

# Accelerator-Driven Nuclear Systems

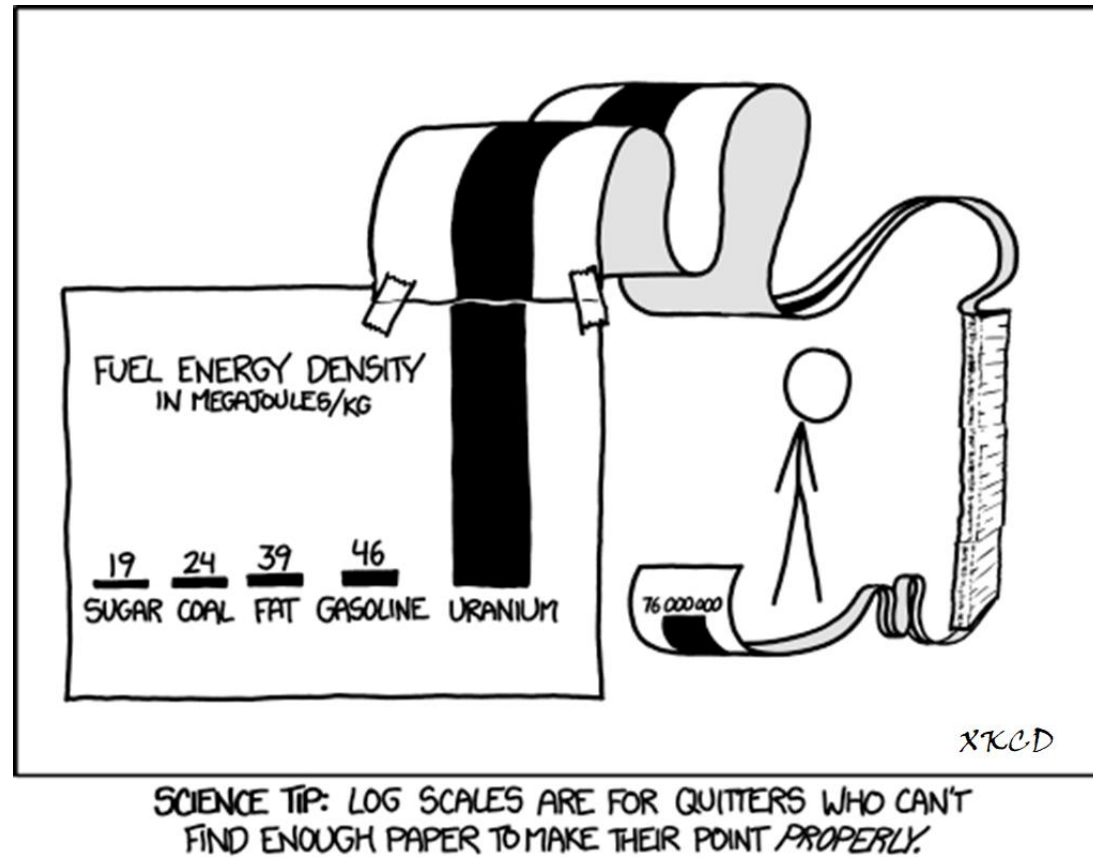
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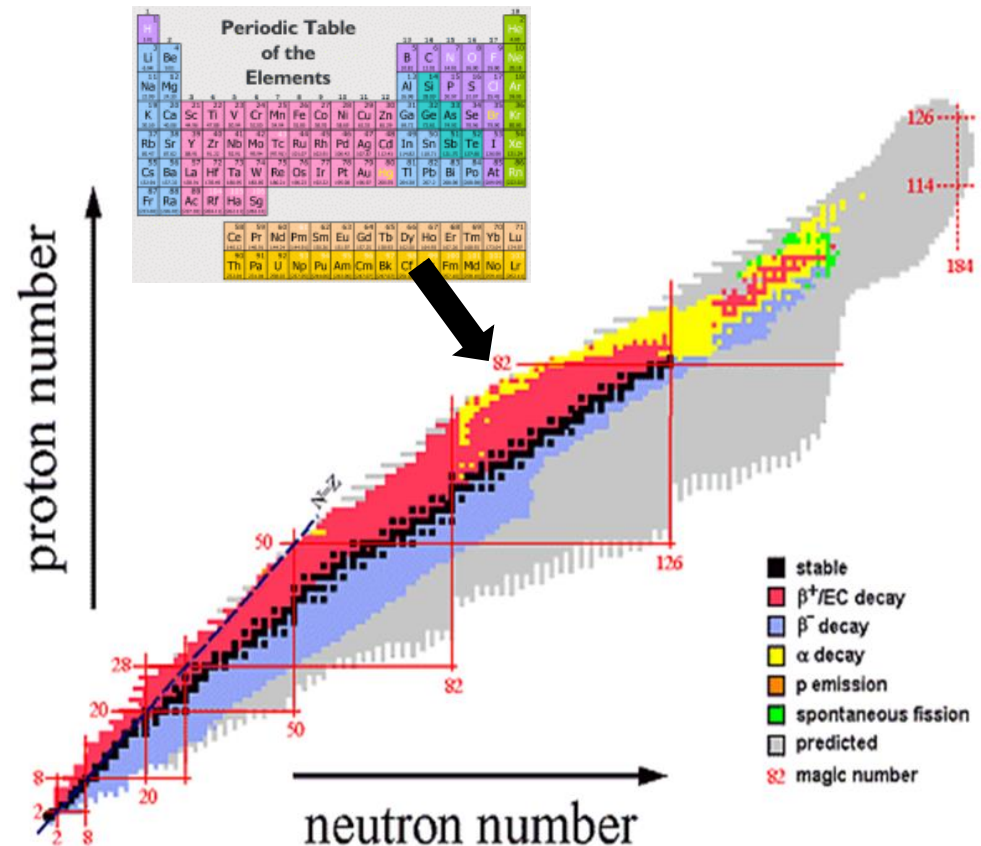
# Outline

- 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

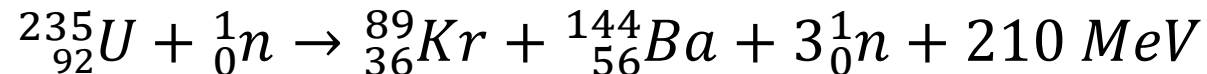


# Mass-Energy Equivalence

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

$$E_0 = mc^2$$

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



# 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 ( $\sigma_f$ ) and release 2 or more neutrons on average per neutron captured
- Chain reaction can be defined by multiplication factor,  $k$

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

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

# Past Reactor Fuels

## $^{235}\text{U}$

- Naturally occurring, small abundance (0.72%)
- Used in  $\text{D}_2\text{O}$  reactors (unenriched) or light water reactors (enriched)
- Requires **thermal neutrons** for adequate fission

## $^{239}\text{Pu}$

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

## $^{233}\text{U}$

- Bred from  $^{232}\text{Th}$  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  $^{235}\text{U}$  and  $^{239}\text{Pu}$  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  $^{233}\text{U}$  from  $^{232}\text{Th}$

# 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<sup>2</sup>s, by this time most nuclei with large cross sections for neutron capture ( $\sigma_c$ ) have been converted to nuclei with smaller  $\sigma_c$

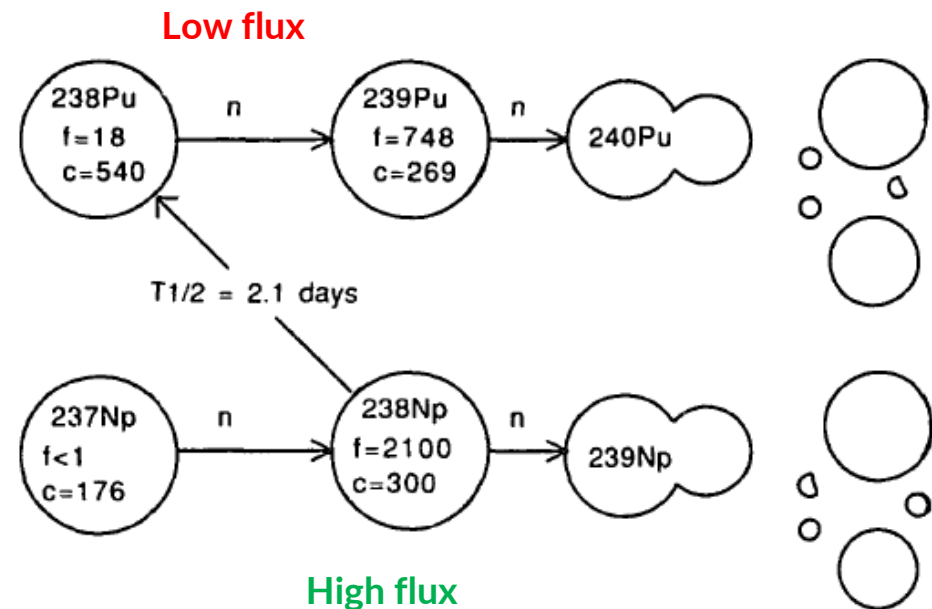
# Two Reactor Parameters

## ➤ Neutron energy

- At thermal conditions,  $\sigma_c \gg \sigma_f$  for  $^{237}\text{Np}$  and  $^{241}\text{Am}$  (primary constituents of actinide waste), therefore thermal neutrons convert the material to heavier nuclei instead of fissioning

## ➤ Neutron flux

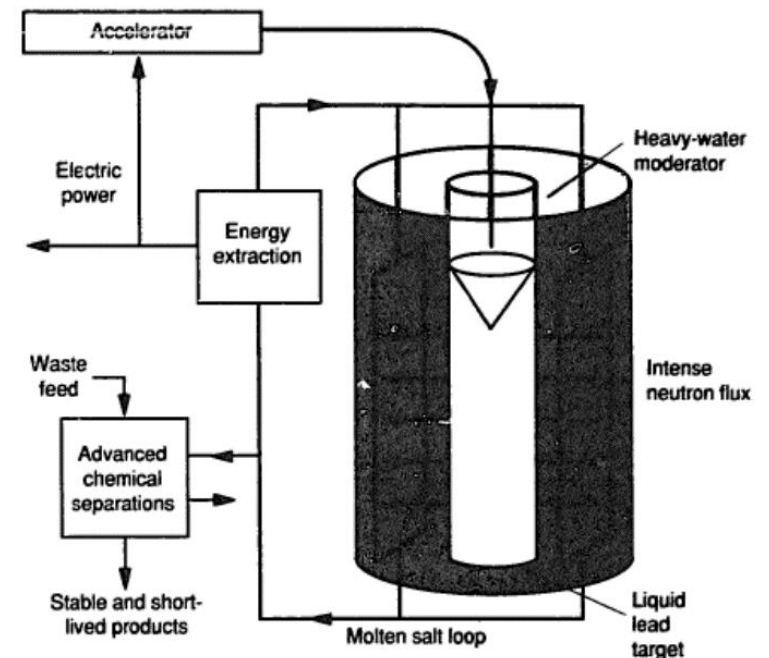
- At flux  $\sim 100$  times greater than nuclear reactors, actinides such as  $^{237}\text{Np}$  can capture two neutrons in succession, (bypasses poisonous  $^{238}\text{Np}$ ) leading to fissionable  $^{239}\text{Np}$



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<sup>2</sup>s,  $0.92 < k < 0.95$
- Due to fast buildup of 'poisonous' fission fragments, circulating liquid flow (molten salt, D<sub>2</sub>O, 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 <sup>233</sup>U from <sup>232</sup>Th



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

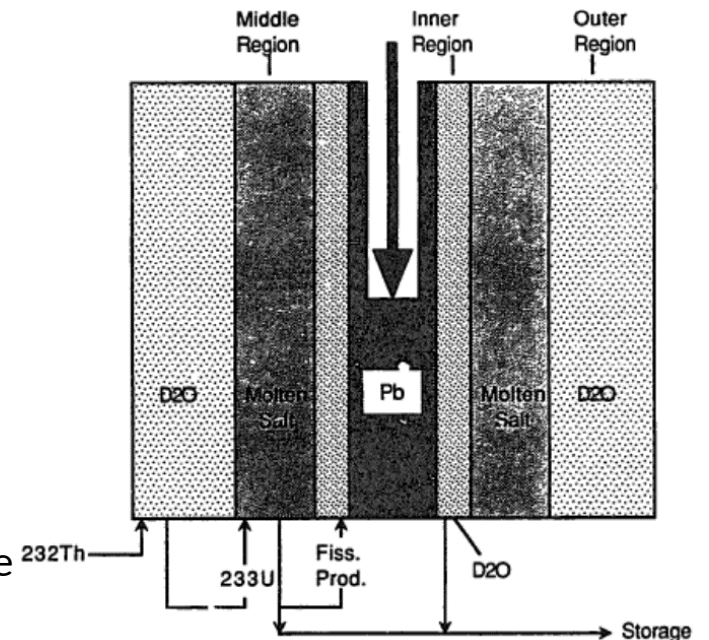
# Design

## ➤ 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<sub>2</sub>O for transmutation of fission products (generally small  $\sigma_c$ )
- Middle sector of molten salt (LiF + BeF<sub>2</sub>) as carrier of fissile material and medium for heat transfer
- Outer sector of D<sub>2</sub>O 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

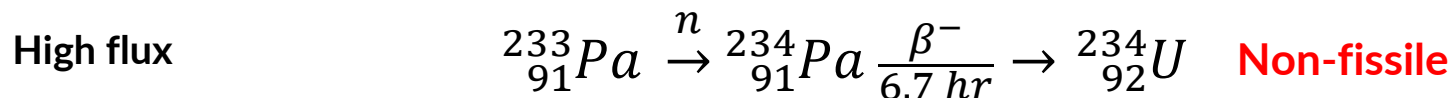
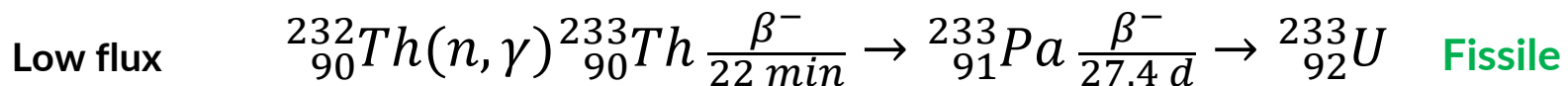
- In thermal spectrum ~half of the nuclides do not undergo fission, instead they capture to the next heaviest nuclei
- Continuous-flow concept would require **considerable chemical separation** of fission fragments, actinides,  $^{233}\text{Pa}$  for milking of  $^{233}\text{U}$  (if using thorium)

# 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  $^{232}\text{Th} \rightarrow ^{233}\text{U}$  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

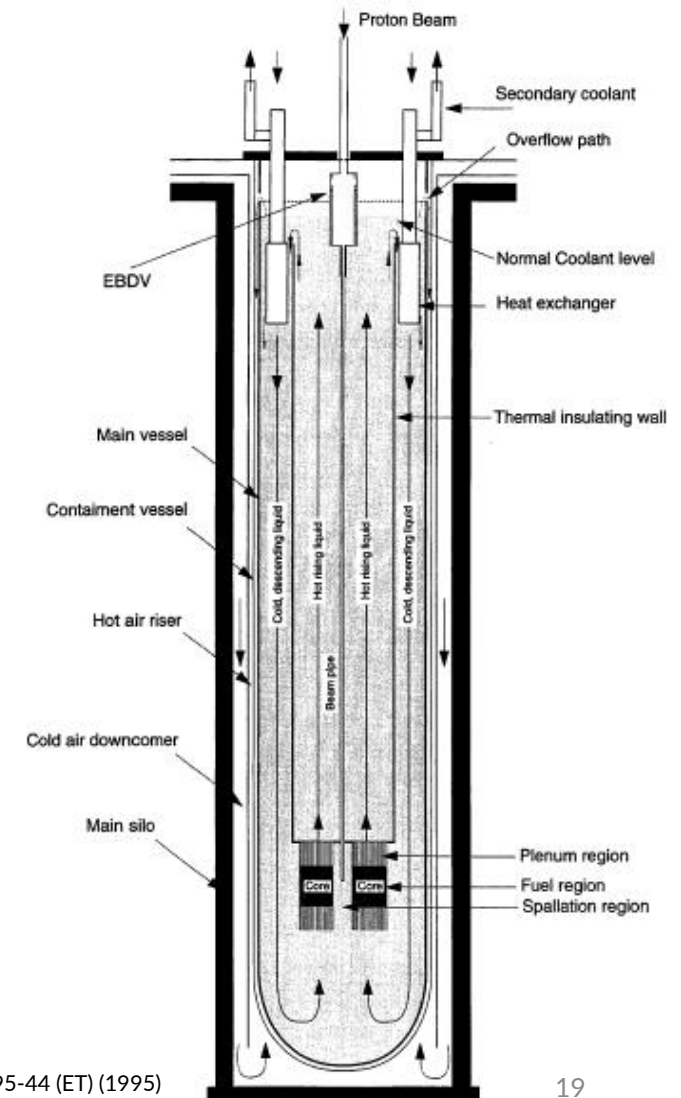
# Fast Energy Amplifier Concept

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



# Design

- Practical layout includes 15 tons of fuel material ( $\text{ThO}_2\text{-UO}_2$ )
- 20 MW proton beam (20 mA @ 1 GeV)
  - operates at level of  $\sim 1 \text{ GW}_{(e)}$  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



## Advantages

- Considerable energy gain **far from criticality**
- [ $^{233}\text{Pa}$ ] 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

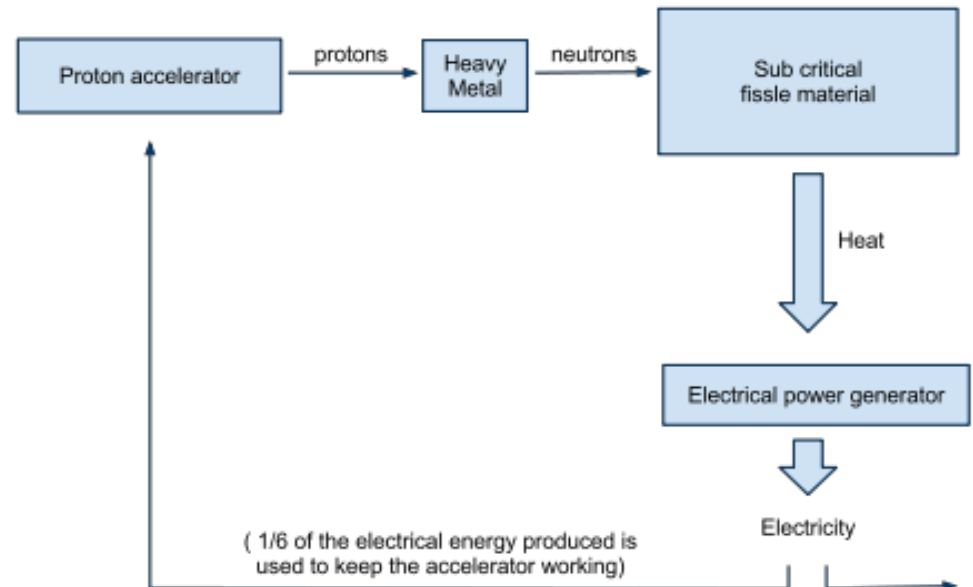
- Radiotoxicity build-up in the lead coolant
- Radioactive fission fragments will still generate heat, **~7%** of total energy emitted by fission, even if the proton beam is switched off; continued cooling is still required to prevent melt-down

# Currently Pursued Accelerator-Driven Systems

## Examples

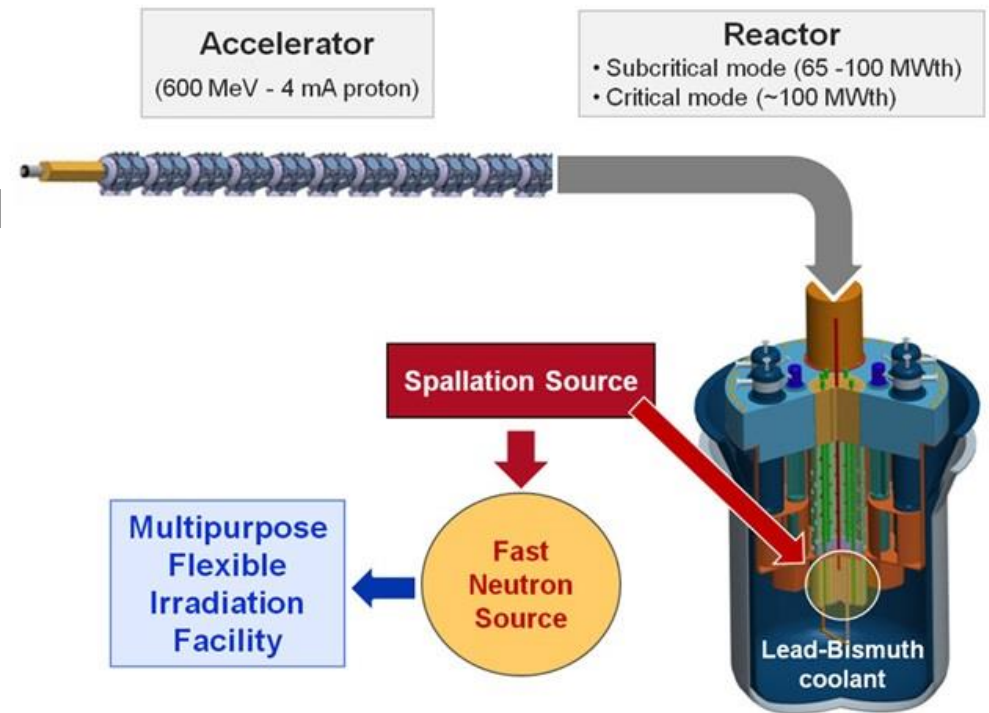
- **MYRRHA**  
Belgium Nuclear Research Centre (Built by 2025)
- **GEM\*STAR**  
Virginia, U.S.A.  
ADNA Corp.  
(building demonstration reactor)

## Accelerator Driven Reactor



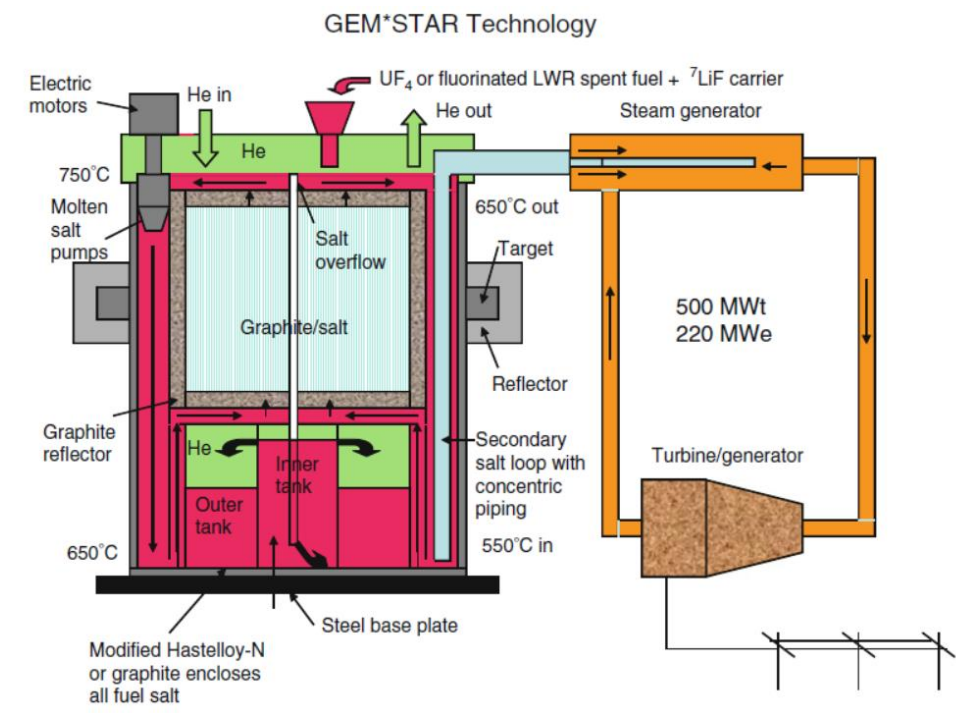
# MYRRHA: Multipurpose hybrid Research Reactor for High-tech Applications

- 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

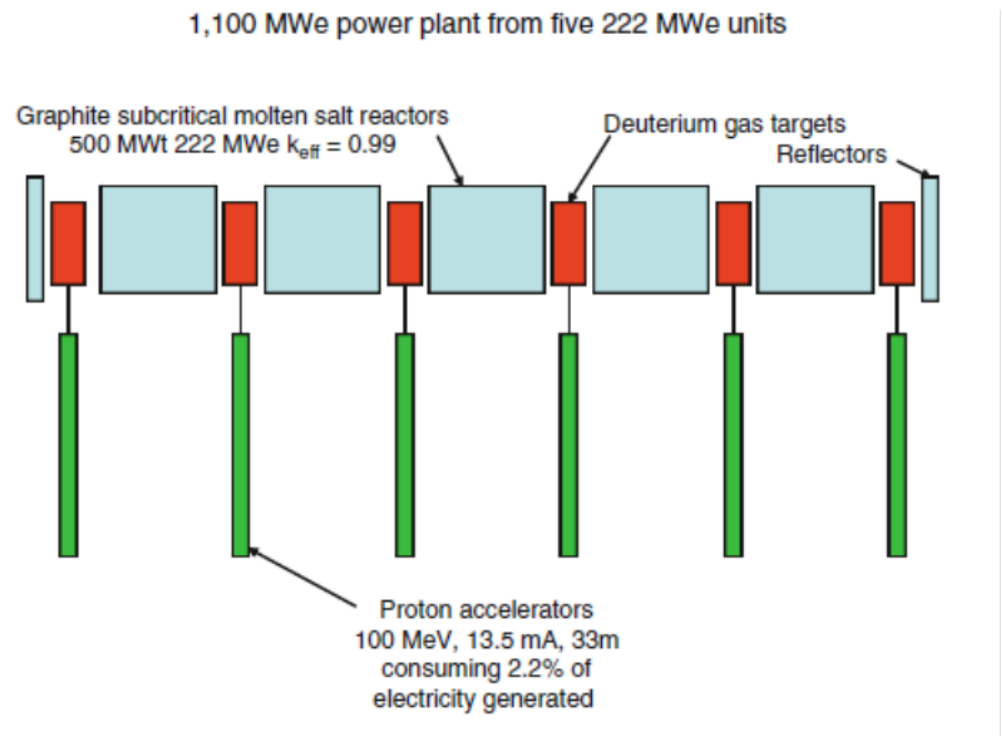
- Being developed by Accelerator Driven Neutron Application Corporation ([Bowman](#)) and Virginia Tech University
- Subcritical **thermal-spectrum** reactor with continuous-flow molten salt fuel in a graphite matrix
- High energy neutrons produced by proton beam on stopping length thickness of deuterium 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

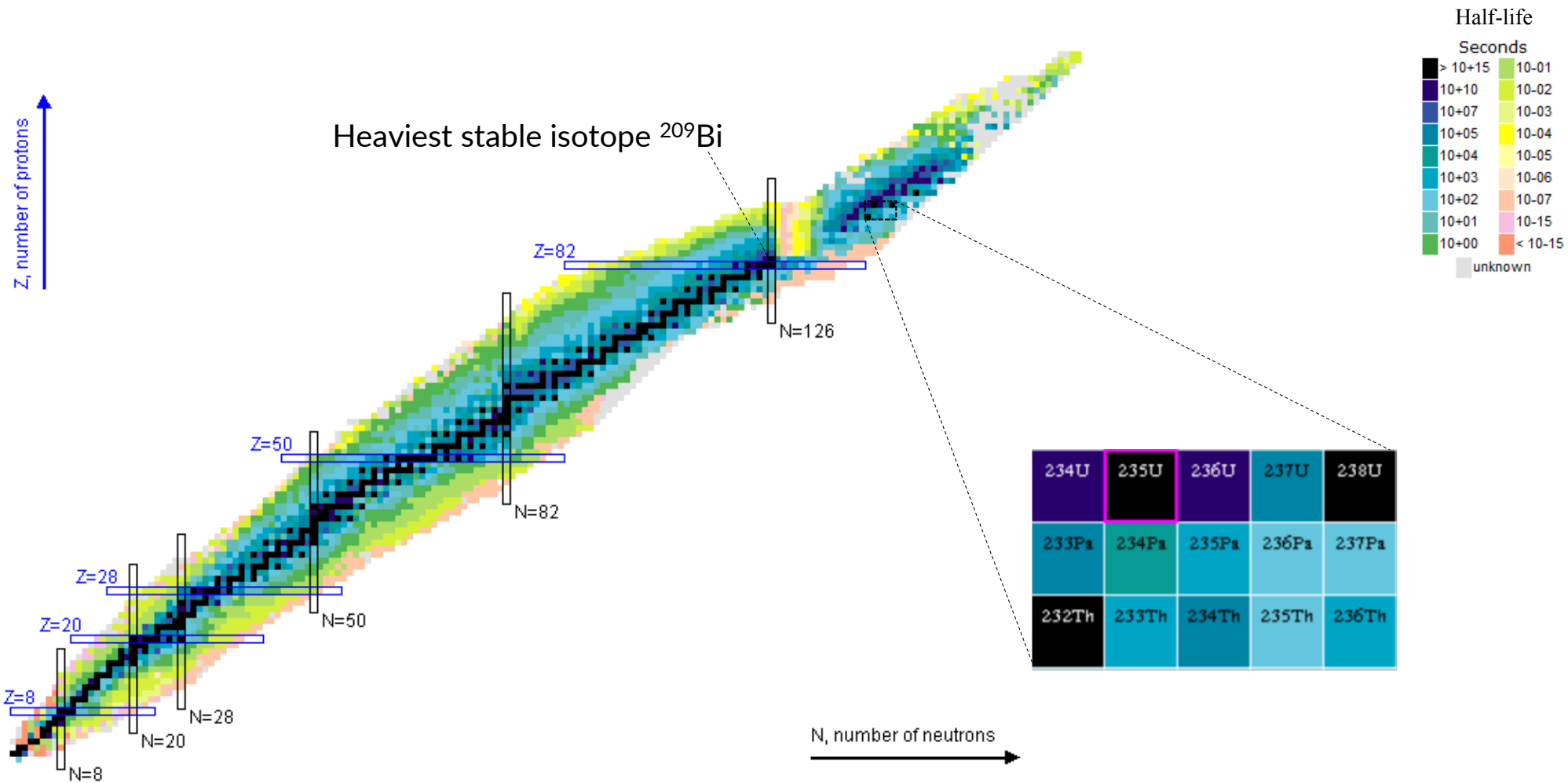


# Summary

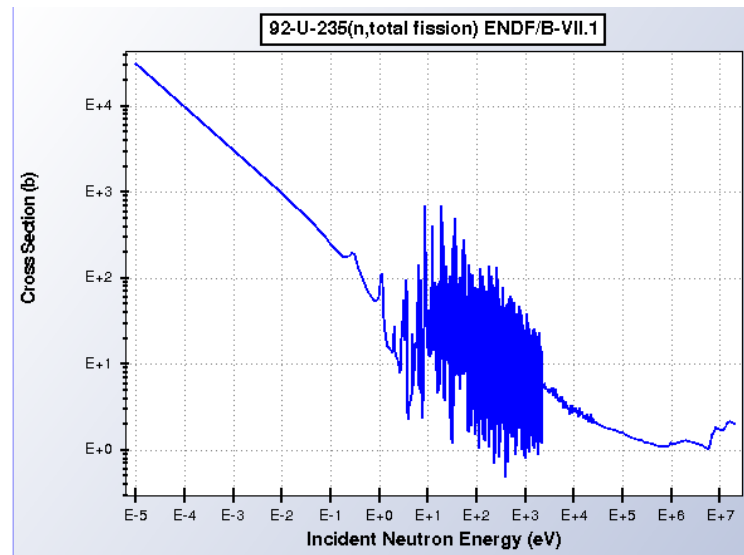
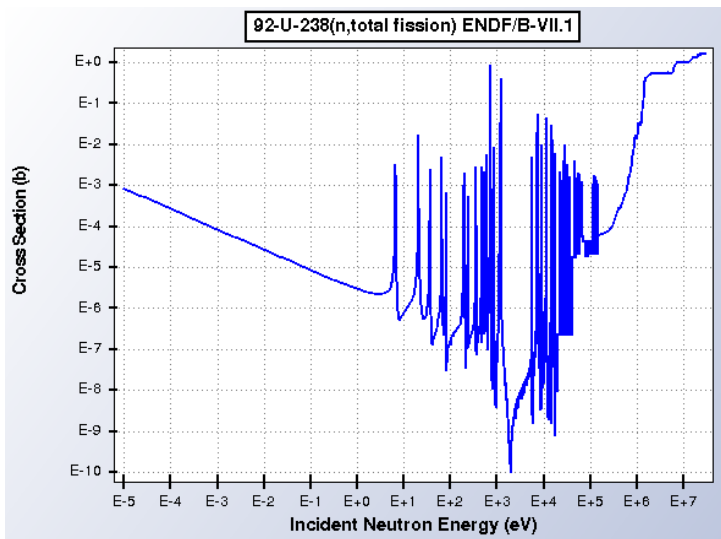
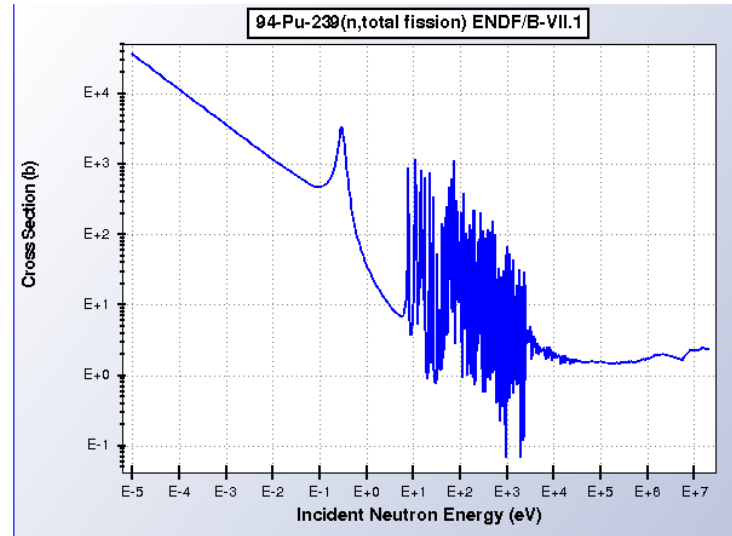
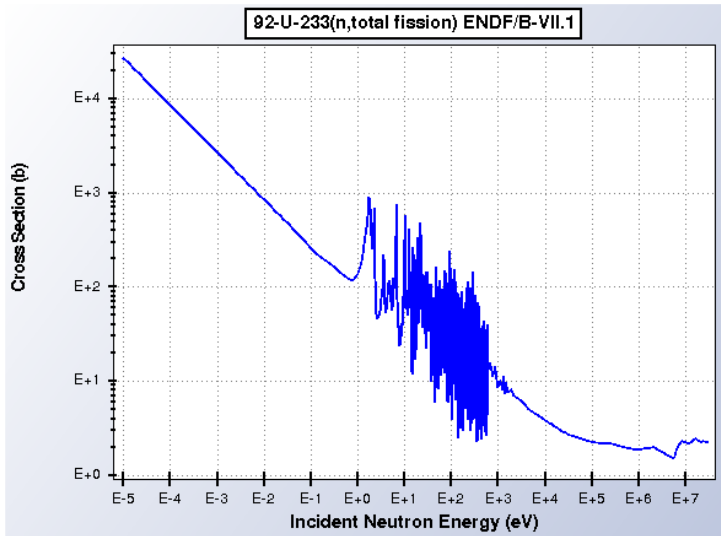
- Accelerator-driven subcritical reactors are **hybrid systems** that promise important advantages over conventional nuclear reactors
- **Thermal** and **fast** neutron spectrum ADS reactors have been examined for use in commercial waste transmutation and energy production
- ADS reactors theoretically 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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<http://www.nndc.bnl.gov/>



Nuclear cross sections for Neutron capture → fission

NNDC