Accelerator Driven Nuclear Energy- The Thorium Option

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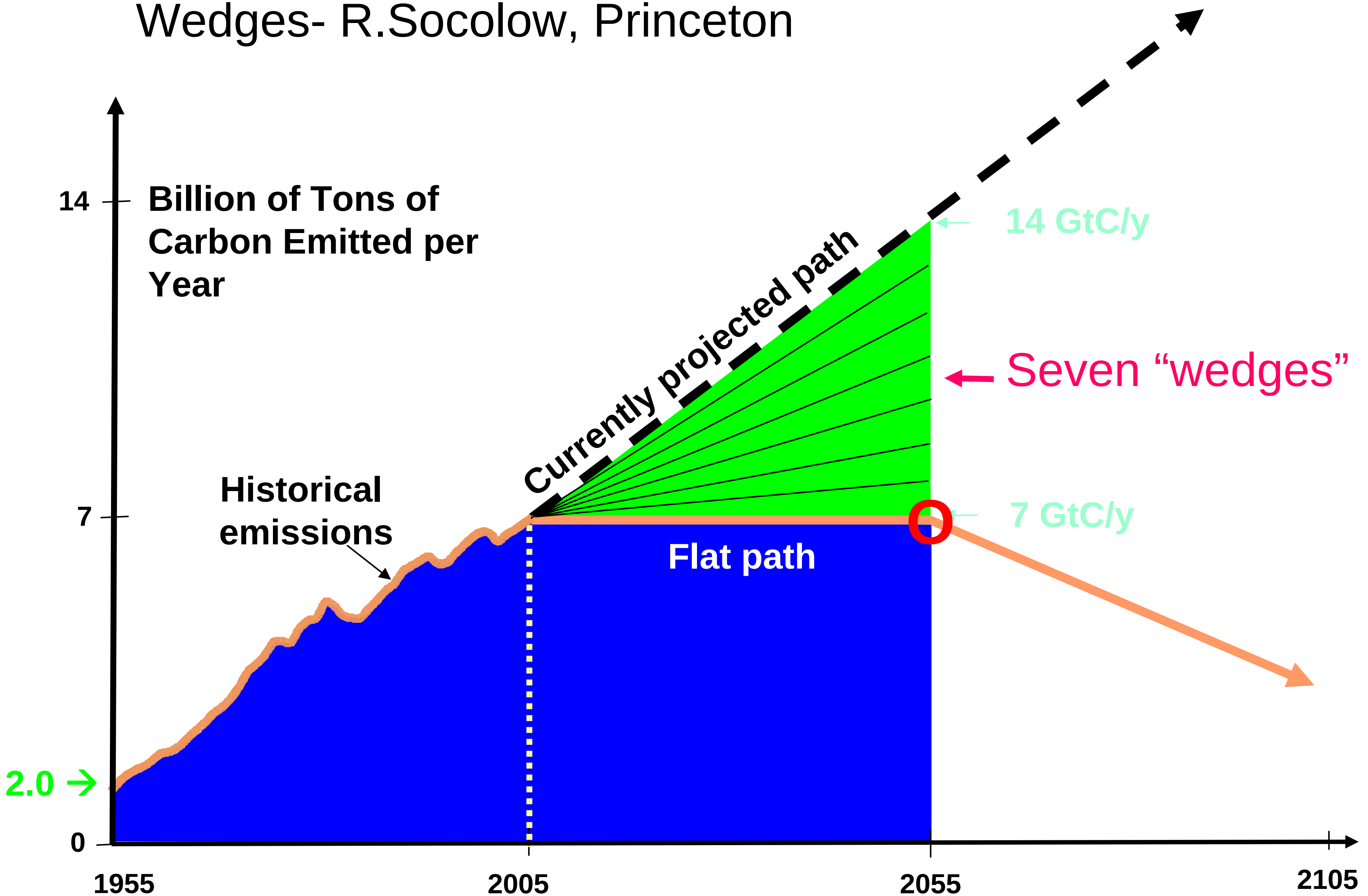
- Gave colloquia at U of Chicago and Argonne.
- A group from Fermilab met with Reactor people at Argonne after colloquim- H. Khalil, R. Hill, T. Taiwo
- It was agreed that we will write a whitepaper on ADS.
- I will give the basic idea, and scenarios for collaboration between Argonne, U of Chicago and Fermilab
- Basic drive is to produce "green Energy" and solve the waste problem in a safe way.
- Needs a 10MegaWatt 1 GeV proton machine—doable using SCRF run in a CW mode. Does not exist yet. Needs R&D
- Reactor needs R&D. Liquid lead used as target producing spallation neutrons. Acts as coolant.
- Can use Thorium, Uranium 238 and existing nuclear waste as fuel.
- Sub-critical and hence more acceptable to public.
- Need to reprocess spent fuel.
- The resultant machine will open up new avenues in particle physics.

Wedges- R.Socolow, Princeton



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

How do we combat global warming?

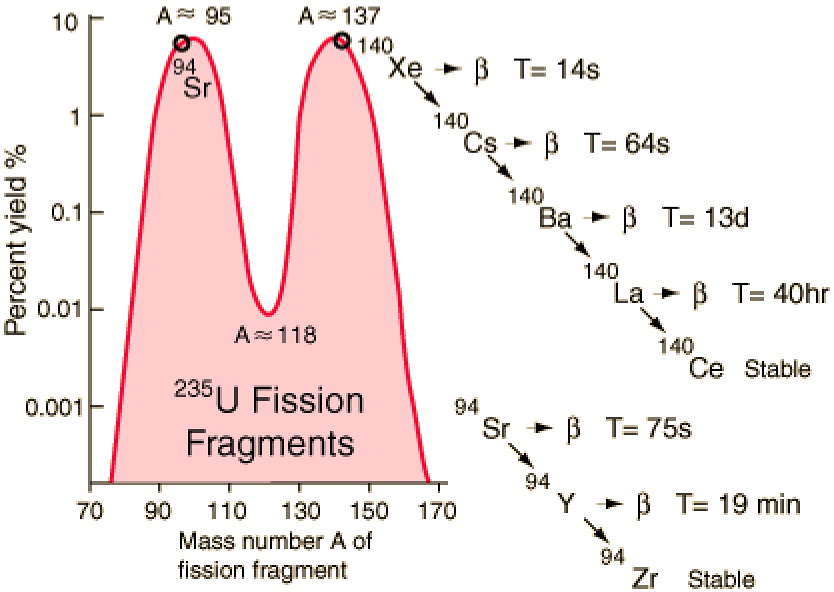
- Conservation
- Cleaner burning of coal, oil, natural gas
- More solar, wind, geothermal—Need Scale up by factor of 10—Unforeseen problems. Transmission grid, storage of power could be such issues.
- Nuclear energy---Fission, Fusion
- Which one shall we choose?
- Answer all of the above.
- Nuclear energy currently has problems-
  - Nuclear Waste—long term storage, use only .7% of natural Uranium (^{235}U).
  - Fast reactors are inherently critical. Have not caught on.
  - Try a new tack– supply fast neutrons using accelerators.

Proliferation Issues

- Talked to one of the scientific advisors to the Obama Campaign—He stated "Proliferation can be achieved through much lower technology than nuclear reactors—eg Centrifuges."
- The higher the tech, the more proliferation resistant the scheme is. ADS is higher tech than conventional nuclear reactors.
- Ultimately, proliferation is a political issue.
- National security can also be compromised by lack of energy independence.

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 reactors" and also the "energy amplifier", the subject of this talk.
- Need to recycle fuel



Mean energy released per fission ~200 MeV

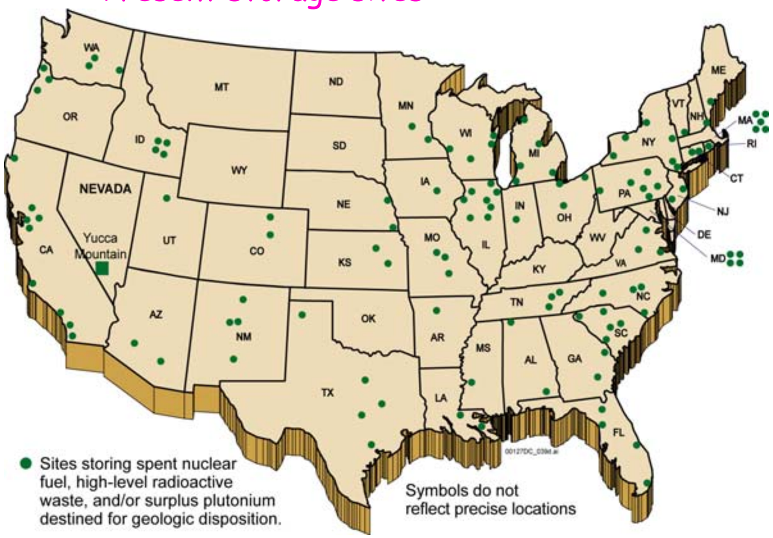
Recycling Strategies

- 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.
- Fast 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



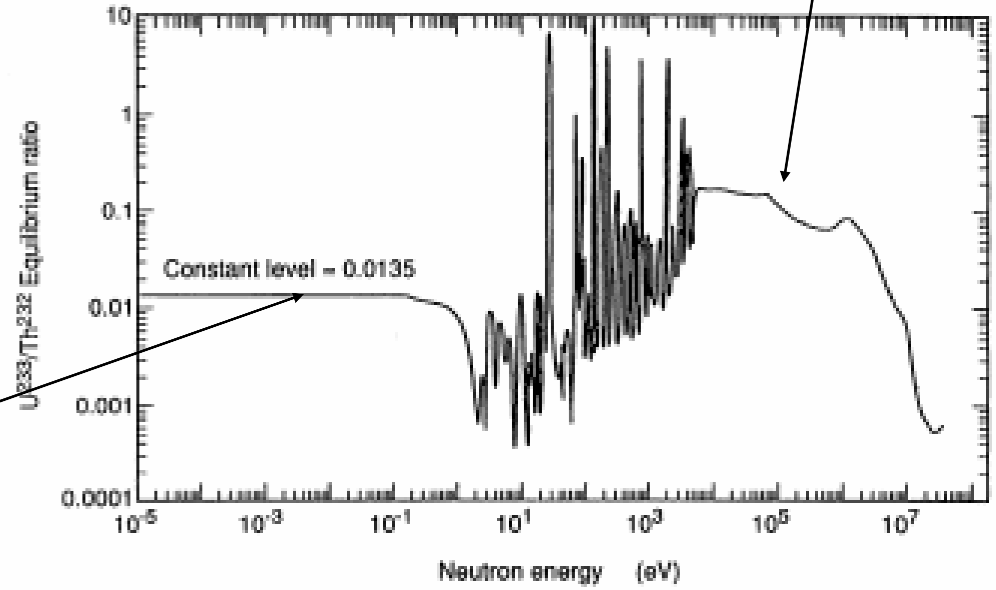
Rubbia Energy Amplifier (EA)

- 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"

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.

Operate with fast neutrons here



Thermal neutron regime

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

Pure thorium initial state.

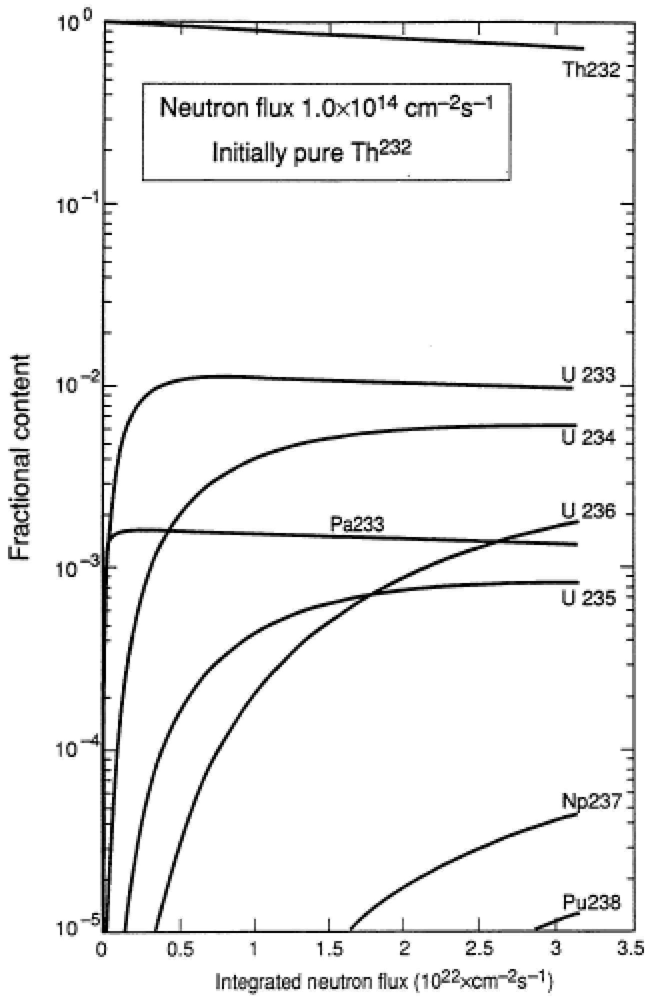


Figure 4

Natural Uranium 238 as fuel

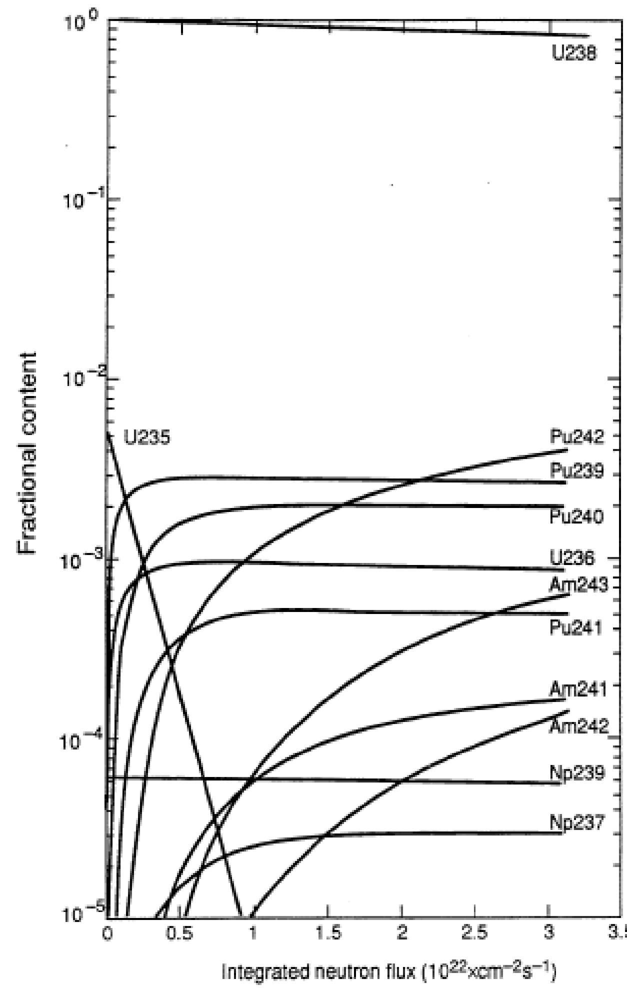
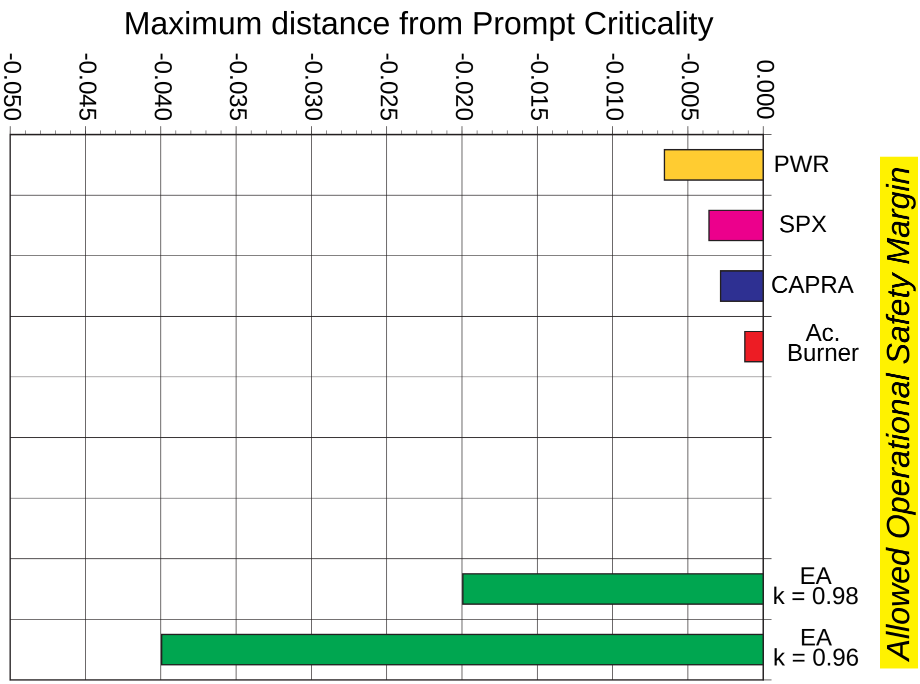
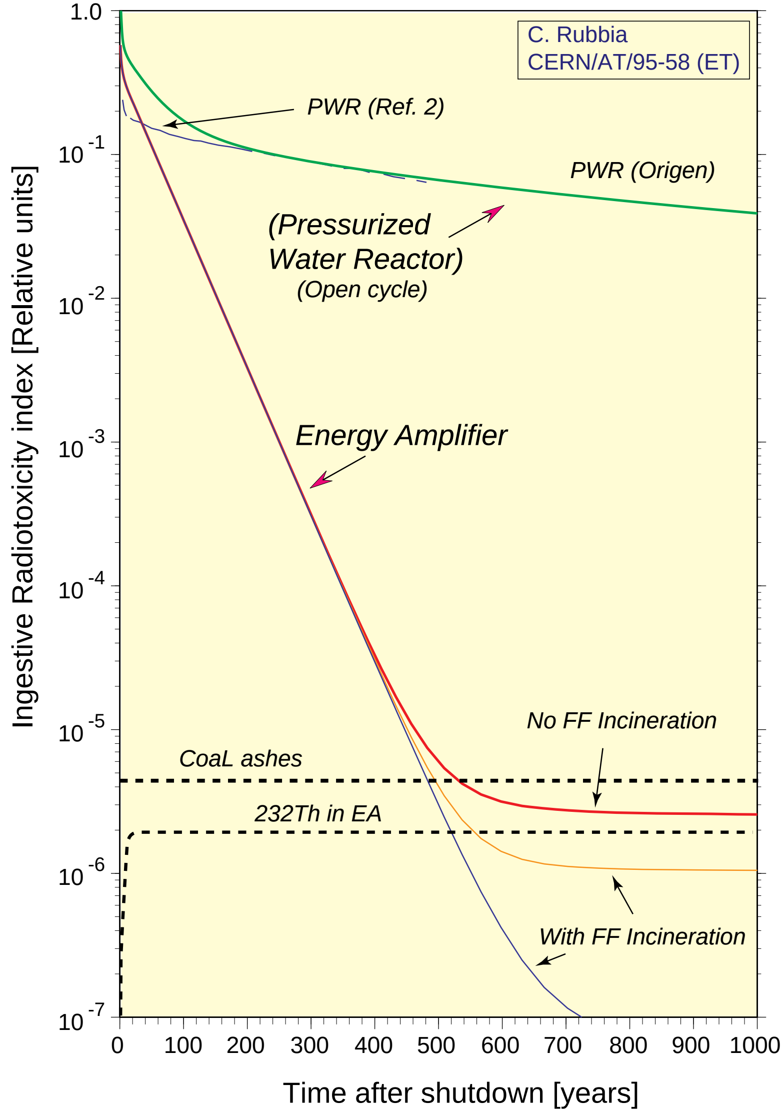


Figure 7

Advantages of the EA:





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

The Conceptual design

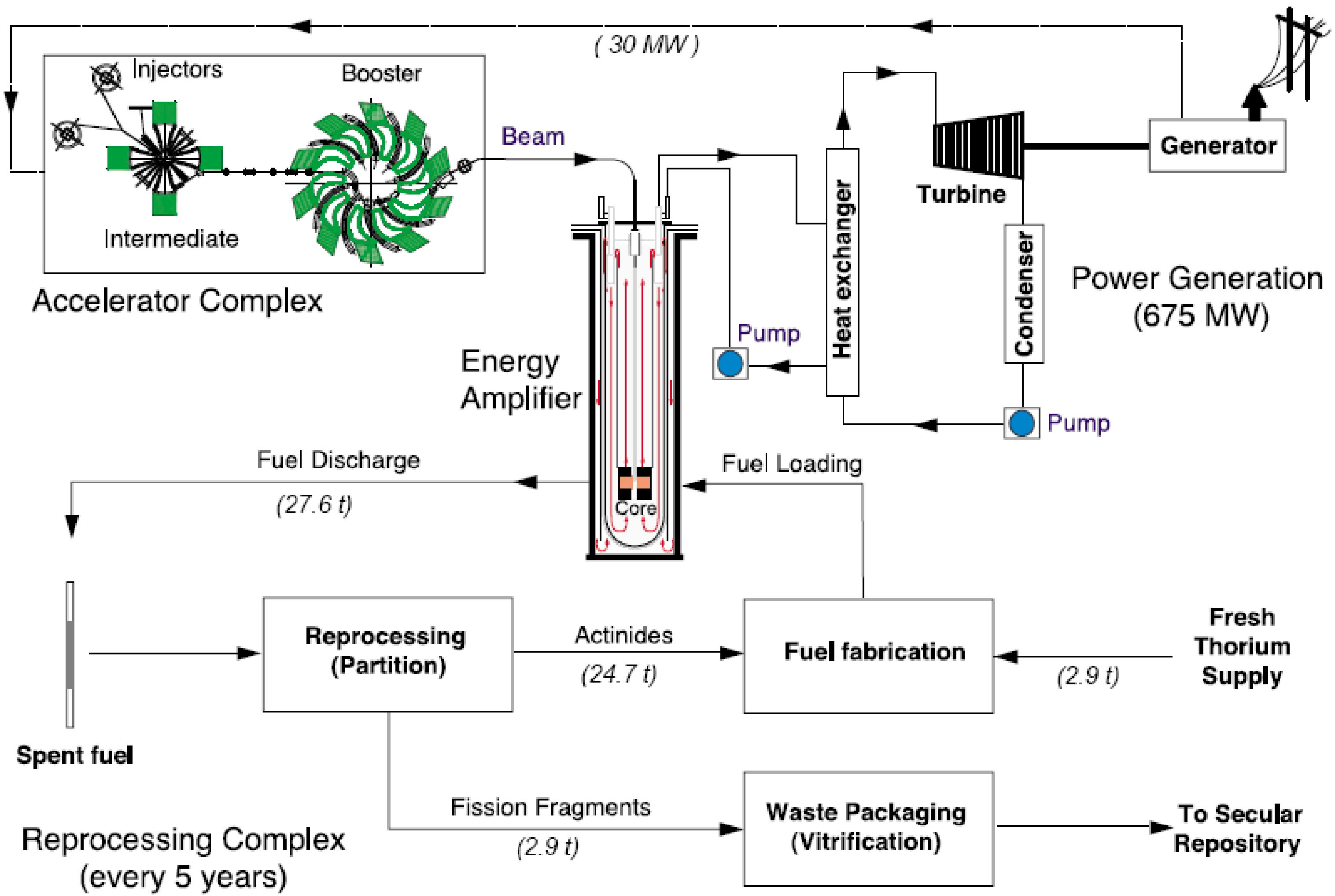
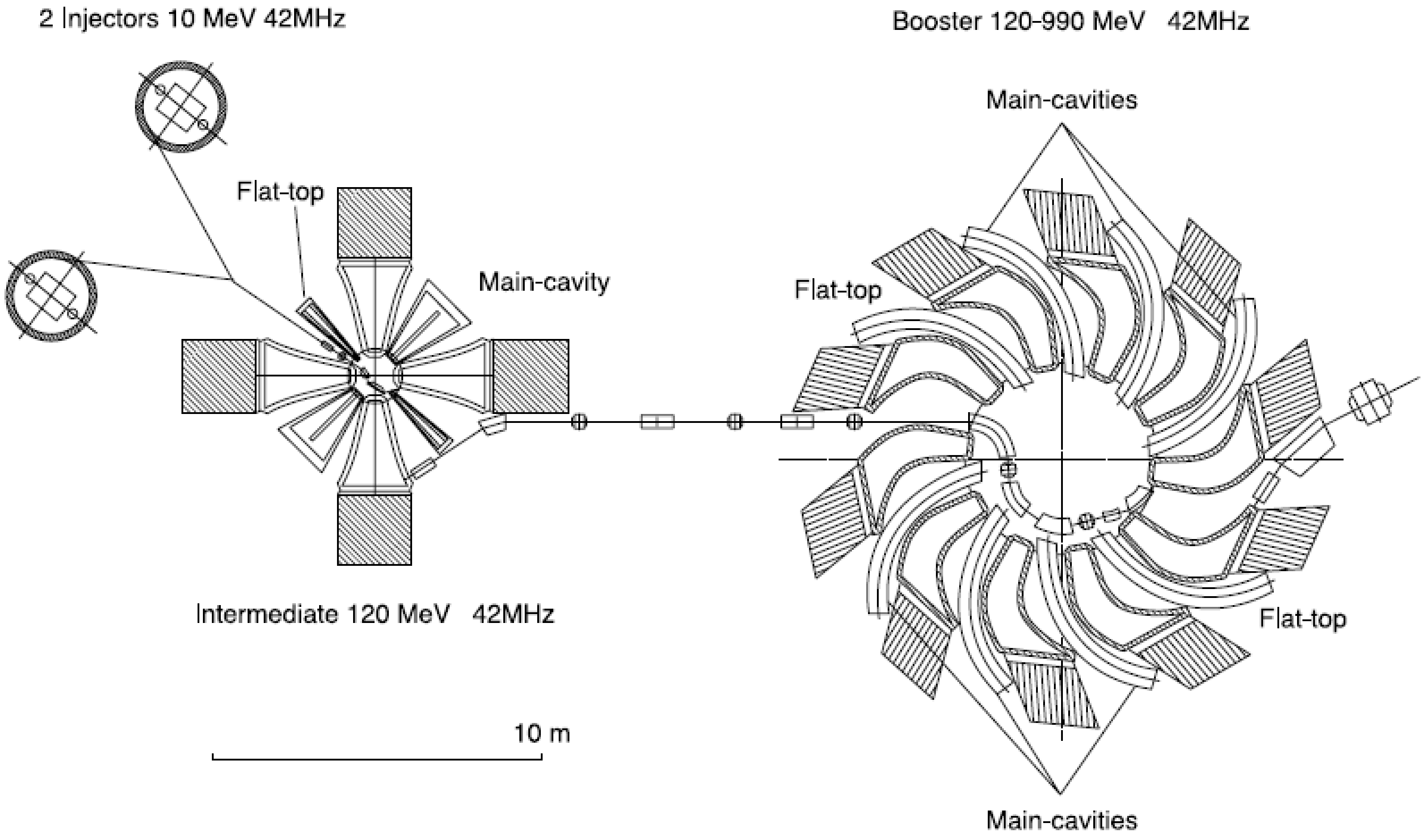


Figure 1.1

Scenarios and Possibilities

- We will now attempt to show that superconducting rf technology may be a candidate used to make the 10-20 MWatt proton source for the project.

EA accelerator design- PSI type solution-1995 vintage-PSI has just started incineration studies with 1 MW beam in liquid target- Cern Courier



SCRF Q factor vs normal rf Q factor

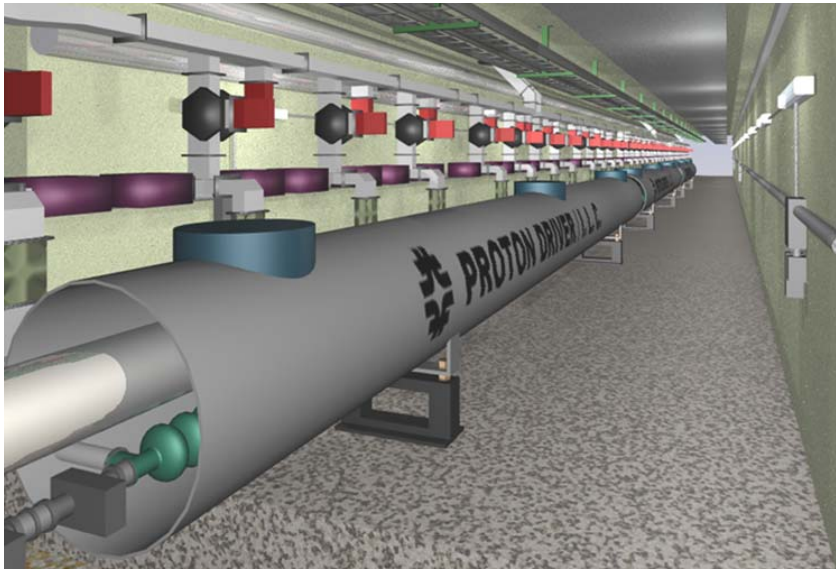
- Q factor of an oscillating system is defined as

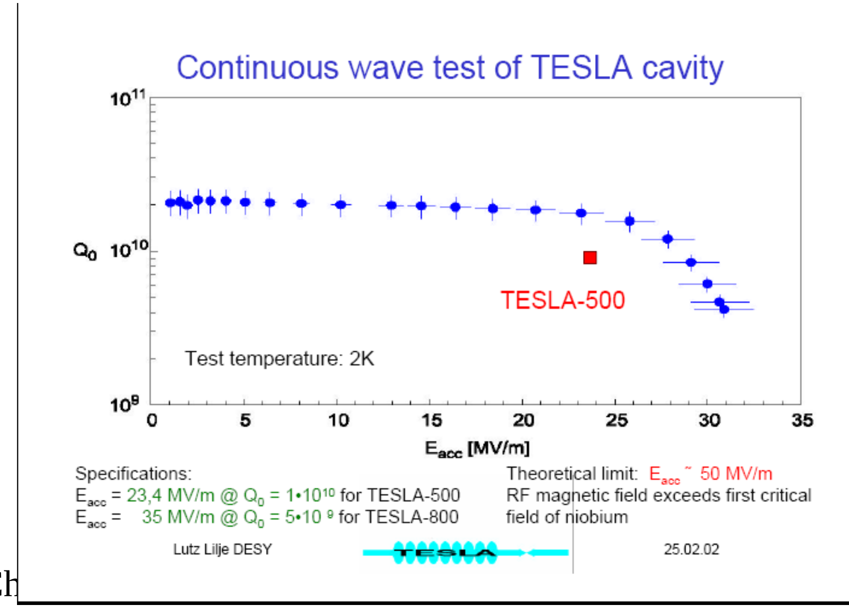
$$Q = \omega \frac{\text{Energy stored in cavity}}{\text{Power lost in cavity}}$$

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

- 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.





Scale Comparisons- B. Webber

	Proton Driver Phase 1	Proton Driver Phase 2	APT Linac (LANL Tritium)	Energy Amplifier Linac
Beam Current	26 mA pulse 62 μA average	9 mA pulse 0.25 mA average	100 mA	10 mA
Pulse Length	3 msec	1 msec	CW	CW
Repetition Rate	2.5 Hz	10 Hz	CW	CW
Beam Duty Factor RF Duty Factor	0.75% 1%	1% 1.3%	CW CW	CW CW
1 GeV Beam Power	0.0625 MW	0.25 MW	100 MW	10 MW

Compare to FRIB capabilities as well

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

Muon Acceleration topologies may be applied to EA proton source as well

- Slide from A. Bogacz.
- Multiple beam pipes and cavities all in one linear section. Multiple arcs. Shortened linear section. Shared cryogenics. More compact machine

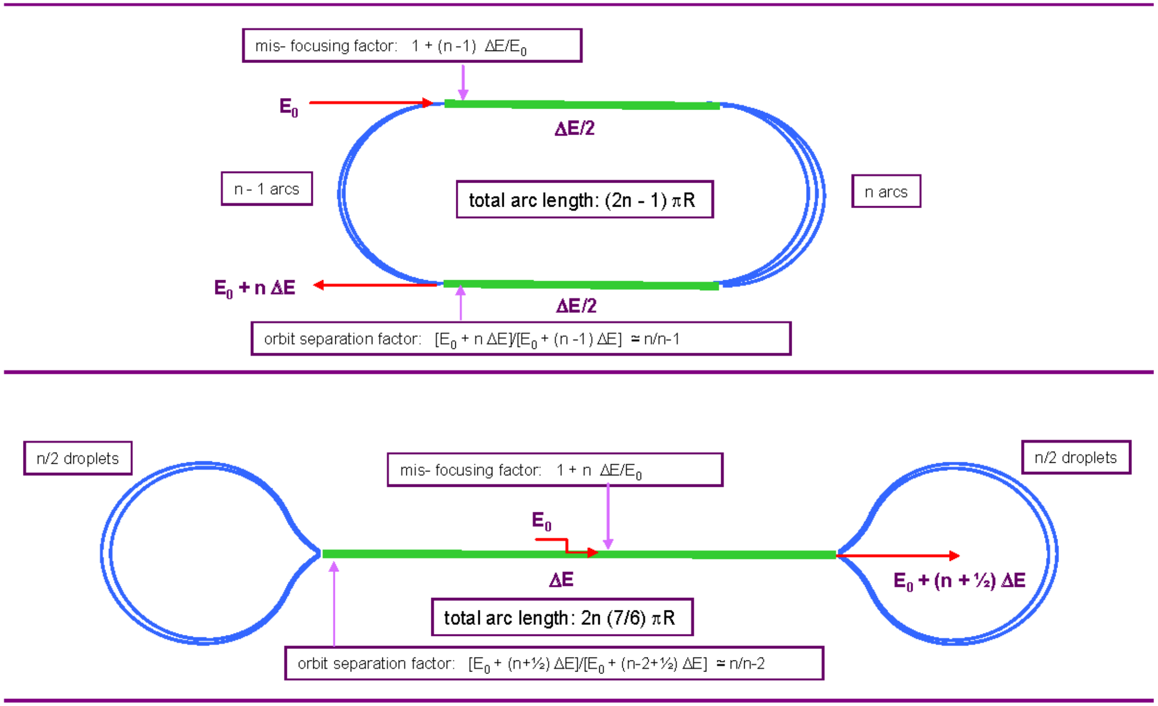


Figure 1. Performance merits of the 'Racetrack' and 'Dogbone' RLA configurations

Major R&D areas

- Design 10 MW, 1 GeV Protons source— Fermilab, Argonne
- Reactor Design, Safety systems -- Argonne
- Targetry, yields, radiation damage -- Argonne, Fermilab
- Fuel Reprocessing techniques -- Argonne
- Suggest directors appoint a joint Argonne, Fermilab, UC task force to produce the whitepaper
- Apply for UC funds to organize an international workshop– Chinese, Indians actively working on this. Much interest in Europe, Japan.
- Deadline for workshop funds application – May, 09.
- The first prototype proton driver can lead directly to a neutrino factory.

Is this in keeping with Fermilab's mission?

- If in doubt about the constitution, ask what the founding fathers intended.
- Wilson as late as 1988, did NOT want Fermilab to be mostly filled with people who did analysis on physics experiments. Rather he wanted the lab to be fully engaged in accelerator R&D that pushed the envelope of what is currently feasible.
- Last time the lab did this was when we invented the Tevatron (1976-83).
- 10 MW proton machine, if realized, will push the envelope of what is currently feasible and will make possible a whole series of HEP experiments including the neutrino factory and may lead to the muon collider.