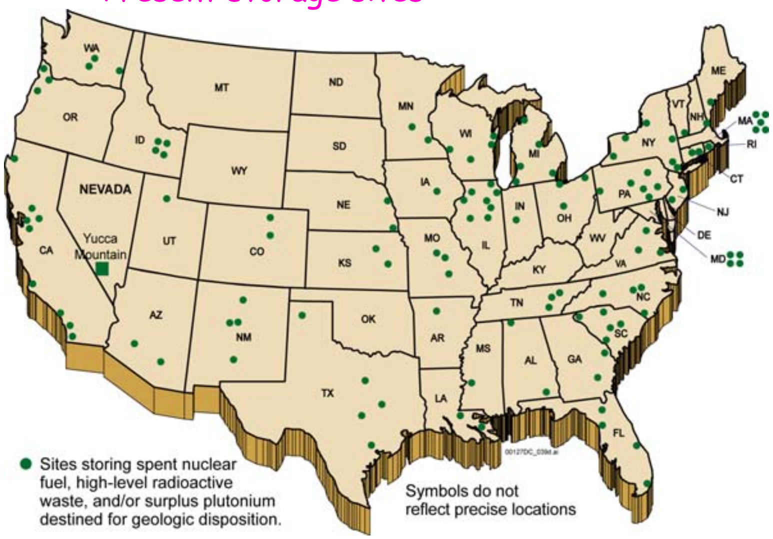
Recycling Strategies

- After years of usage, fission fragments rise in the reactor core. These absorb ("poison") thermal neutrons and the reactor can no longer operate at criticality.
- U.S currently stores away the "nuclear waste" after a single such pass.- Collossal "waste" of energy, since the spent fuel contains actinides.
- France and other European nations, recycle the fuel by removing the fission fragments. There is some small amount of breeding in conventional reactors.
- Breeder reactors are needed to address the fuel supply problem.

Waste Management-Yucca Mountain Repository

- $10Billion spent- Should have been ready by 1998
- Storing nuclear waste after single pass is wasting energy.
- ADS approach makes this unnecessary

Present storage sites



Accelerator Driven Energy Amplifier

- Idea developed by 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"

Worldwide distribution of Thorium

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.

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.

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 $\sim 10^{14}$ 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 $\lambda_1 << \lambda_2$ and $\lambda_1 << \lambda_3$, 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

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

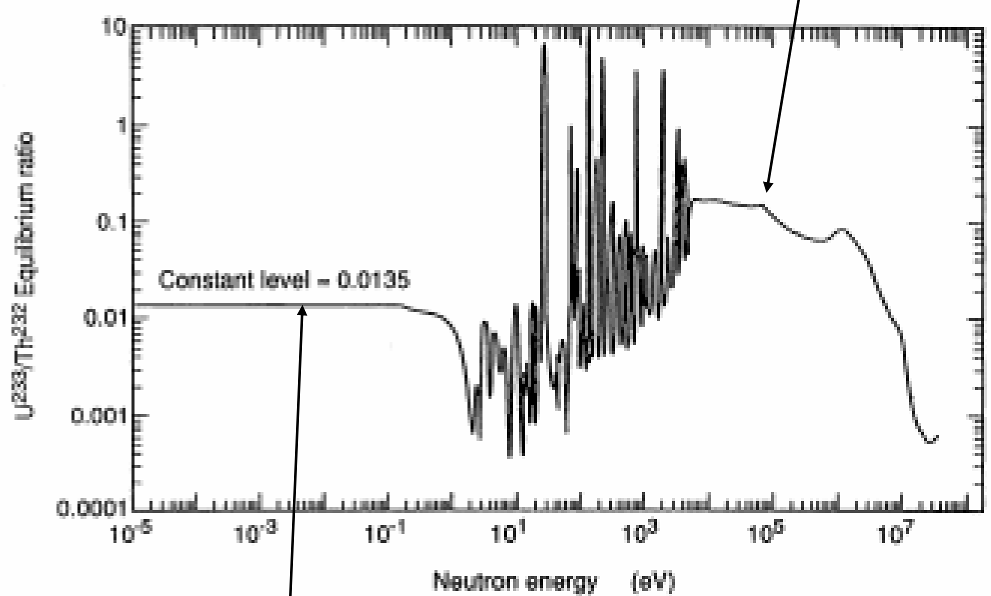
- Independent of neutron flux Φ
- Power of reactor is given by

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

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.

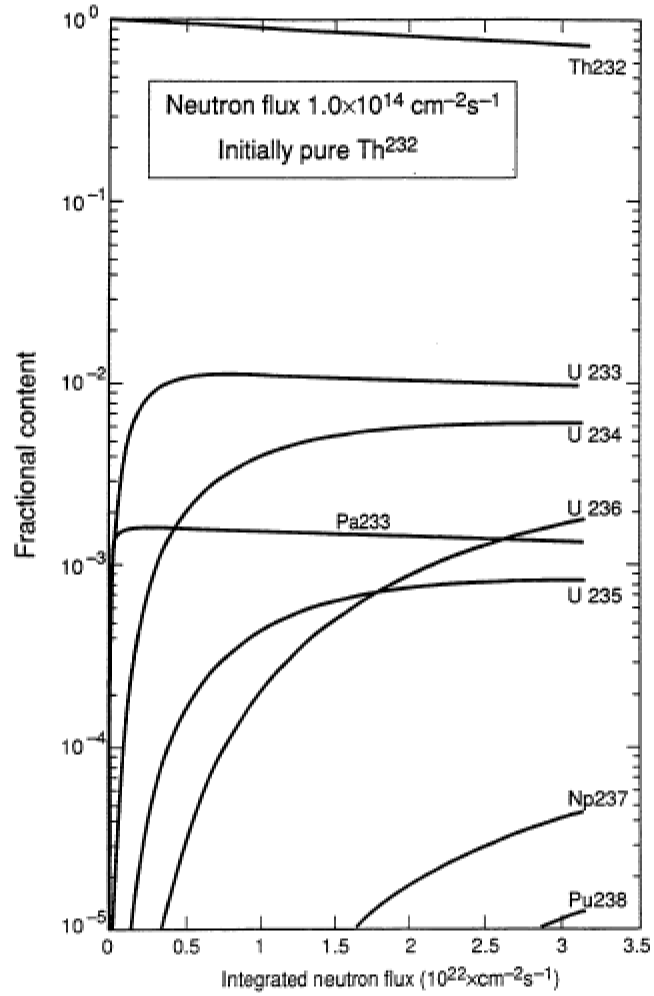


Figure 4

Thorium with initial ^{233}U as fuel

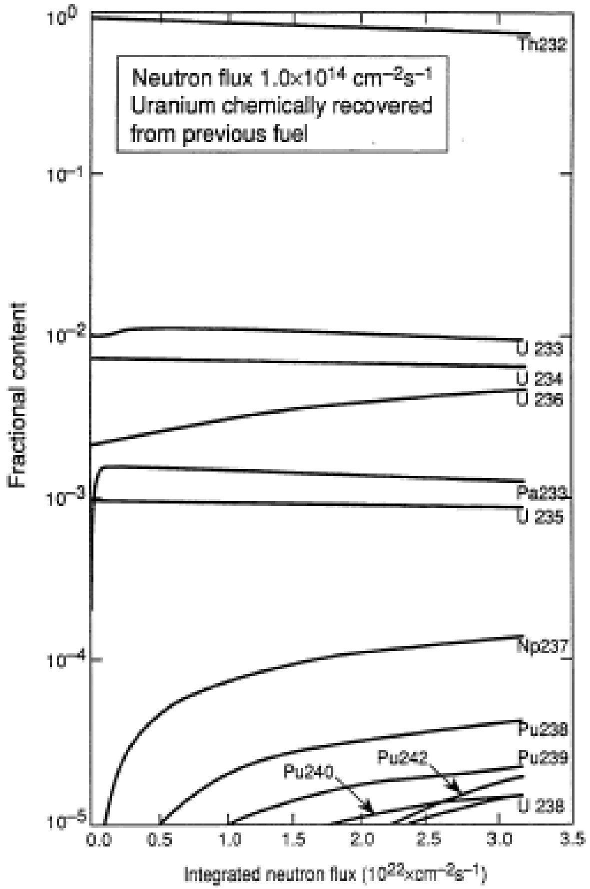


Figure 5

Natural Uranium 238 as fuel

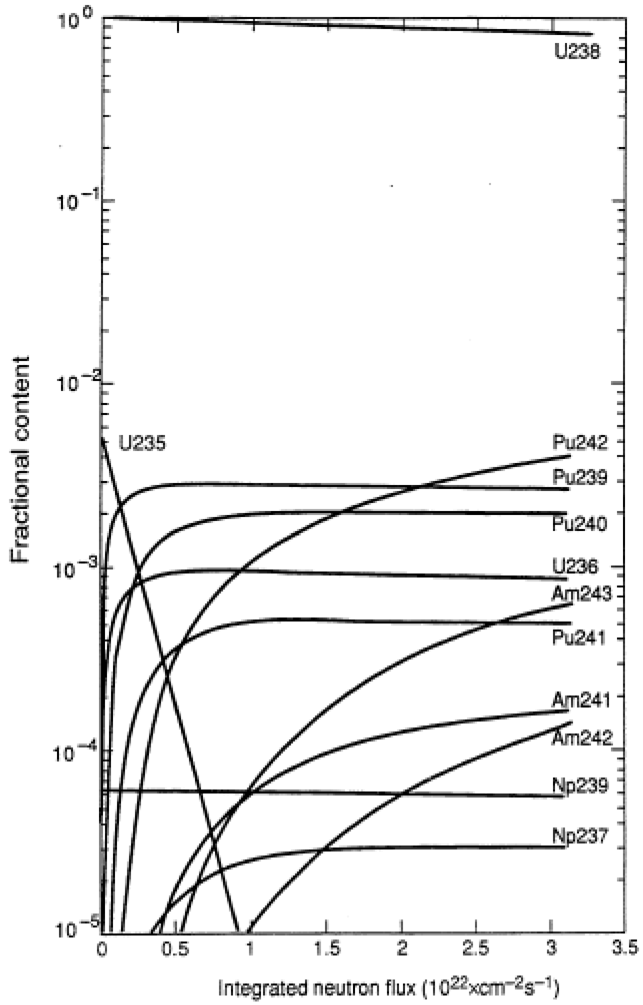
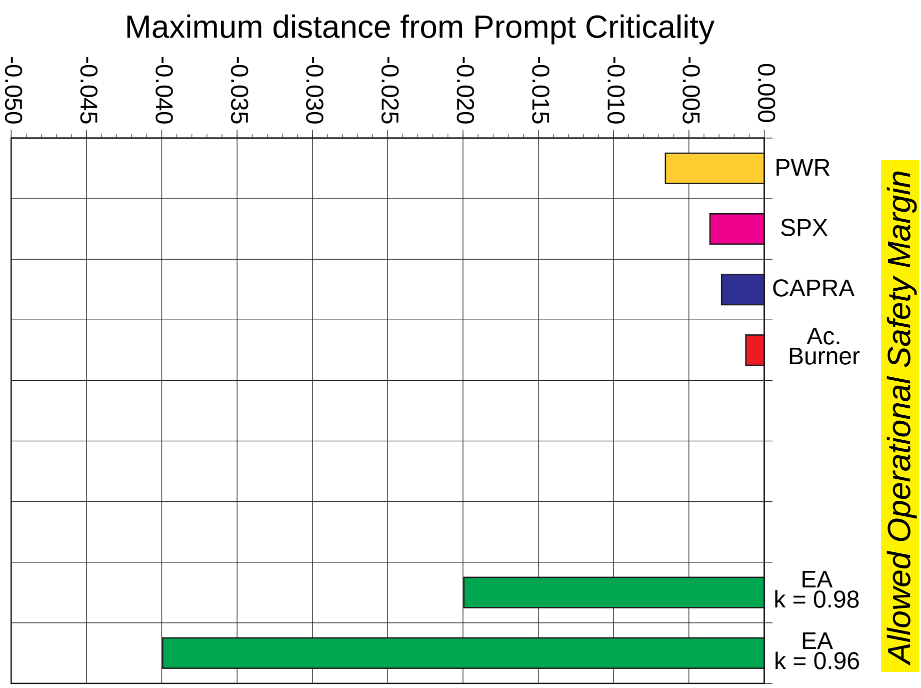
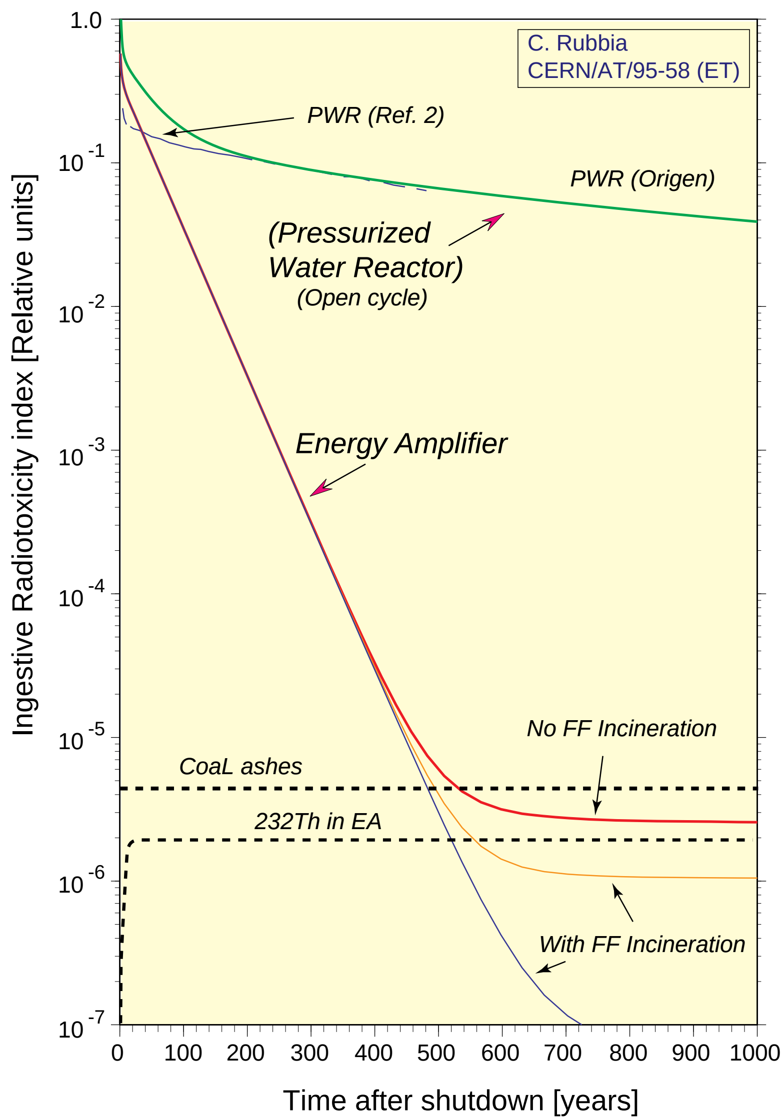


Figure 7

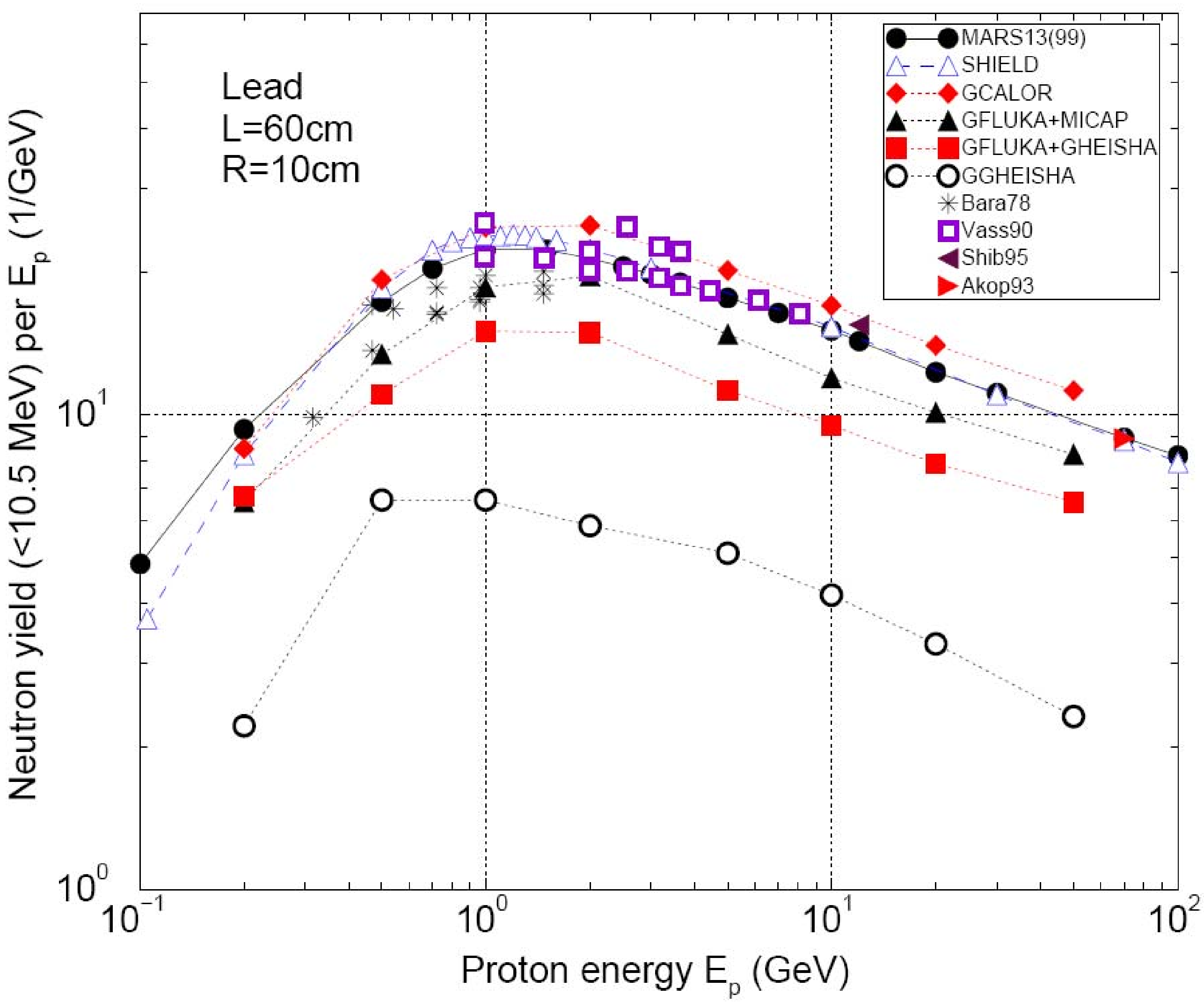
Advantages of the EA:



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



Neutron Yield from Lead Absorber for p, d, α and C



The Conceptual design

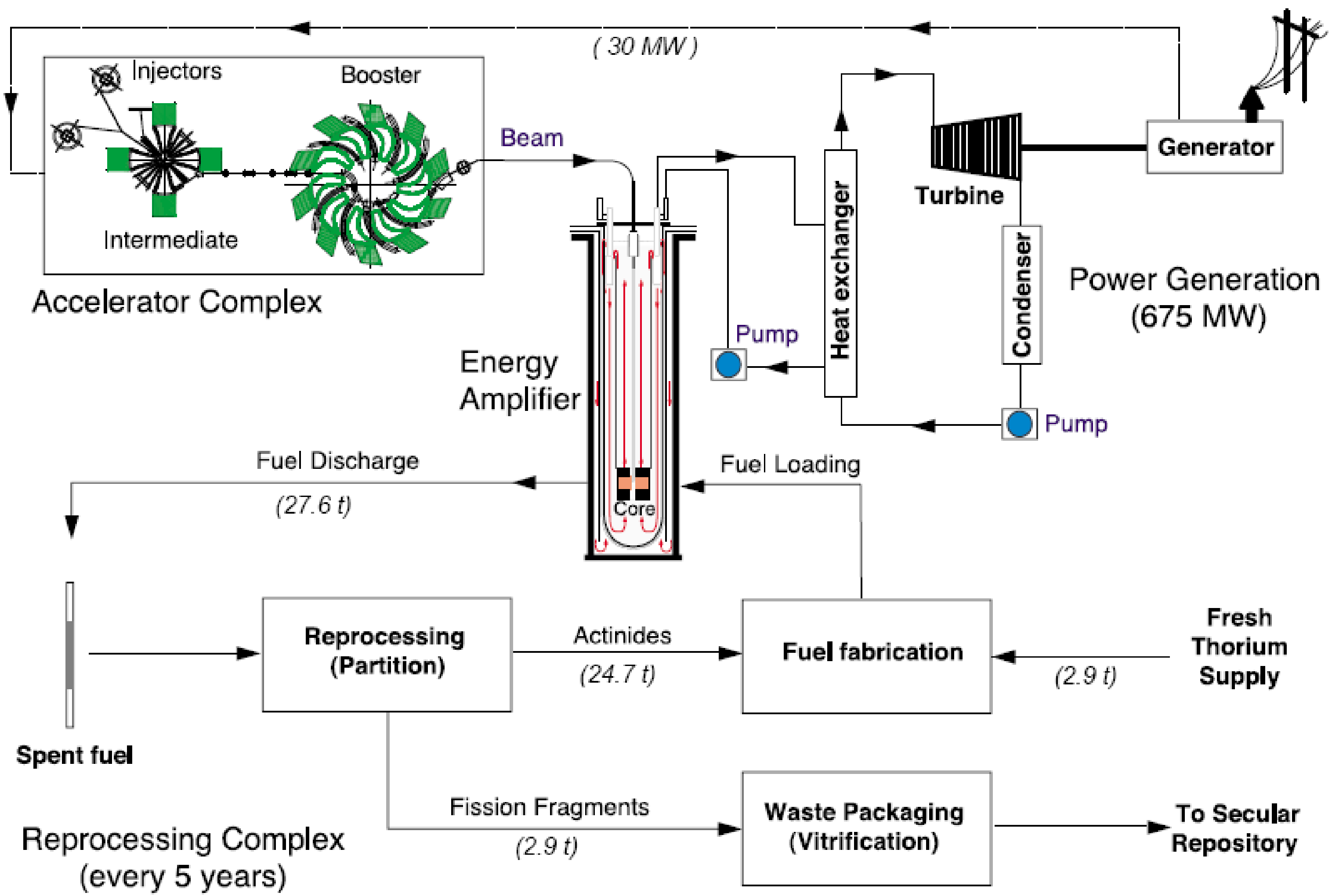
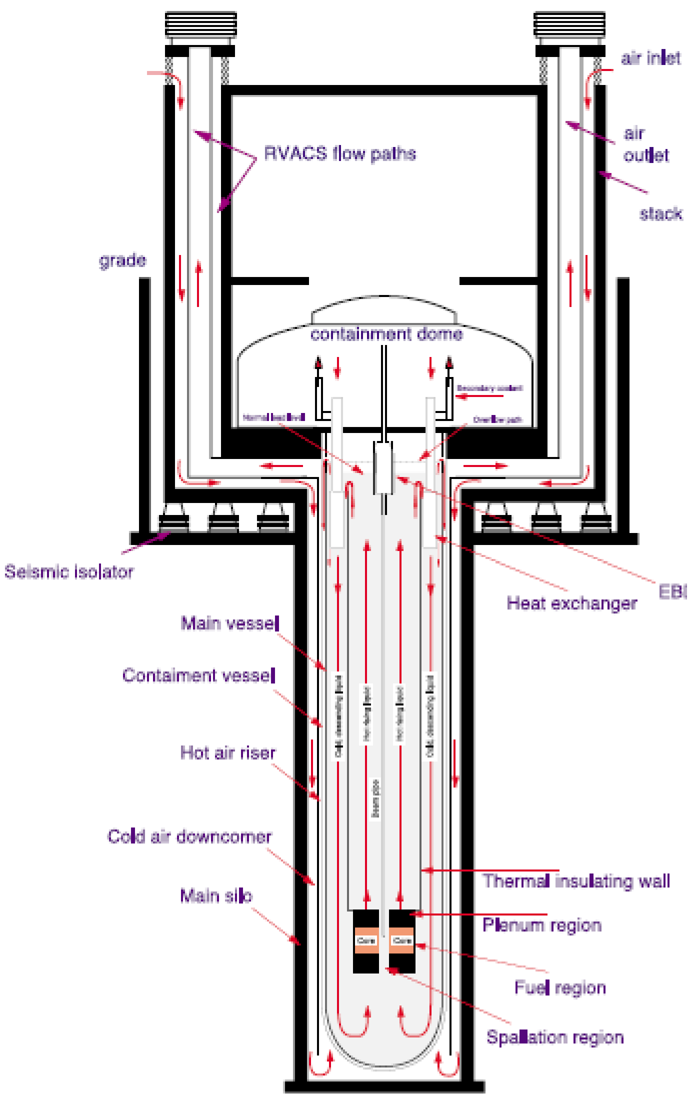
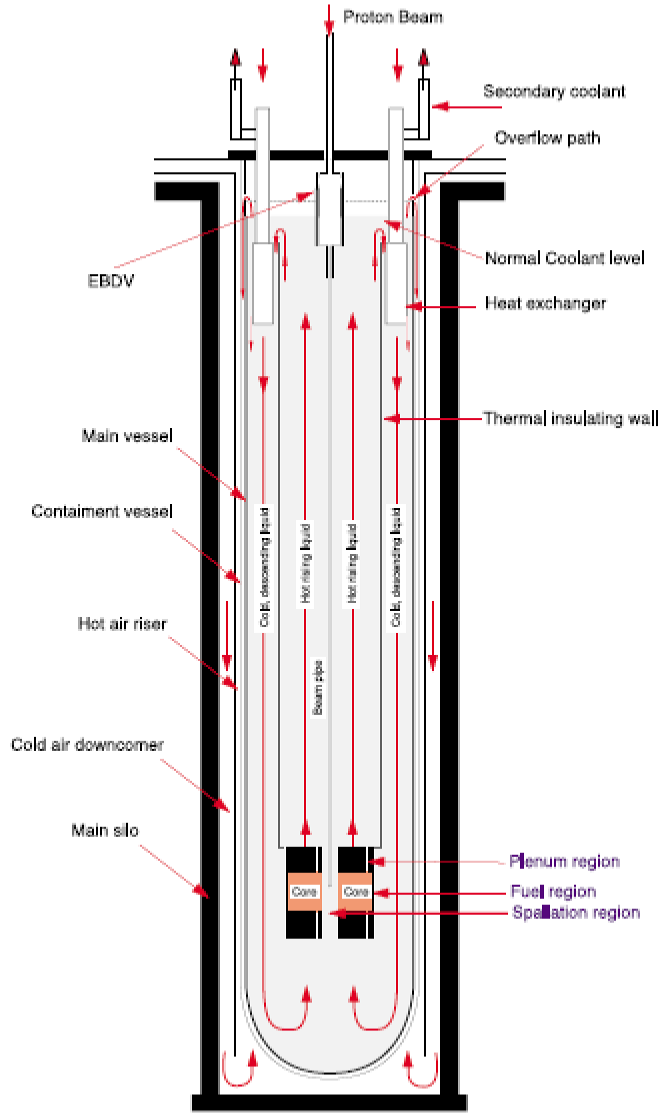


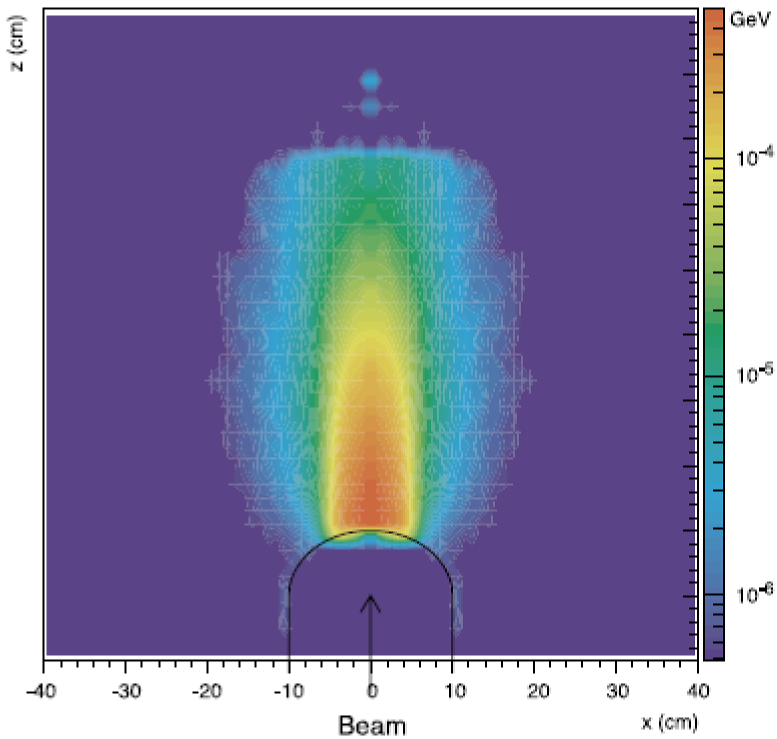
Figure 1.1

EA reactor details





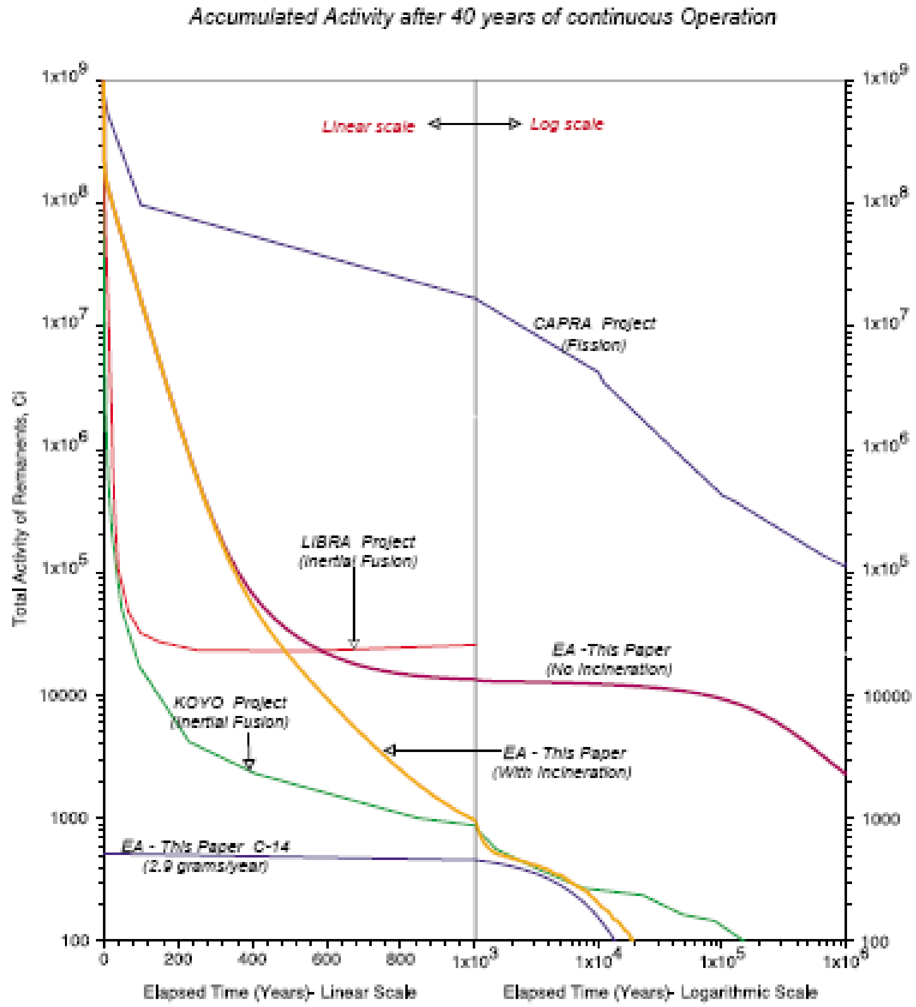
Map of the energy deposit of a 1 GeV proton into the FEA target



- Each 10MW EA will produce ~700MW of electricity. A complex of 2 GWe will have three such reactors and machines. Mass production of machines and industrialization of EA systems will be needed.
- Also, each reactor may need to have more than one beam entry point to make the neutron flux more uniform. Window design easier.
- Much R&D needed here.

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.



IAEA Proceedings

IAEA-TECDOC-1319

Many articles on ADS and Thorium—eg

Too many to mention all

Thorium fuel utilization:

Options and trends

Proceedings of three IAEA meetings held in Vienna in 1997, 1998 and 1999

India, Japan, China actively interested in this approach.

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

November 2002

Comparison of ADS and Fast Reactors (350 page study)by Nuclear Energy Agency (NEA) and Organization for Economic Co-operation and Development (OECD)

Nuclear Development

Accelerator-driven Systems (ADS)
and Fast Reactors (FR) in
Advanced Nuclear Fuel Cycles

A Comparative Study

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Executive Summary

- Fuel cycles with multiple recycling of the fuel and very low fuel losses are required to achieve the desired hundred-fold radiotoxicity reduction.
- All transmutation strategies with multiple recycling of the fuel can achieve similar radiotoxicity reductions, but the choice of the strategy strongly influences fuel cycle requirements.
- The ADS is particularly suited as a “dedicated” minor actinide burner in steady-state scenarios and provides flexibility in transient scenarios.
- The ADS-based evolutionary, and the FR-based innovative, approaches appear to be attractive transmutation strategies, from both technical and economic viewpoints.
- The full potential of a transmutation system can be exploited only if the system is utilised for a minimum time period of about a hundred years.
- A considerable amount of R&D on sub-critical reactors, advanced fuels, and materials would be needed before ADS-based transmutation technology could be deployed.

Two stage Cyclotron solution

- 30 MW in and 10 MW out. Efficiency achievable (so claimed) because lot of the power costs are "overheads" and do not scale with beam intensity. So higher the beam power, the greater the efficiency. Can we pump 10 MW into the rf cavities? No one has done this to date. This is the greatest challenge for the EA and one that calls for accelerator R&D.

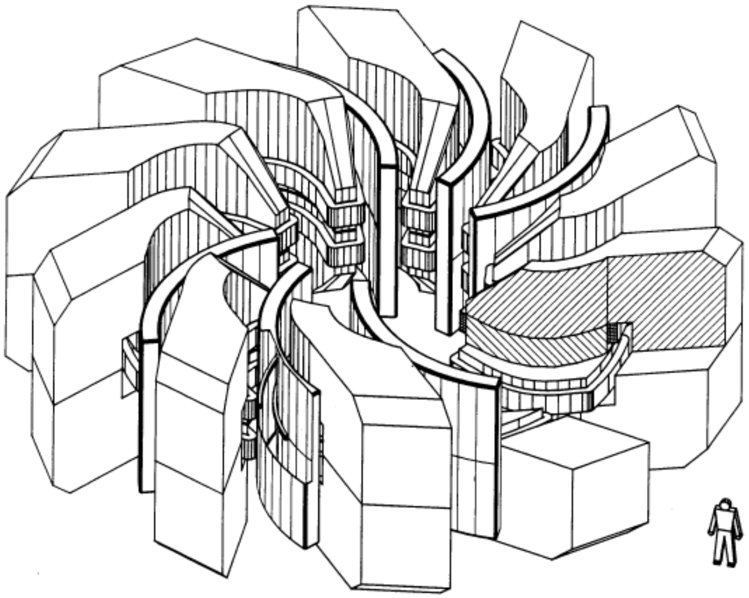


Figure 3.7

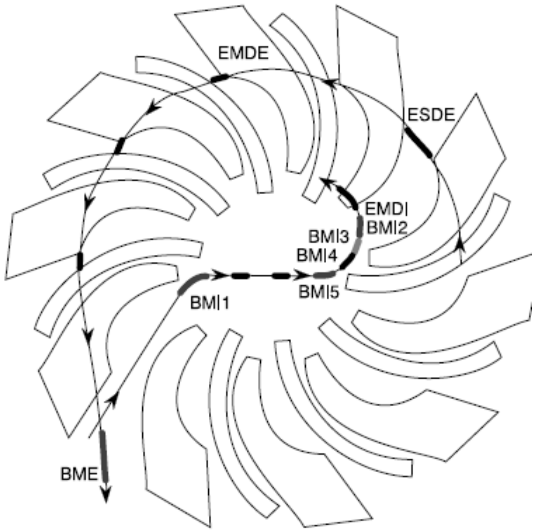


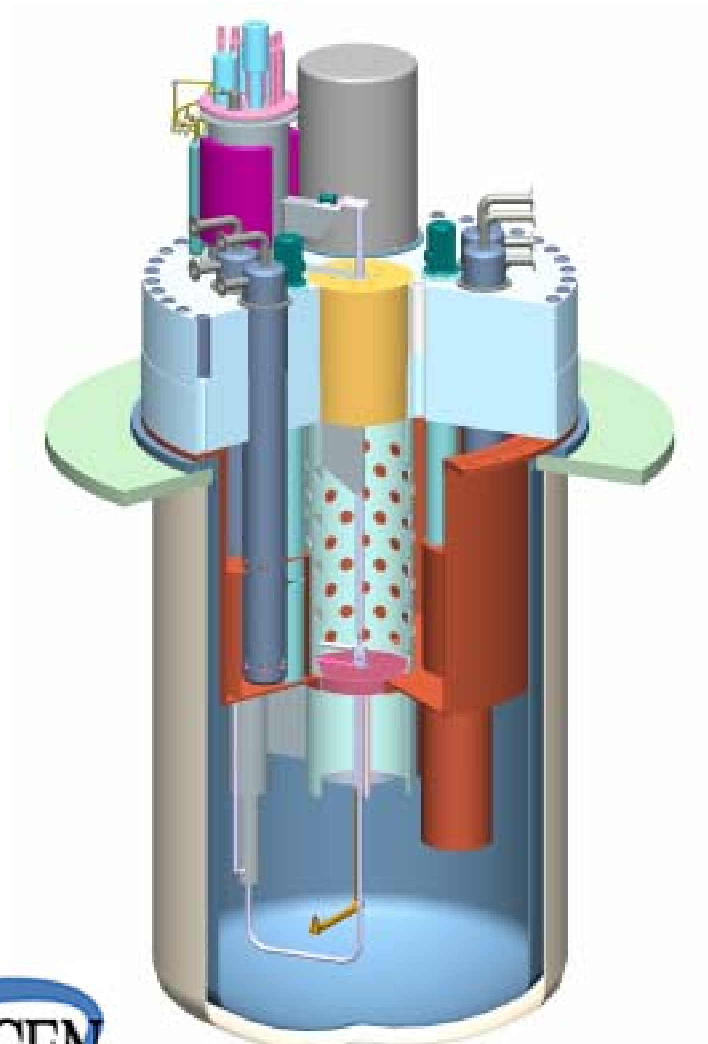
FIG. 3.9 Location of the injection and extraction channel elements of the booster ring cyclotron

Can the 2 stage FFAG do the job?

- Reliability of accelerator is a big issue. FFAG has an great advantage. No ramping magnets.
- Non-Scaling FFAG's can be made isochronous. So stable rf.

MYRRHA (located in Belgium)

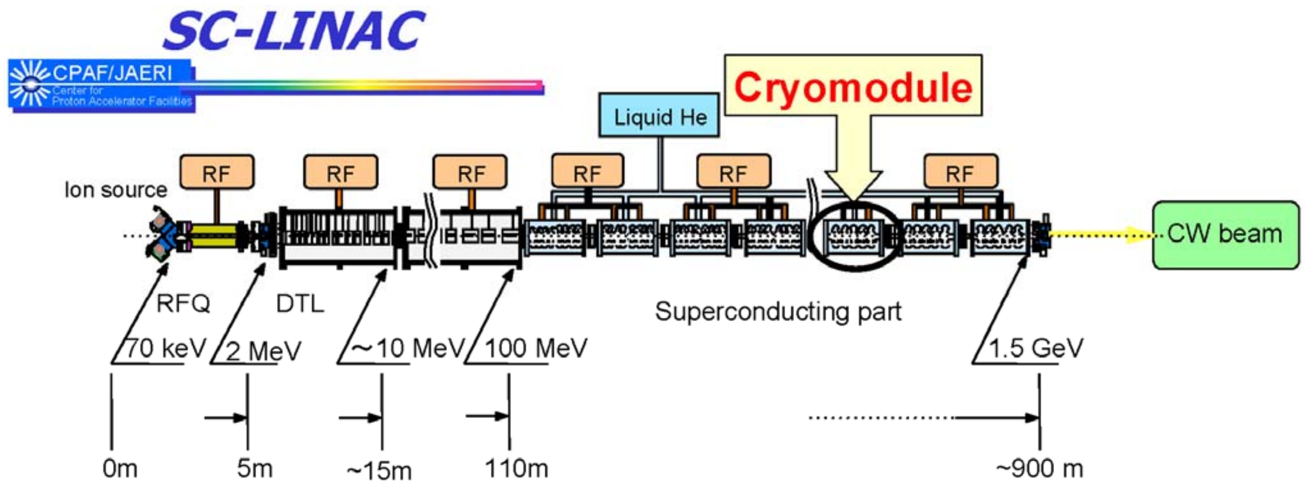
- Chosen Linac technology to do transmutation.
- Expect to do this by 2020
- Experimental demonstration. Not intended for commercial energy production.
- Have chosen Lead/Bismuth Eutectic as spallation target/coolant

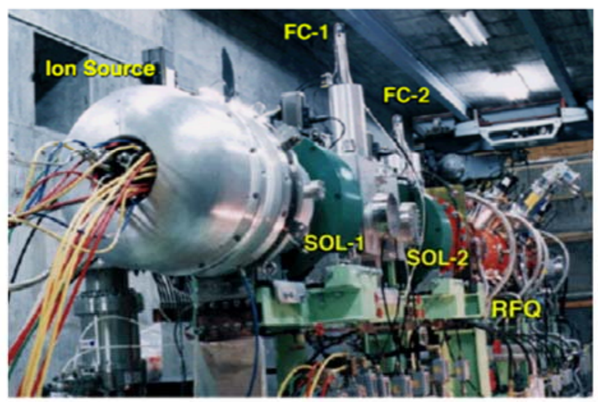


SCK•CEN

Japanese Experiment on ADS—J-PARC transmutation facility.

Scaling FFAg already doing experiments with nuclear piles—Y.Mori





RFQ high current test :
70 mA

SC-cavity single cell test :
44 MV/m (2.1 K)

7/30

Scenarios and Possibilities

- Can use FFAG and or SCRF techlogies to produce 10 MW 1 GeV machine.
- Reliability of accelerators has to be improved greatly. Easier with FFAG?
- Costs will come down in mass production. We need ~ 200 copies.
- Can think of waste burning and breeding centers.

Where more than 1 of these machines operate.

Conclusions

- SCRF technology and FFAG technology hold great promise in producing a high power proton source that can add to the mix of nuclear technologies. Sub-criticality is an advantage. Challenging accelerator R&D.
- ADS are better at burning Minor Actinide Waste than fast reactors.
- We hope to make further progress in the workshop on Applications of High Intensity Accelerators AHIPA'09 Fermilab, October 19-21. Will have reactor experts and accelerator experts as well.
- Do join us !
- Website http://conferences.fnal.gov/App-Proton-Accelerator/index.html