Accelerator-Driven Nuclear Systems

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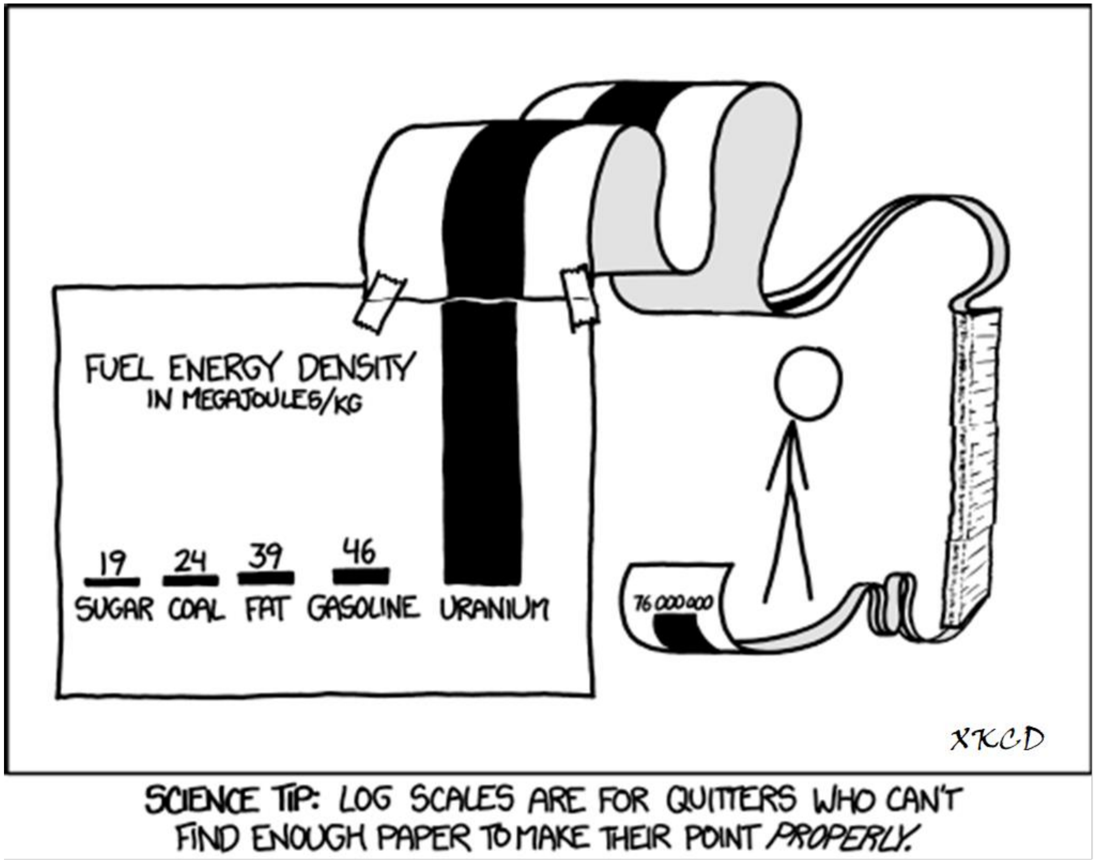
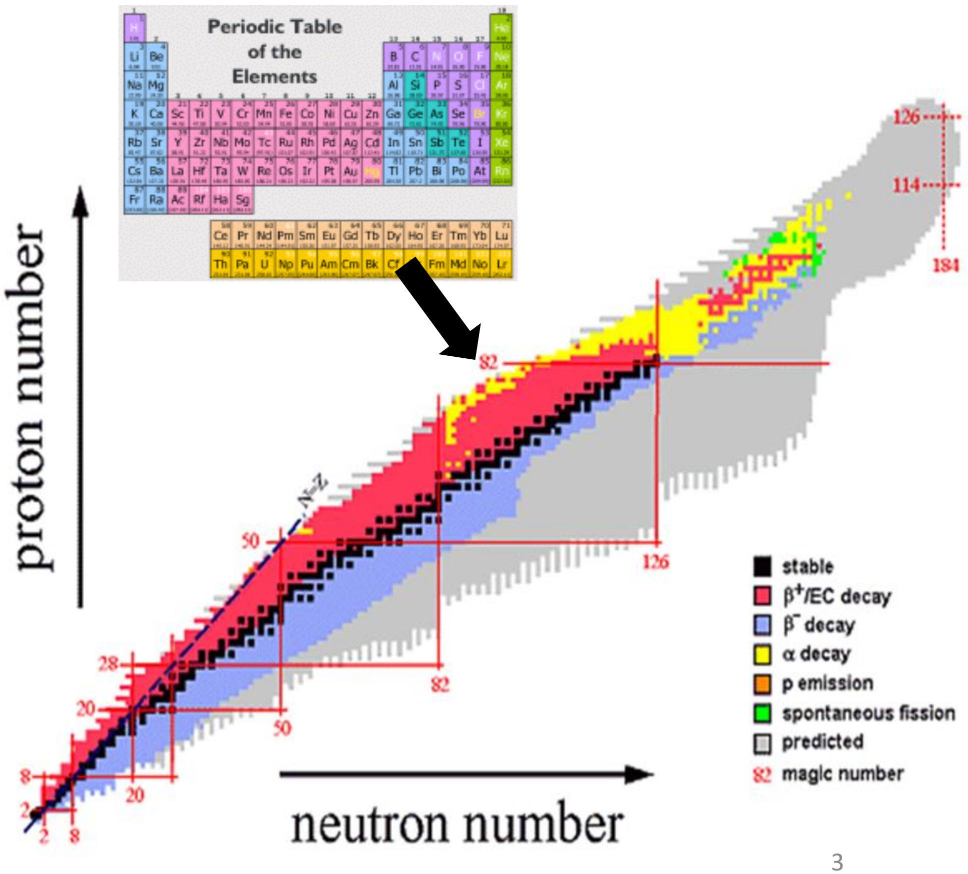
Outline

- Fundamentals of Nuclear Reactions
- Nuclear Fission Reactors
- History of Accelerator-Driven Nuclear Systems (ADS)
- Highlight Currently Pursued ADS Technologies



Fundamentals of Nuclear Reactions

- All elements have isotopes, large range of stabilities
- Radioactive decay occurs in unstable isotopes, resulting in spontaneous emission of particles and/or electromagnetic radiation
- Repulsive force between protons must be balanced by a strong attractive force for nuclei stability



Mass-Energy Equivalence

- In 1905 Albert Einstein identified the mass-energy relationship of an object at rest

$$E_o = mc^2$$

- Energy of nuclear decay comes from mass conversion, on the energy scale of MeV (1.6×10^{-13} J) released for every nuclear reaction
- Mass-energy conversion, during decays or reactions, occurs in nuclei

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{89}_{36}Kr + {}^{144}_{56}Ba + 3\,{}^{1}_{0}n + 210\ MeV$$

Barriers in Nuclear Reactions

Charged particles (protons) must overcome an electrostatic potential energy barrier

- Barrier scales with Z, on the order of a few MeV per proton pair
- Abundance of charged reactants (e.g. protons in elements)
- Can overcome barrier with kinetic energy, propelled by electromagnetic fields of an accelerator

Neutral particles (neutrons) have no electrostatic potential barrier

- Neutrons require less kinetic energy to initiate nuclear reactions
- Free neutron is short lived (lifetime ~15 min), therefore a source is required for any use of neutrons

Conventional Nuclear Fission Reactor

- Uses heavy fissile elements that are capable of nuclear fission
- Fissile material struck by thermal neutrons, breaks apart and emits neutrons, releasing energy and continuing the self-sustaining chain reaction
- Fissile fuel must have high probability of fission (σ_f) and release 2 or more neutrons on average per neutron captured
- Chain reaction can be defined by multiplication factor, k

$$k = \frac{\#\, neutrons\ in\ one\ generation}{\#\, neutrons\ in\ preceding\ generation}$$

Subcritical: $k<1$ Critical: $k=1$ Supercritical: $k>1$

Past Reactor Fuels

^{235}U

- Naturally occurring, small abundance (0.72%)
- Used in D_2O reactors (unenriched) or light water reactors (enriched)
- Requires thermal neutrons for adequate fission

^{239}Pu

- Bred from ^{238}U (which is naturally occurring, large abundance)
- ^{238}U captures neutrons and is eventually converted to ^{239}Pu
- Smaller critical mass, cheaper than enriched ^{235}U : used in nuclear weapons

^{233}U

- Bred from ^{232}Th which is ~3-4 times more abundant than uranium on Earth
- Can be bred using fast neutrons or thermal neutrons

Fission Reactor Issues: Nuclear Waste

Majority of fission reactors worldwide are light-water reactors

- Power from fission of ^{235}U and ^{239}Pu produced in the reactor
- Plutonium isotopes and minor actinides produced (Np, Am, Cm, Cf) are main source of long lived radioactivity
- Plutonium could be used in reactor again as mixed-oxide fuel, but not all isotopes and minor actinides are destroyed

Some fission products and remaining actinides have half-lives >1000 years

- Designing storage containers to permanently confine waste is not possible
- Currently above-ground concrete containers have been adopted
- Geologic confinement has also been considered

Issues with storing radioactive waste

- Possibility for criticality to occur in repositories
- Plutonium could still be recovered for weapons use

Long Term Solutions?

Current long-term management

Dry cask storage

Proposed method for implementation

Deep geological repository

Can we eliminate radioactive waste faster than natural decay, and at the same time make a net energy gain?

Accelerator-Driven Systems (ADS)

- Traditional nuclear reactors operate at or above criticality to generate the required extra neutrons
- ADS relies on subcritical reactor with an external supply of neutrons
  - Neutron source is needed to maintain constant fission and power levels
  - Neutrons supplied by bombarding heavy metal target (spallation) with high-energy proton beam from an accelerator
  - A fraction of reactor's energy output is used to power the accelerator
  - Self-sustained chain reaction is not possible
- Can be used for waste transmutation and/or breeding ^{233}U from ^{232}Th

History of ADS

- 1930s Ernest Lawrence develops cyclotron accelerator
  - Circulating particles accelerate inside a chamber, between poles of an electromagnet
  - Magnetic field held protons in a spiral path while they accelerated between semicircular electrodes
- 1949 Lawrence proposes construction of 25 MeV linear accelerator, 'Materials Test Accelerator'
  - Attempted electronuclear conversion of fertile to fissile material by accelerator-produced neutrons from high energy proton and deuteron target-bombardment
  - Goal was to make tritium for a hydrogen bomb (Cold War)

A new idea for transmutation?

- 1992 Charles Bowman (Los Alamos National Laboratory) describes new approach for nuclear energy generation and waste transmutation using an accelerator
- Proposed accelerator-driven device that ‘incinerates’ radioactive waste (long-lived actinides as well as fission products) by using neutrons for transmutation
- Assumes that thermal neutron flux within nuclear reactors is not adequate for waste transmutations
  - Nuclear waste spends ~1 year in reactor thermal flux of 10^{14} neutrons/cm^{2}s, by this time most nuclei with large cross sections for neutron capture (σ_c) have been converted to nuclei with smaller σ_c

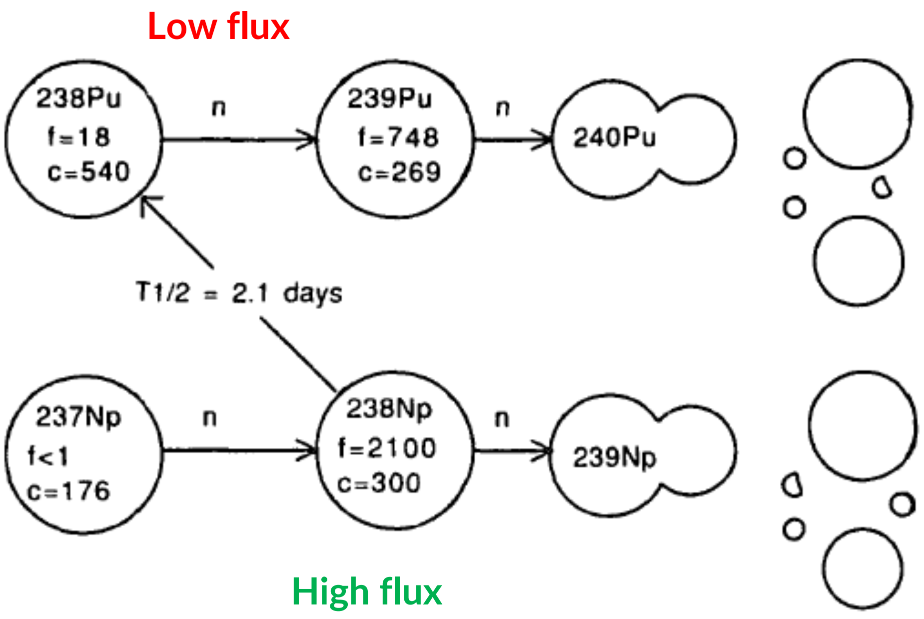
Two Reactor Parameters

➢Neutron energy

- At thermal conditions, σ_c >> σ_f for ^{237}Np and ^{241}Am (primary constituents of actinide waste), therefore thermal neutrons convert the material to heavier nuclei instead of fissioning

➢Neutron flux

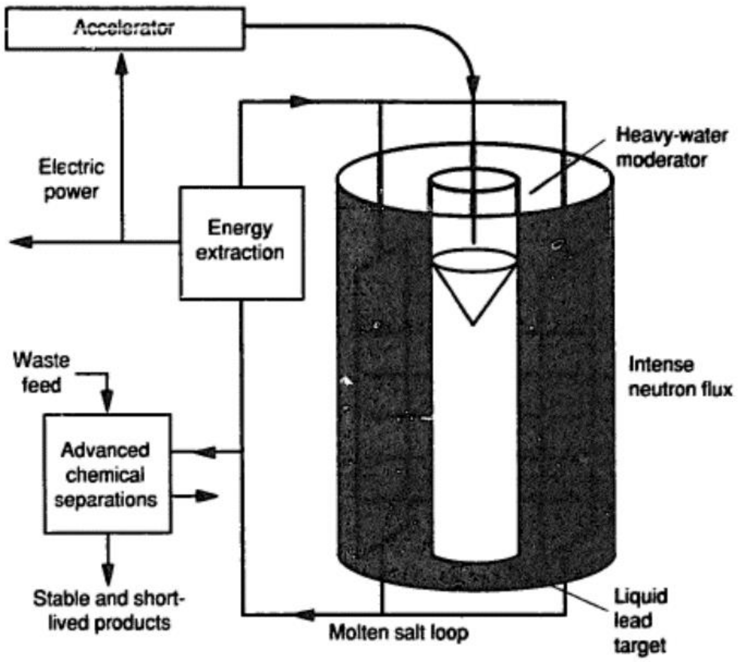
- At flux ~100 times greater than nuclear reactors, actinides such as ^{237}Np can capture two neutrons in succession, (bypasses poisonous ^{238}Np) leading to fissionable ^{239}Np



Bowman, C.D. et al. *Nucl. Instrum. Meth. A*, **1992**

Waste Incinerator Concept

- Protons (1.6 GeV) strike liquid heavy metal target ~55 neutrons generated per proton, thermal flux on the order of 10^{16} n/cm^{2}s, $0.92 < k < 0.95$
- Due to fast buildup of ‘poisonous’ fission fragments, circulating liquid flow (molten salt, D_2O, Pb-Bi eutectic) would be used so that fuel, moderating agent, spallation target, spend only a fraction of the time within high flux
- Also proposed ability to breed ^{233}U from ^{232}Th



Bowman, C.D. et al. *Nucl. Instrum. Meth. A*, **1992**

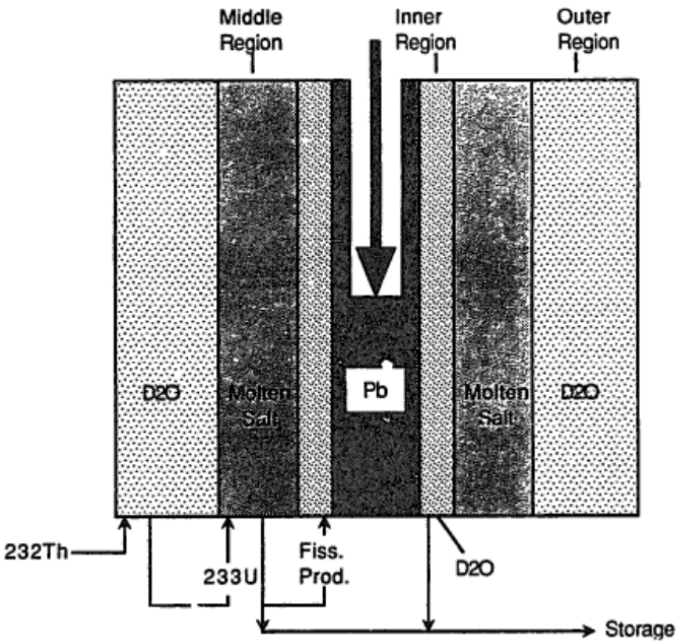
Design

➢Liquid lead target continuously circulates

- Transmutation of spallation products, which eventually neutron capture back towards mass of Pb parent
- Pb target need only be replenished ~1 kg/yr

➢Three-sector blanket

- Inner sector of D_2O for transmutation of fission products (generally small σ_c)
- Middle sector of molten salt (LiF + BeF_2) as carrier of fissile material and medium for heat transfer
- Outer sector of D_2O acting as reflector or site for breeding fissile material (energy production from natural Th or U)



Bowman, C.D. et al. *Nucl. Instrum. Meth. A*, **1992**

Advantages

- System can operate well below criticality at high power
- Effective average number of neutrons can be enhanced by as much as 50%
- Fission-product transmutation time is inversely proportional to the flux
- Liquid heavy metal target avoids heat conductivity/transfer limitations and radiation damage of a solid target
- Energy produced is 30-50 times the energy dissipated by high energy proton beam

Disadvantages

- In thermal spectrum ~half of the nuclides do not undergo fission, instead they capture to the next heaviest nuclei
- Continuous-flow concept would require considerable chemical separation of fission fragments, actinides, ^{233}Pa for milking of ^{233}U (if using thorium)

A new idea: The Energy Amplifier

- Proposed by Carlo Rubbia at CERN in 1993, idea much like Bowman, to ‘amplify’ the energy deposition of an incident high energy beam to pay off the energy for its production and achieve a net gain
- More focus on the ^{232}Th → ^{233}U breeding chain, as external source of neutrons removes limitations when using thorium in traditional nuclear reactors
- Burning thorium in conditions that are essentially free of higher actinide waste, especially plutonium
- Initially considered using thermal neutrons and solid target, later decided (1995) on fast spectrum neutrons and liquid target

Fast Energy Amplifier Concept

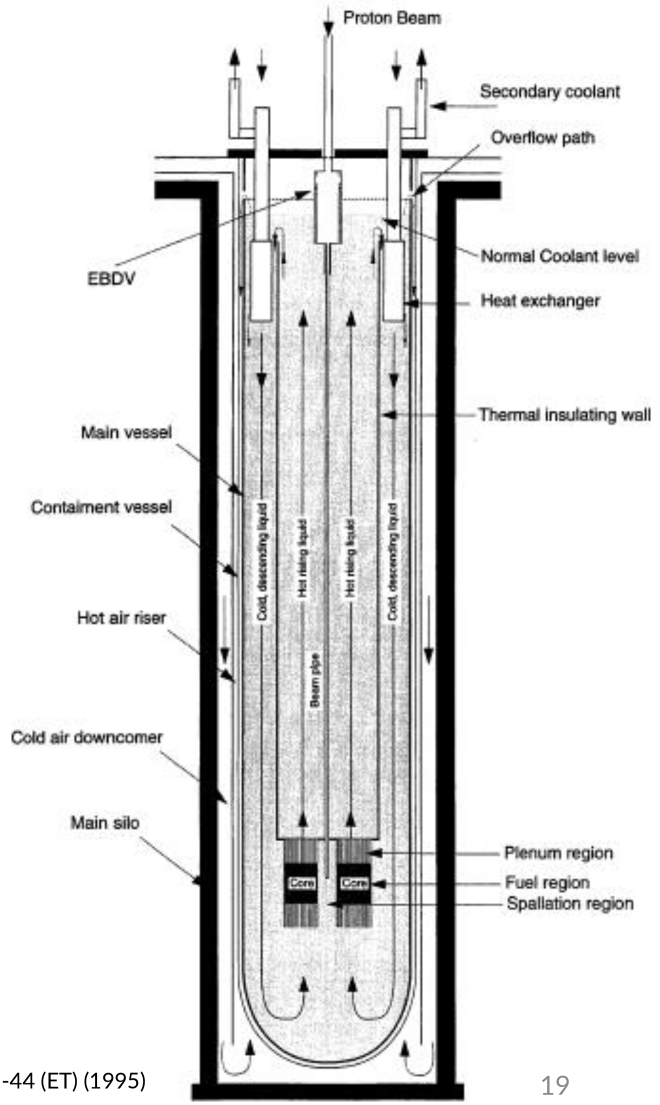
- No moderator, fast neutrons with energy ~0.1-1 MeV
- Larger neutron yield due to decreased σ_c, versus use of thermal neutrons
- Production of higher mass actinides is strongly supressed
- Lower flux, 10^{14} n/cm^{2}s (like traditional reactor), allows for decay-dominated regime with a smaller amount of ^{233}Pa intermediate (capture is less likely with fast neutrons)

Low flux $${}^{232}_{90}Th(n,\gamma){}^{233}_{90}Th \xrightarrow[22\ min]{\beta^-} {}^{233}_{91}Pa \xrightarrow[27.4\ d]{\beta^-} {}^{233}_{92}U$$ **Fissile**

High flux $${}^{233}_{91}Pa \xrightarrow{n} {}^{234}_{91}Pa \xrightarrow[6.7\ hr]{\beta^-} {}^{234}_{92}U$$ **Non-fissile**

Design

- Practical layout includes 15 tons of fuel material (ThO_2-UO_2)
- 20 MW proton beam (20 mA @ 1 GeV)
  - operates at level of ~1 $GW_{(e)}$ with k = 0.98
- Non-moderating coolant required, Pb or Pb-Bi eutectic which also acts as first target for high energy proton beam
- Criticality parameter k is tuned to the desired value, depending on the use of the reactor for breeding new fuel or incinerating waste



Rubbia, C. et al. CERN Rep. CERN/AT/95-44 (ET) (1995)

Advantages

- Considerable energy gain far from criticality
- [^{233}Pa] is small enough that on line ‘hot chemistry’ extraction not required
- Energy produced is 100-150 times the energy dissipated by high energy proton beam
- Irradiation of thorium produces minimal amounts of plutonium and minor actinides

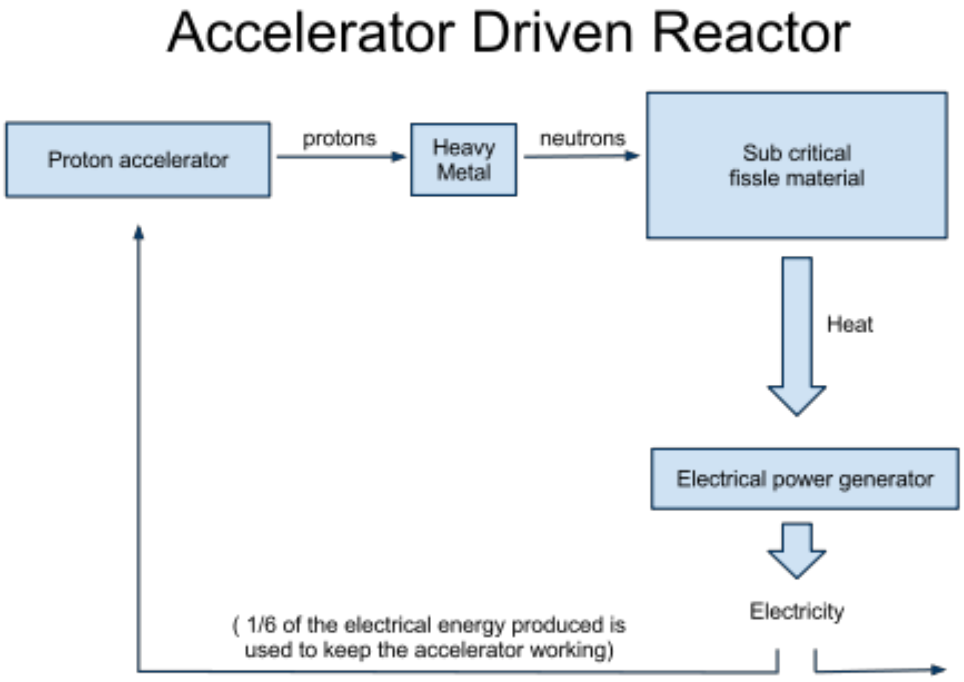
Disadvantages

- Radiotoxicity build-up in the lead coolant
- Radioactive fission fragments will still generate heat, ~7% of total energy emitted by fission, even if the proton beam is switched off; continued cooling is still required to prevent melt-down

Currently Pursued Accelerator-Driven Systems

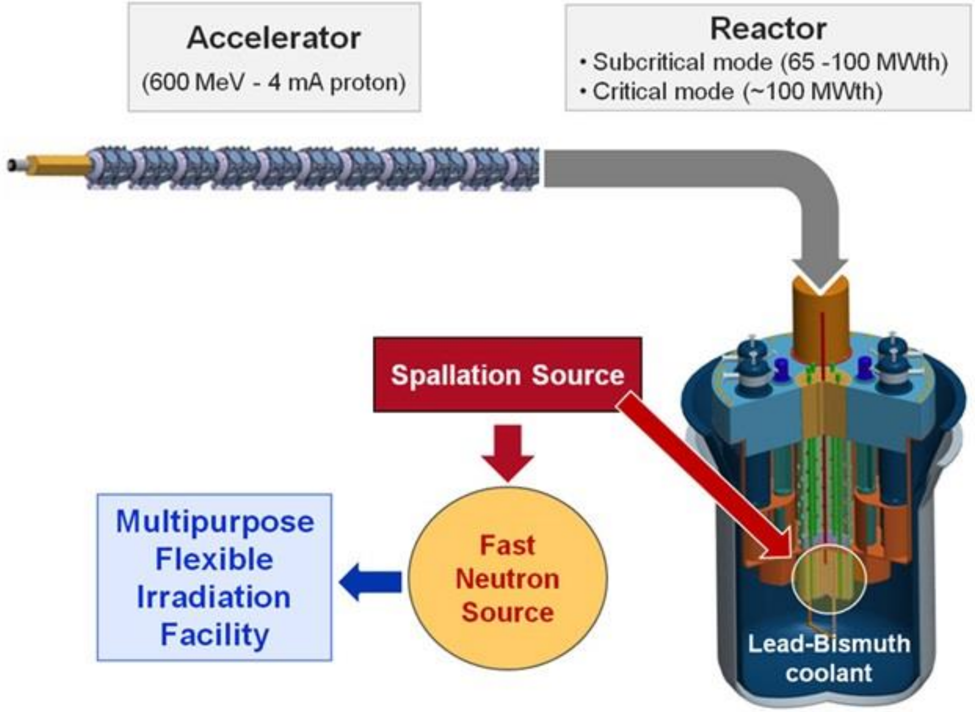
Examples

- MYRRHA
  Belgium Nuclear Research Centre (Built by 2025)
- GEM*STAR
  Virginia, U.S.A.
  ADNA Corp.
  (building demonstration reactor)



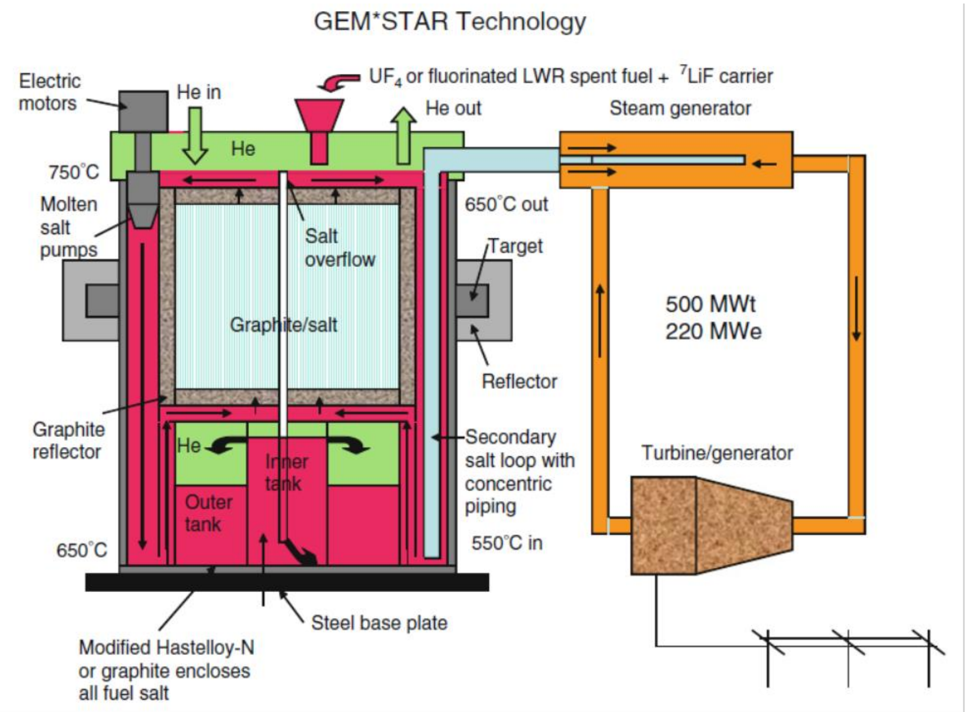
MYRRHA: Multipurpose hYbrid Research Reactor for High-tech Applications

- Fast spectrum research reactor
- ADS, can operate in sub-critical and critical modes
- Pb-Bi eutectic is used as a coolant and liquid heavy metal target
- Mixed plutonium-uranium oxide fuel (MOX)
- Applications
  - Waste transmutation
  - Neutron irradiated silicon
  - Radioisotope production
  - Materials research



GEM*STAR

- Being developed by Accelerator Driven Neutron Application Corporation (Bowman) and Virginia Tech University
- Subcritical thermal-spectrum reactor with continuous-flow molten salt fuel in a graphite matrix
- High energy neutrons produced by proton beam on stopping length thickness of deuterium gas in beryllium tube
- Be acts as a neutron multiplier

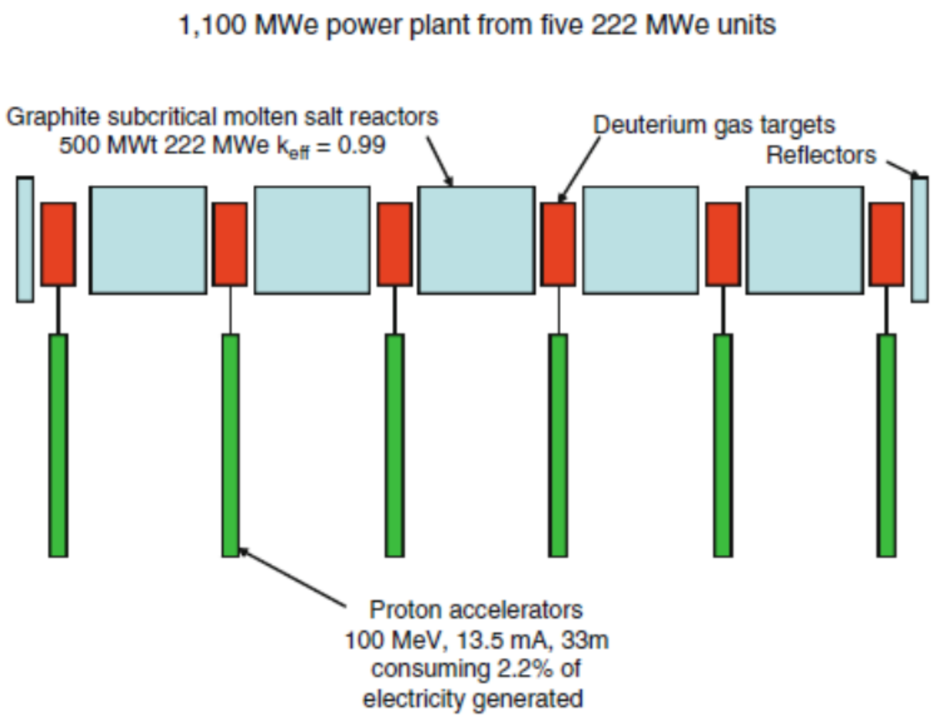


Cacuci, D. G., *Handbook of Nuclear Engineering*, (2010)

Modular Setup

- Deuterium targets could produce neutrons with same energy cost as a proton beam (1.35 mA @ 1 GeV) on Pb spallation target

- Can use natural uranium and spent fuel from light water reactors



Cacuci, D. G., *Handbook of Nuclear Engineering*, (2010)

Summary

- Accelerator-driven subcritical reactors are hybrid systems that promise important advantages over conventional nuclear reactors
- Thermal and fast neutron spectrum ADS reactors have been examined for use in commercial waste transmutation and energy production
- ADS reactors theoretically eliminate the risk of criticality accidents as fissile material is far from critical mass, unlike traditional nuclear reactors
- Implementation of research-scale ADS reactors is still in the beginning stages

References

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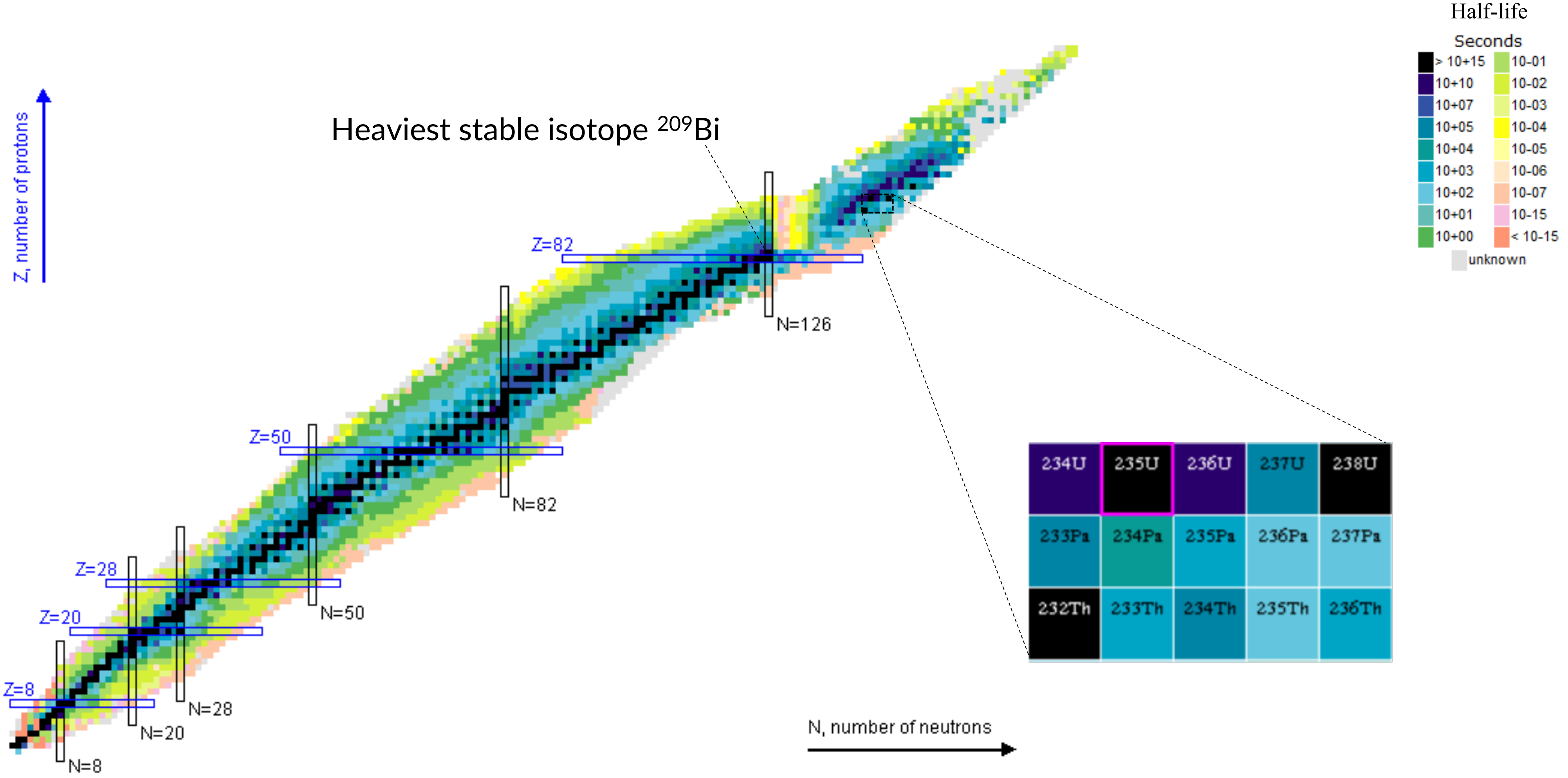
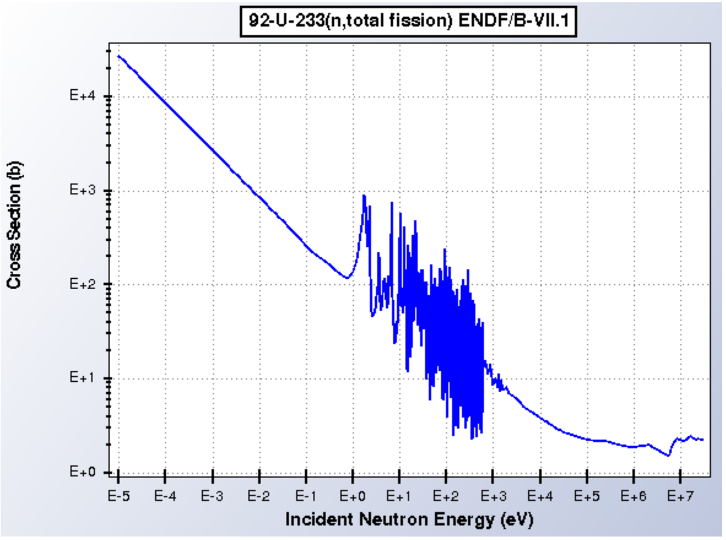
Heaviest stable isotope ^{209}Bi

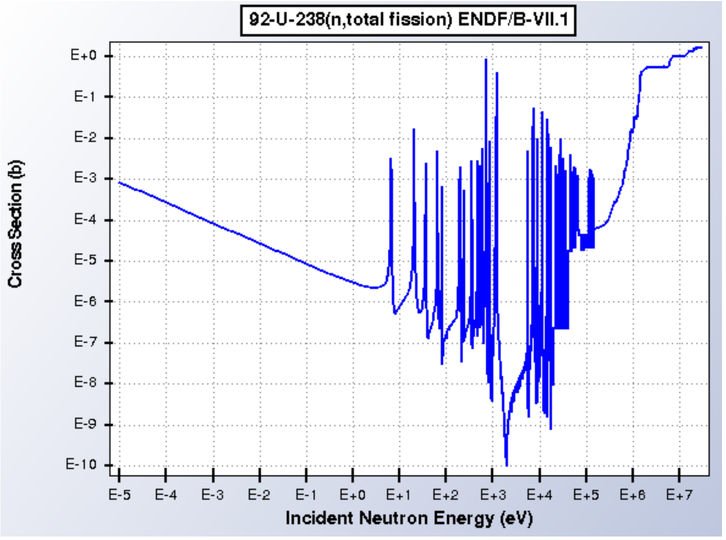


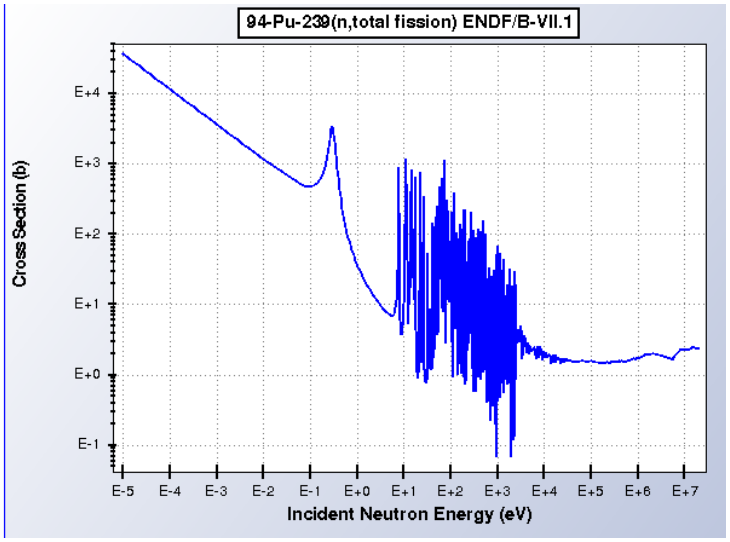
234U	235U	236U	237U	238U
233Pa	234Pa	235Pa	236Pa	237Pa
232Th	233Th	234Th	235Th	236Th

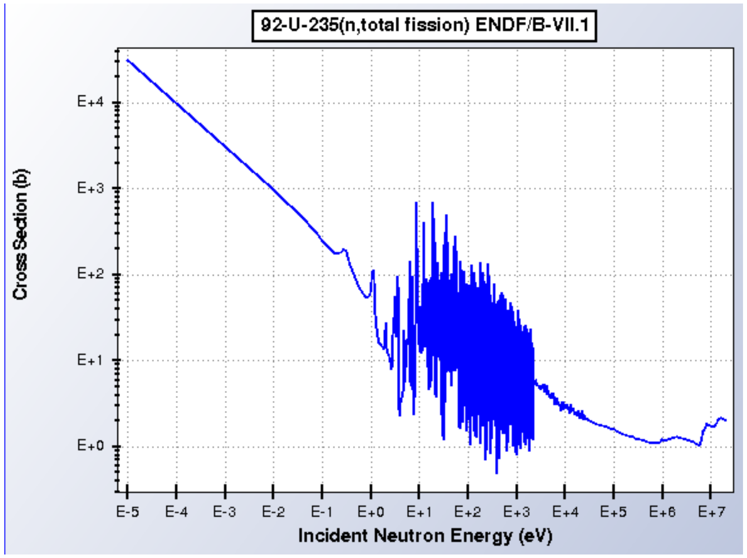
http://www.nndc.bnl.gov/

Nuclear cross sections for Neutron capture →fission









NNDC