Overview of Accelerator-Driven System (ADS)

Tae-Yeon Lee (이태연)
Pohang Accelerator Lab.

For 2020 KNS Spring Meeting
ADS Workshop

Google 크롬.lnk

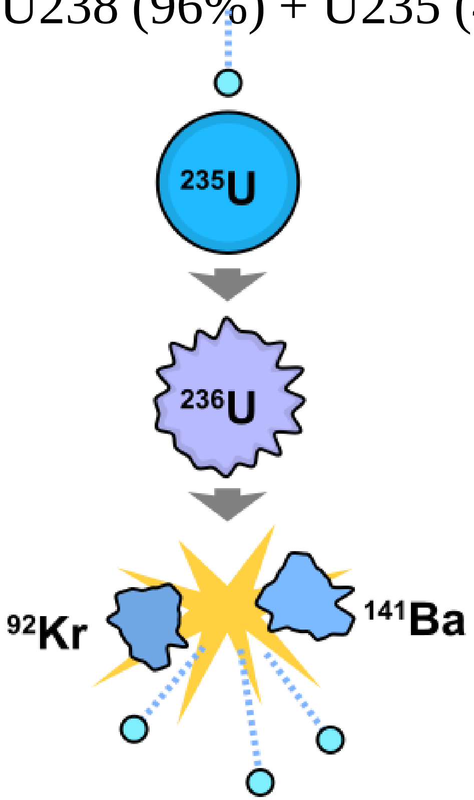
PAL

Introduction to Nuclear Fission

Fission is triggered by Neutrons

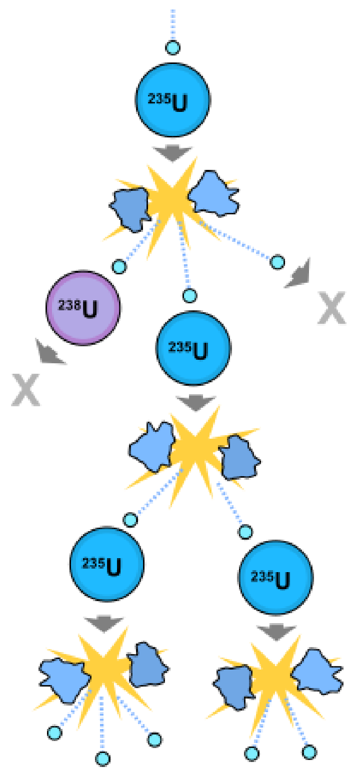
Common fuel for a typical light water reactor:

U238 (96%) + U235 (4%) (Natural Uranium: U238(99.3%))

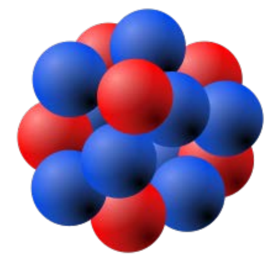


Energy + average 2.6 N

Fission



Chain Reaction

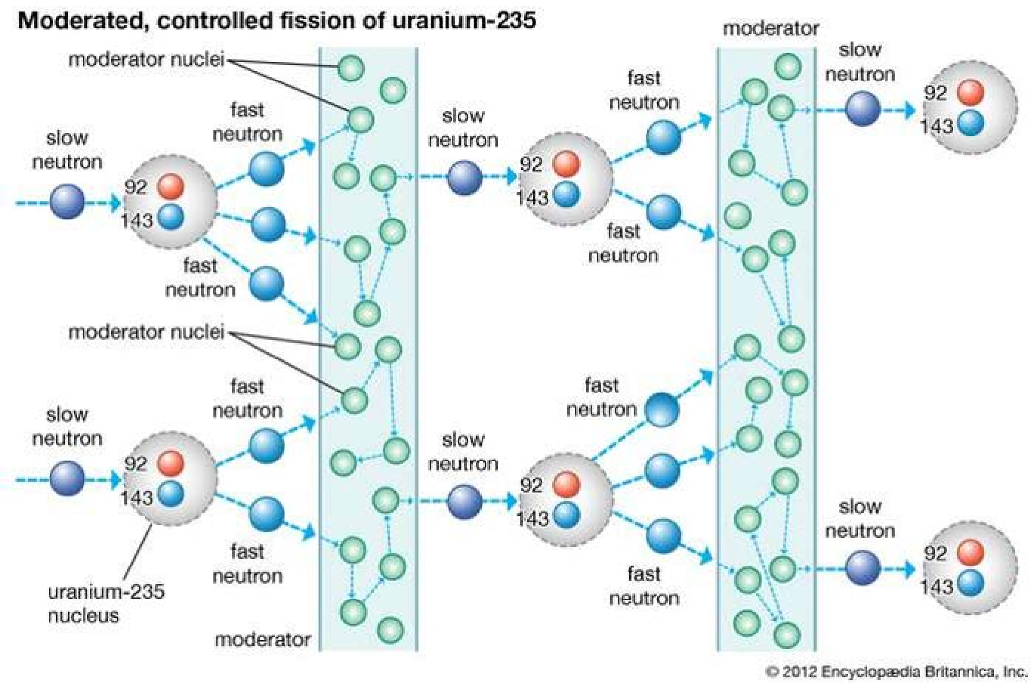


Nucleus= P (red balls) + N (blue balls)
Neutrons are essential for fission.

Slow and Fast Neutrons in a Critical Reactor

- **Slow (thermal) neutrons**
  $E_{therm} \leq 0.4$ e V
  typical thermal energy E_{therm} = 0.025 eV
- **Epithermal neutrons**
  0.4 eV < E_{epi} < 10 keV
- **Fast neutrons**
  $E_{fast} \geq$ 10 keV

Application of research reactors



This is a critical slow reactor that uses slow neutrons for fission. In a sub-critical reactor, the number of fissions and the number of emitted neutrons decrease as time. A reactor with no moderator is called fast reactor.

ADS uses a sub-critical reactor

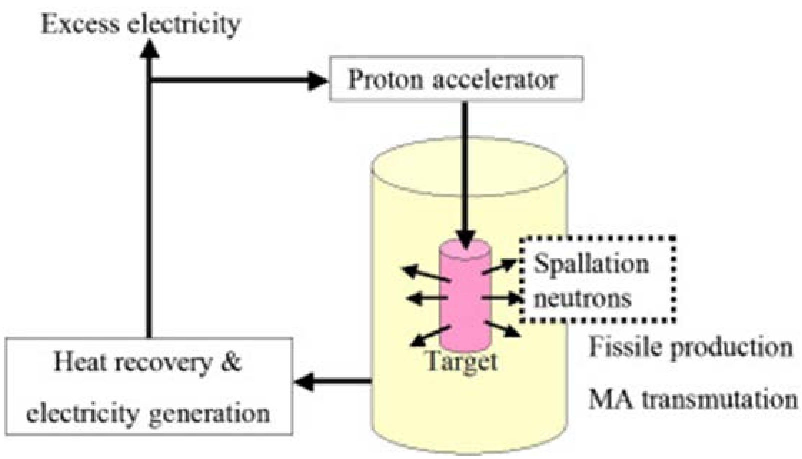
- Ordinary nuclear fission reactor is a critical reactor in which nuclear fission is self-sustained. On the other hand, ADS uses a sub-critical reactor in which nuclear fission is not self-sustained.
- For stable operation of ADS, extra neutrons should be supplied from outside just as many as to make the sub-critical reactor + external neutron supply system critical again.

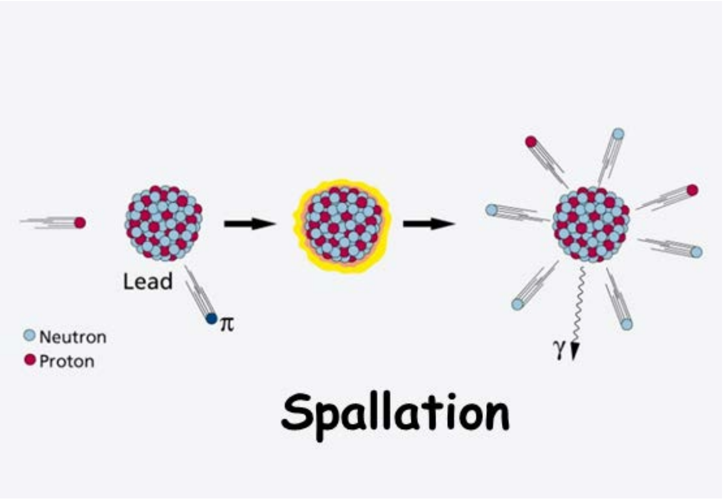
Features of Accelerator Driven System (ADS)

What is ADS?

ADS = sub-critical reactor + [proton accelerator + heavy-metal target]

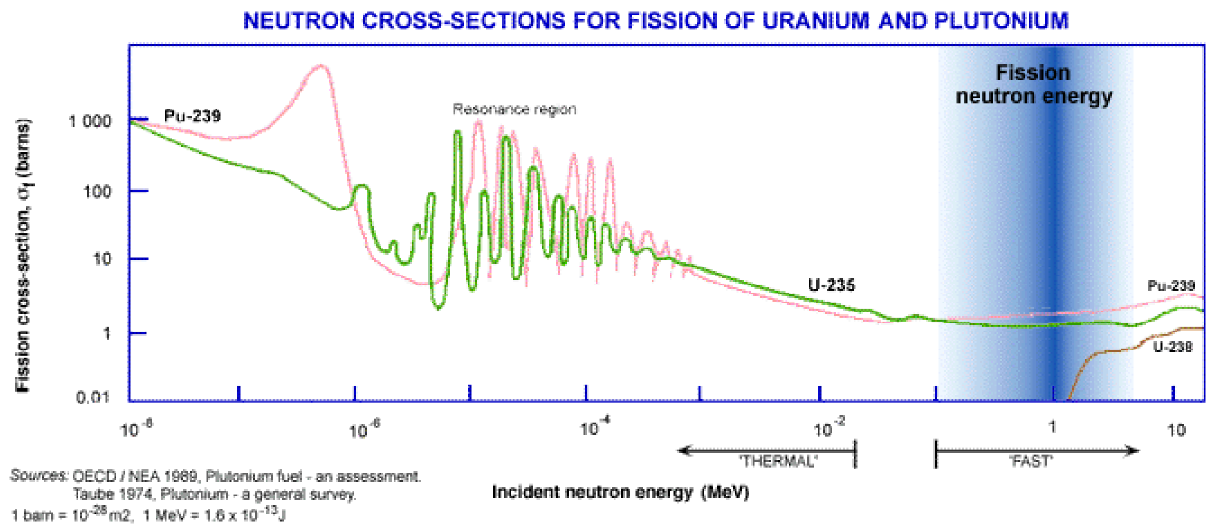
The extra neutrons required to make a sub-critical reactor critical is supplied by external spallation neutrons generated when protons hit heavy-metal target.

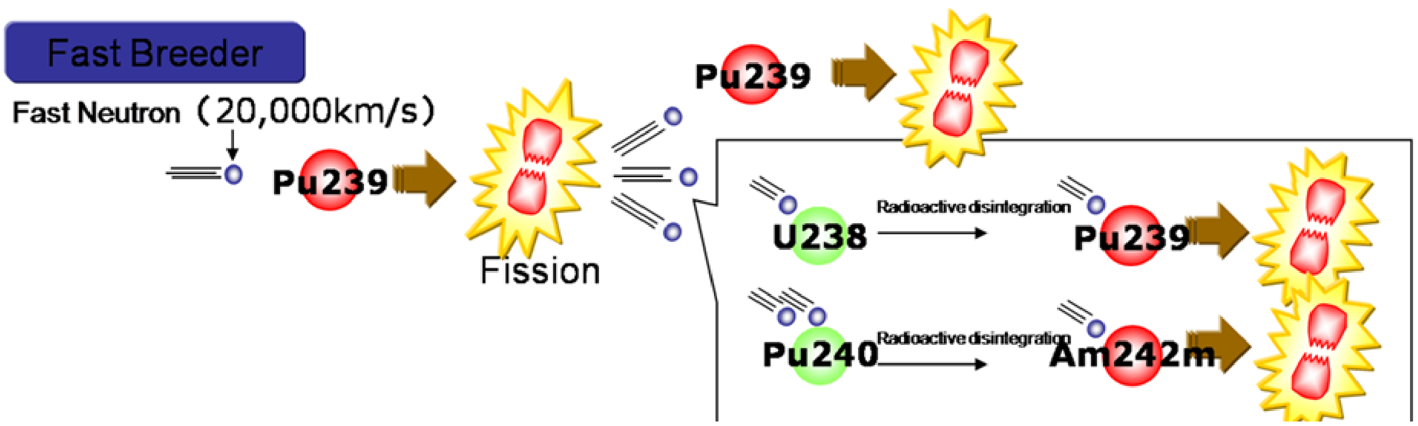




- In general, ADS has no moderator and makes use of fast neutrons for fission -> fast reactor

Fast Reactor for Plutonium



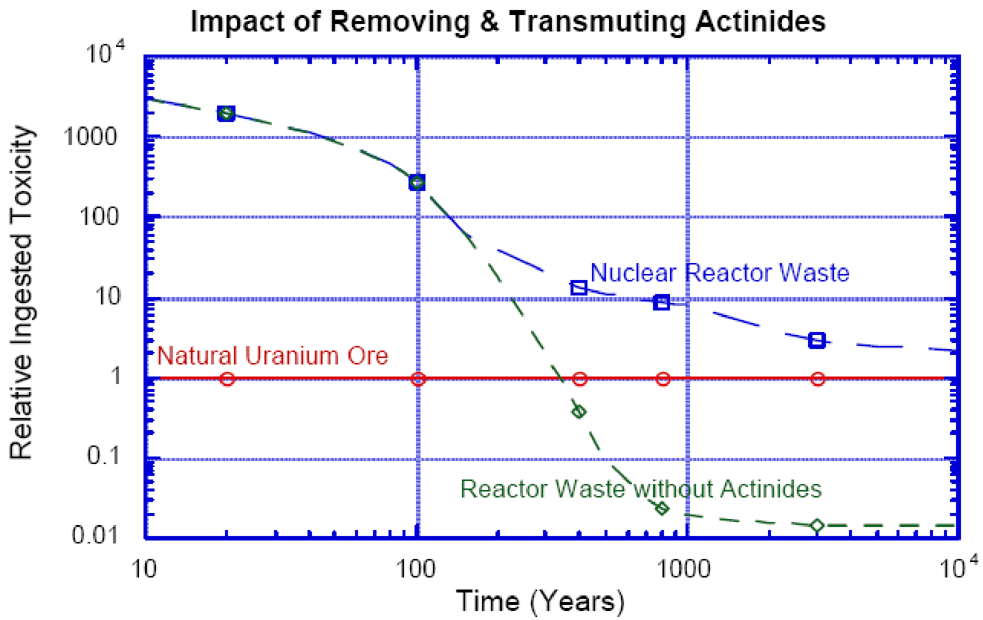


Why ADS?

Purpose of ADS: Power Generation + Transmutation (safely)

What is transmutation in a reactor?

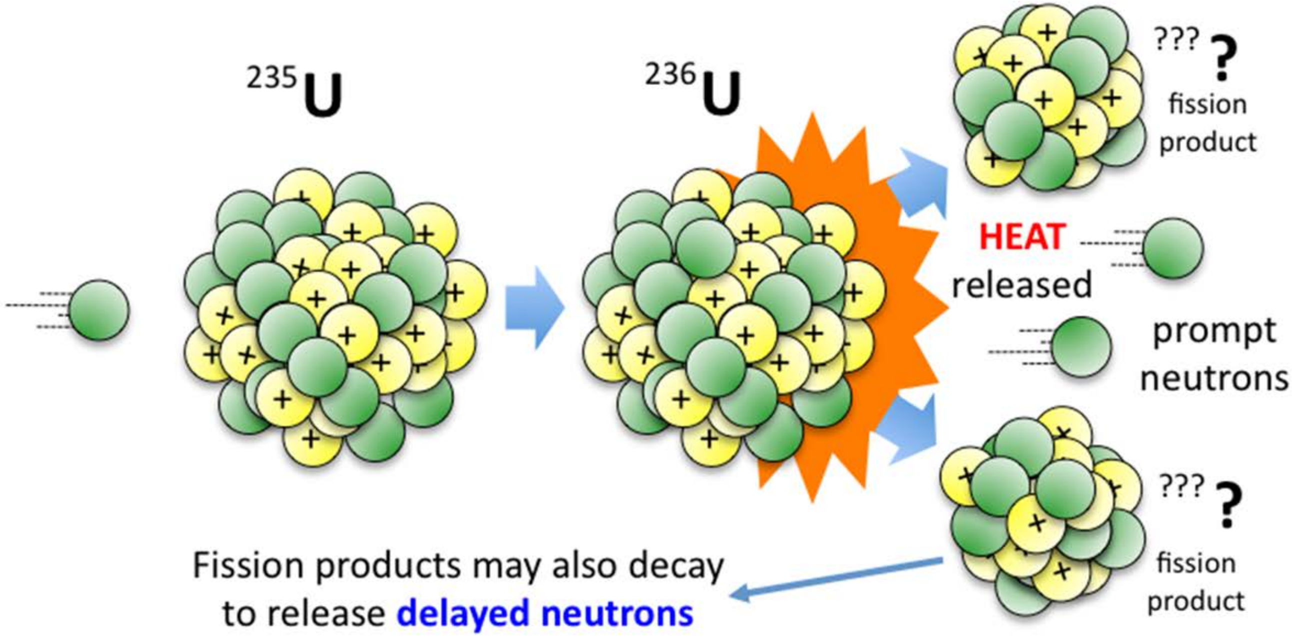
Long-lived (several hundred thousand years) nuclear waste (Actinides) can be transmuted to short-lived waste (several hundred years) by fast neutrons.



Critical fast reactor (CR) can also perform power generation + transmutation. But, ADS is safer and more effective as will be shown.

Why is ADS safer?

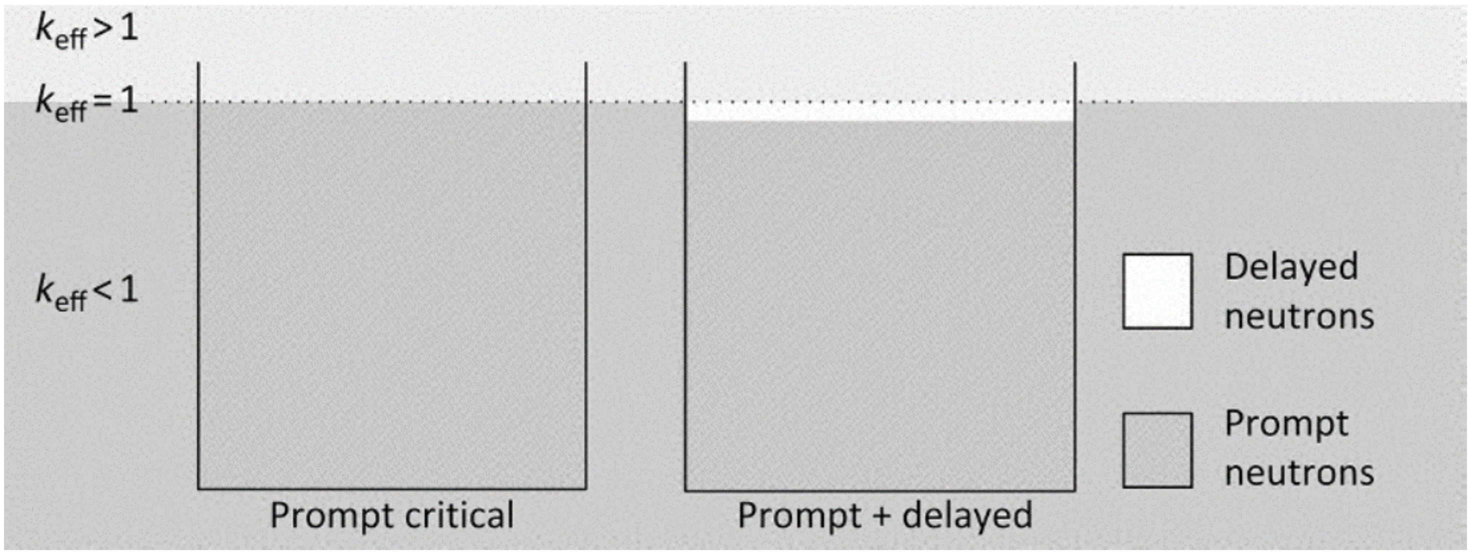
In ADS, external neutrons from targets are delayed-neutrons.



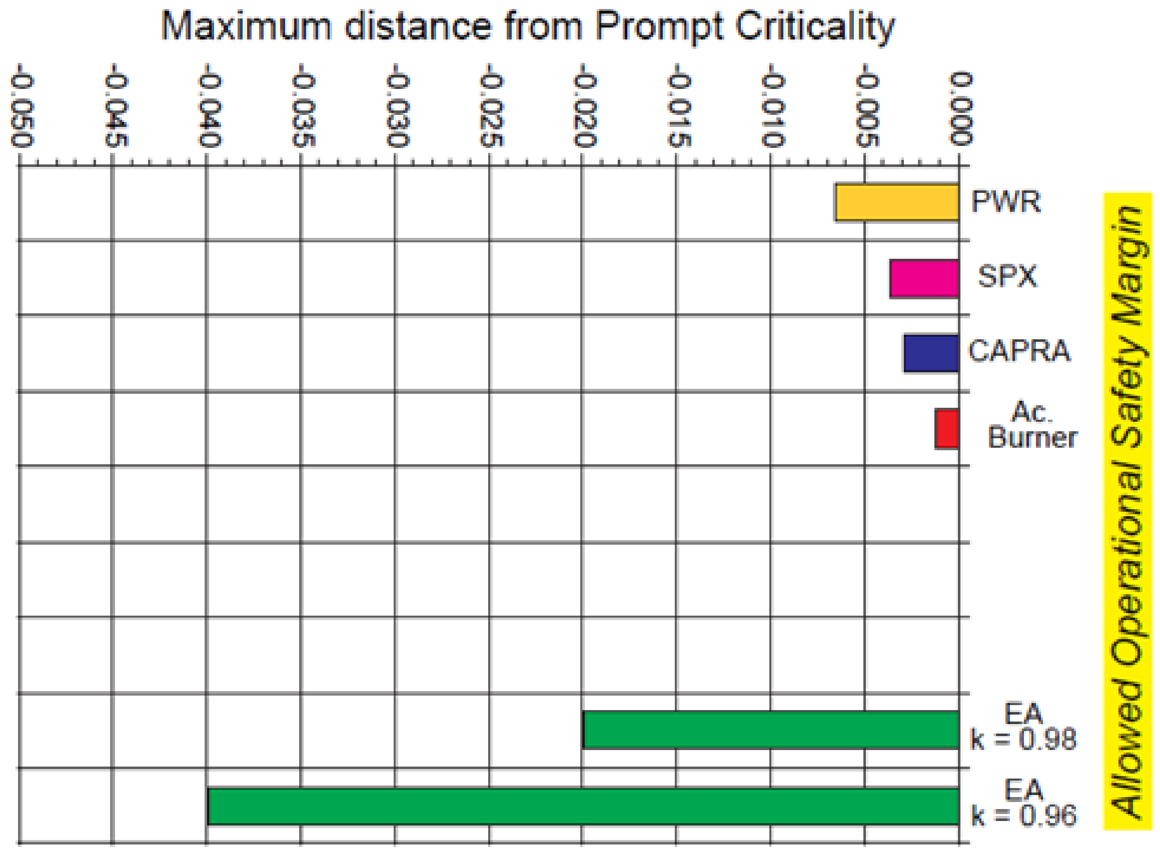
Why is ADS safer?(2)

Delayed-neutrons make a reactor more controllable.

- **ADS has higher ratio of delayed neutrons. This makes ADS safer than other scenarios: More delayed neutrons, larger safety margin.**



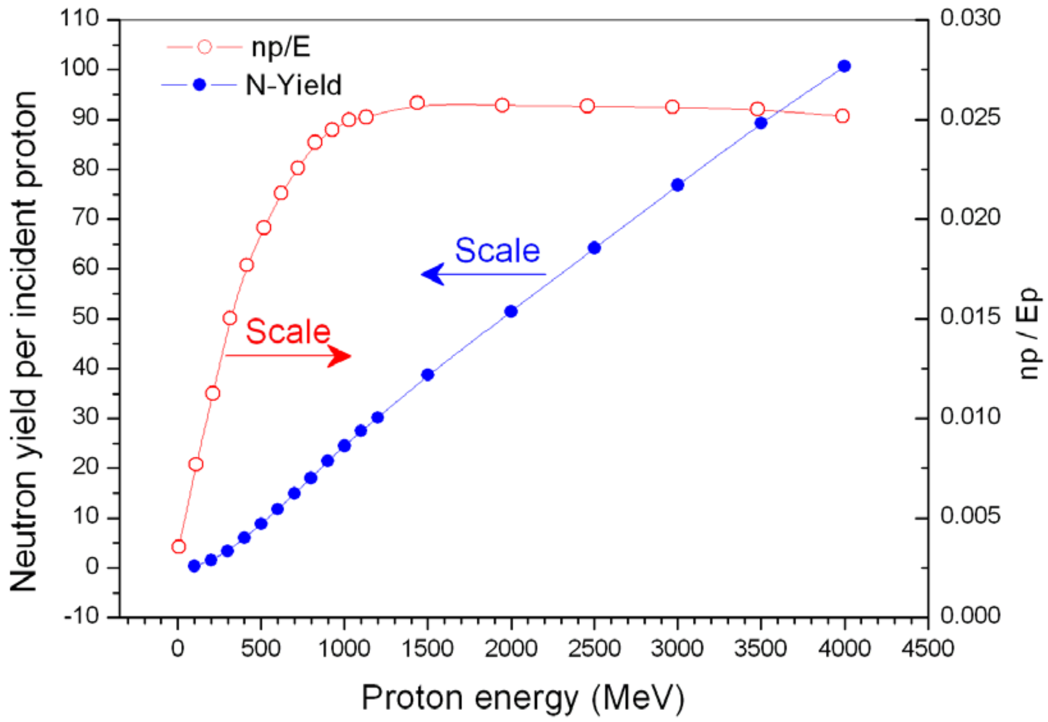
ADS has larger Safety Margin than CR



Accelerators for ADS

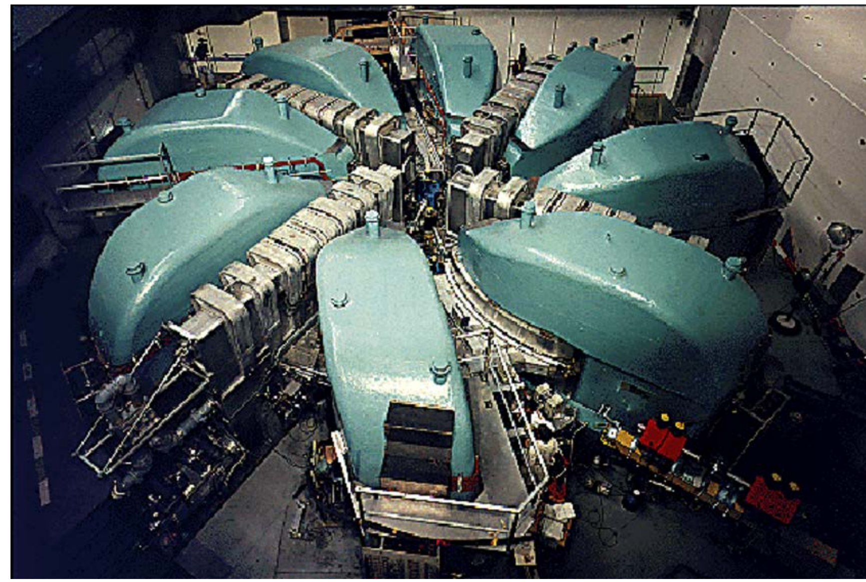
Accelerator Requirements

ADS requires high proton beam energy (typically 1 GeV) and high power (10 MW or higher depending upon safety margin).



Operational reliability: Accelerator operation should be very stable.

Typical Proton Accelerator Types for ADS



Superconducting Linear Accelerator

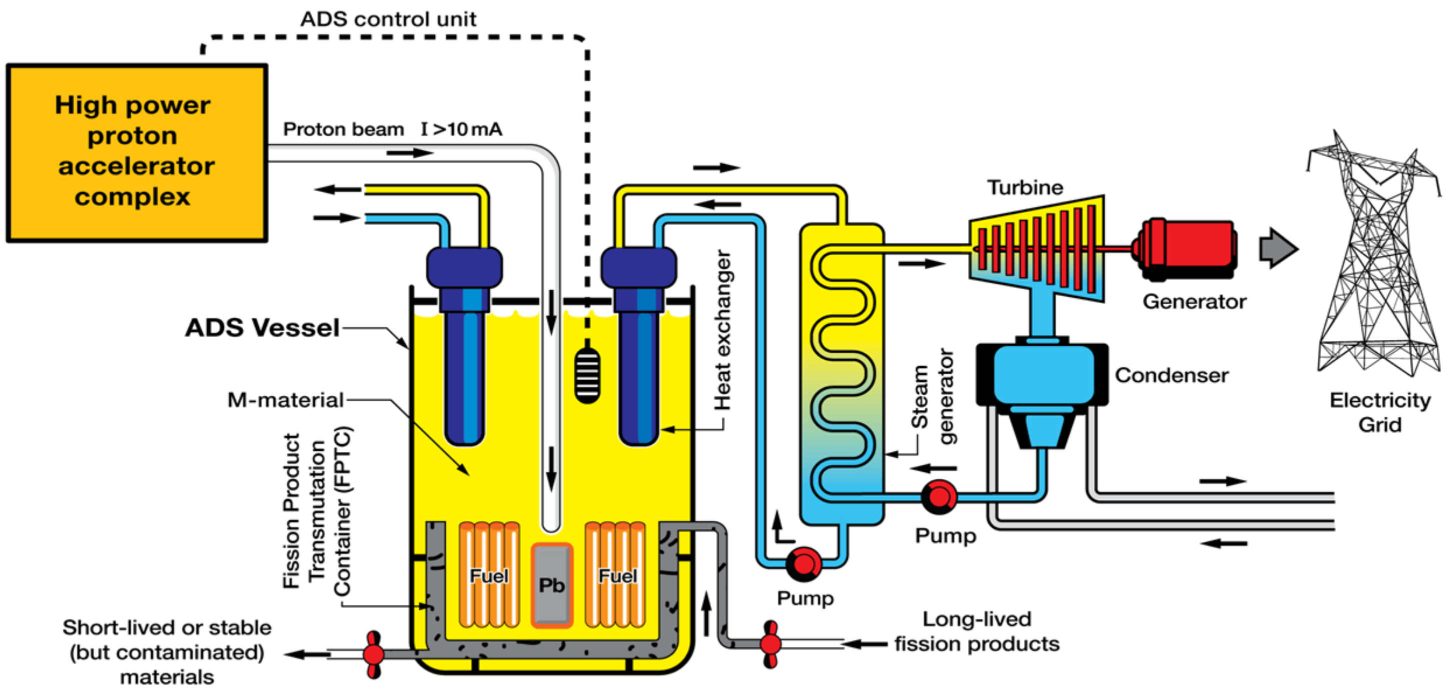
Capable of high energy and power.
High cost and big size.

Cyclotron

Limitation in energy and power.
Lower cost and smaller size.

Current Status of ADS

Ideal ADS = Transmutation + Power Generation



Commercial Power Generation is more difficult than **Transmutation**.

Ideal ADS is more difficult to achieve

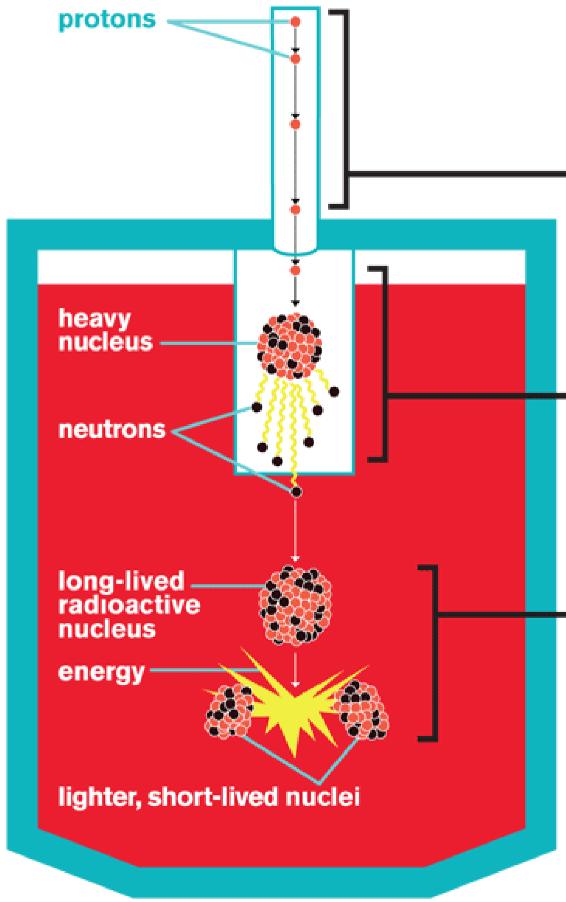
Stability Requirement for Accelerator

	Transmutation Demonstration	Industrial Scale Transmutation	Industrial Scale Power Generation with Energy Storage	Industrial Scale Power Generation without Energy Storage
Beam Power	1-2 MW	10-75 MW	10-75 MW	10-75 MW
Beam Energy	0.5-3 GeV	1-2 GeV	1-2 GeV	1-2 GeV
Beam Time Structure	CW/pulsed (?)	CW	CW	CW
Beam trips (t < 1 sec)	N/A	< 25000/year	<25000/year	<25000/year
Beam trips (1 < t < 10 sec)	< 2500/year	< 2500/year	<2500/year	<2500/year
Beam trips (10 s < t < 5 min)	< 2500/year	< 2500/year	< 2500/year	< 250/year
Beam trips (t > 5 min)	< 50/year	< 50/year	< 50/year	< 3/year
Availability	> 50%	> 70%	> 80%	> 85%

Commercial Power Plant is difficult to realize with current technology mainly because of stability requirement.

Dedicated Transmuter is more realistic

Transmutation of nuclear waste with a subcritical ADS reactor



Graphic: Sandbox Studio

Accelerator
An accelerator provides an intense, continuous beam of protons.

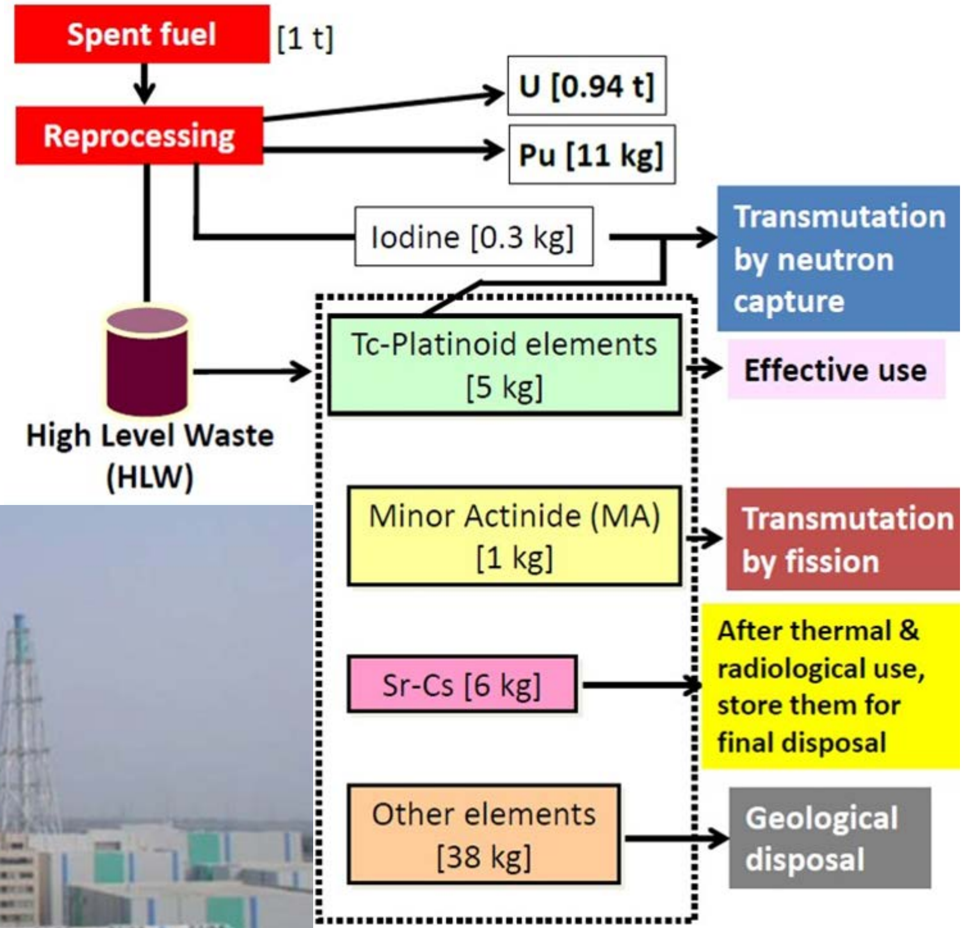
Spallation target
The protons hit heavy nuclei and "shake loose" neutrons, which enter the reactor vessel.

Transmutation
The neutrons hit and split long-lived nuclei, such as americium and curium, creating energy and short-lived nuclei that are easier to process and store.

Subcritical operation
When the accelerator is switched off or loses power, the reactor no longer has enough neutrons to sustain the transmutation process and the nuclear reactions automatically slow down.

Reprocessing is Required for ADS

Korea: pyro-processing?



Rokkasho Reprocessing Plant

Critical Fast Reactor is also capable of transmutation

Comparison of ADS and Critical Fast Reactor (CR) for Transmutation

Advantage of ADS over CR

Subject materials of transmutation (actinides) emit very low percentage of delayed neutrons as shown in the Table below. To compensate for the lacking delayed neutrons, **ADS can obtain extra delayed neutrons from the accelerator but CR can obtain them only by adding extra U238 into the fuel.** But, then, this U238 generates additional Pu that should also be removed by transmutation.

Nuclide	β
^{238}U	0.0172
^{237}Np	0.00388
^{238}Pu	0.00137
^{239}Pu	0.00214
^{240}Pu	0.00304
^{241}Pu	0.00535
^{242}Pu	0.00664
^{241}Am	0.00127
^{243}Am	0.00233
^{242}Cm	0.000377

Hence, ADS needs no U238 and can burn more actinides than CR. Critical reactor is difficult to use as a pure TRU or MA burner because of U238 that should be included in the fuel.

ADS can use Uranium-free fuel and be very effective in transmutation.

PAL

Comparison of ADS and Critical Reactor

	Advantages of accelerator-driven systems	Disadvantages of accelerator-driven systems
Design and operation	♦ The possibility to operate a reactor core at a *neutron multiplication factor below 1* opens opportunities for new reactor concepts, including concepts which are otherwise ruled out by an insufficient neutron economy ♦ In particular, this allows transmuters to be designed as pure TRU or MA burners and hence the fraction of specialised transmuters in the reactor park to be minimised ♦ The proportionality of the reactor power to the accelerator current simplifies the reactor control	♦ *Accelerator:* Very high reliability required to protect structures from thermal shocks ♦ *Beam window and target* subjected to unusual stress, corrosion and irradiation conditions ♦ *Sub-critical core:* Increased power peaking effects due to external neutron source ♦ Compromises between neutron multiplication factor and accelerator power required ♦ Increased overall complexity of the plant ♦ Reduction in net plant electrical efficiency due to power consumption of accelerator
Safety	♦ The reactivity margin to prompt criticality can be increased by an extra margin which does *not depend on the delayed neutrons* ♦ This enables the safe operation of cores with degraded characteristics as they are typical e.g. for pure MA burners ♦ *Excess reactivity can be eliminated*, allowing the design of cores with a reduced potential for reactivity-induced accidents	♦ New types of reactivity and source transients have to be dealt with (external neutron source can vary rapidly and reactivity feedbacks in TRU- and MA-dominated cores are weak)

Example: ADS Plan in Japan

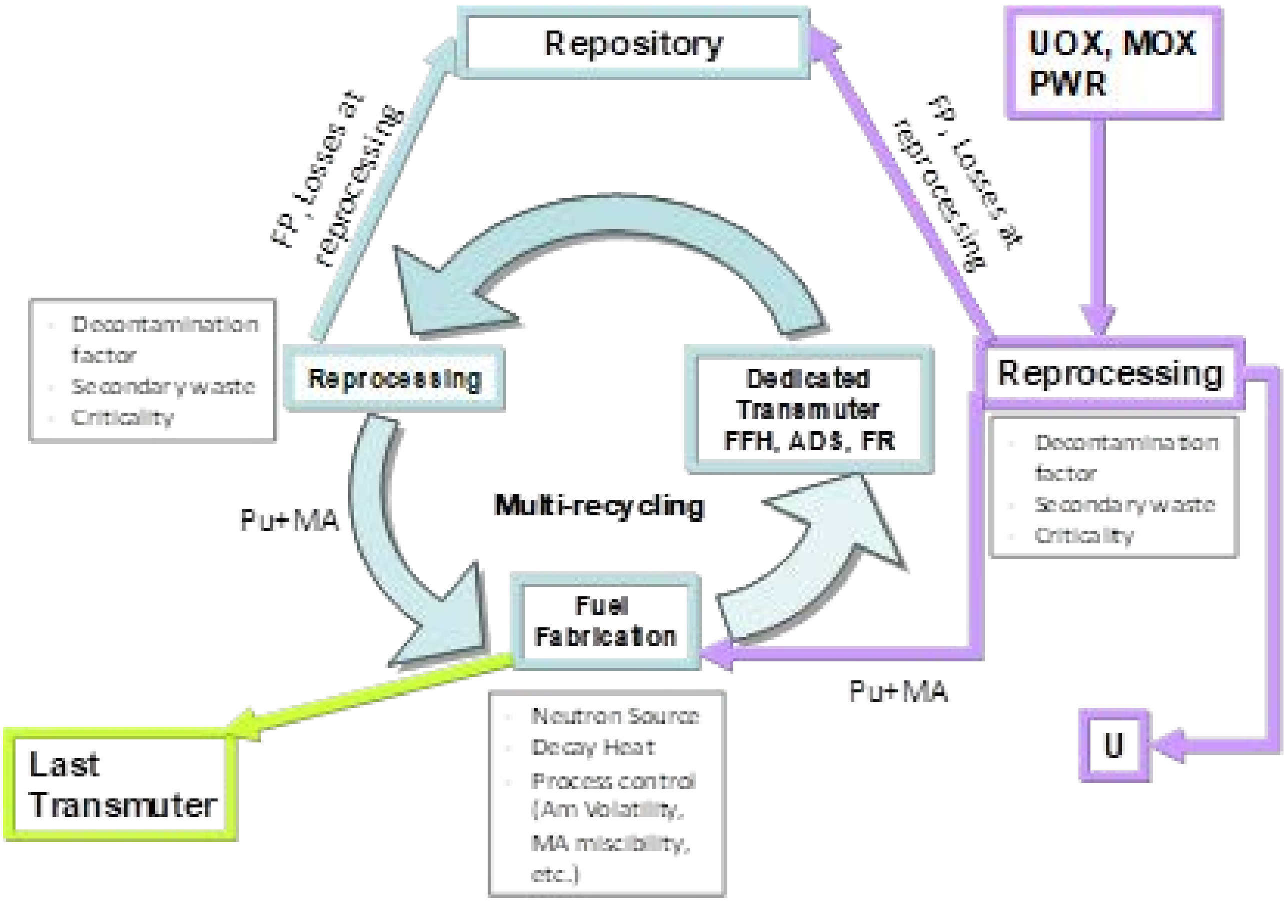
- Proton beam : 1.5GeV ~20MW
- Spallation target : Pb-Bi
- Coolant : Pb-Bi
- Subcriticality : $k_{eff} = 0.97$
- Thermal output : 800MWt
- Core height : 1000mm
- Core diameter : 2440 mm
- MA initial inventory : 2.5t
- Fuel composition :

  (60%MA + 40%Pu) Mono-nitride
- Transmutation rate :

  10%MA / Year (**10 units of LWR**)

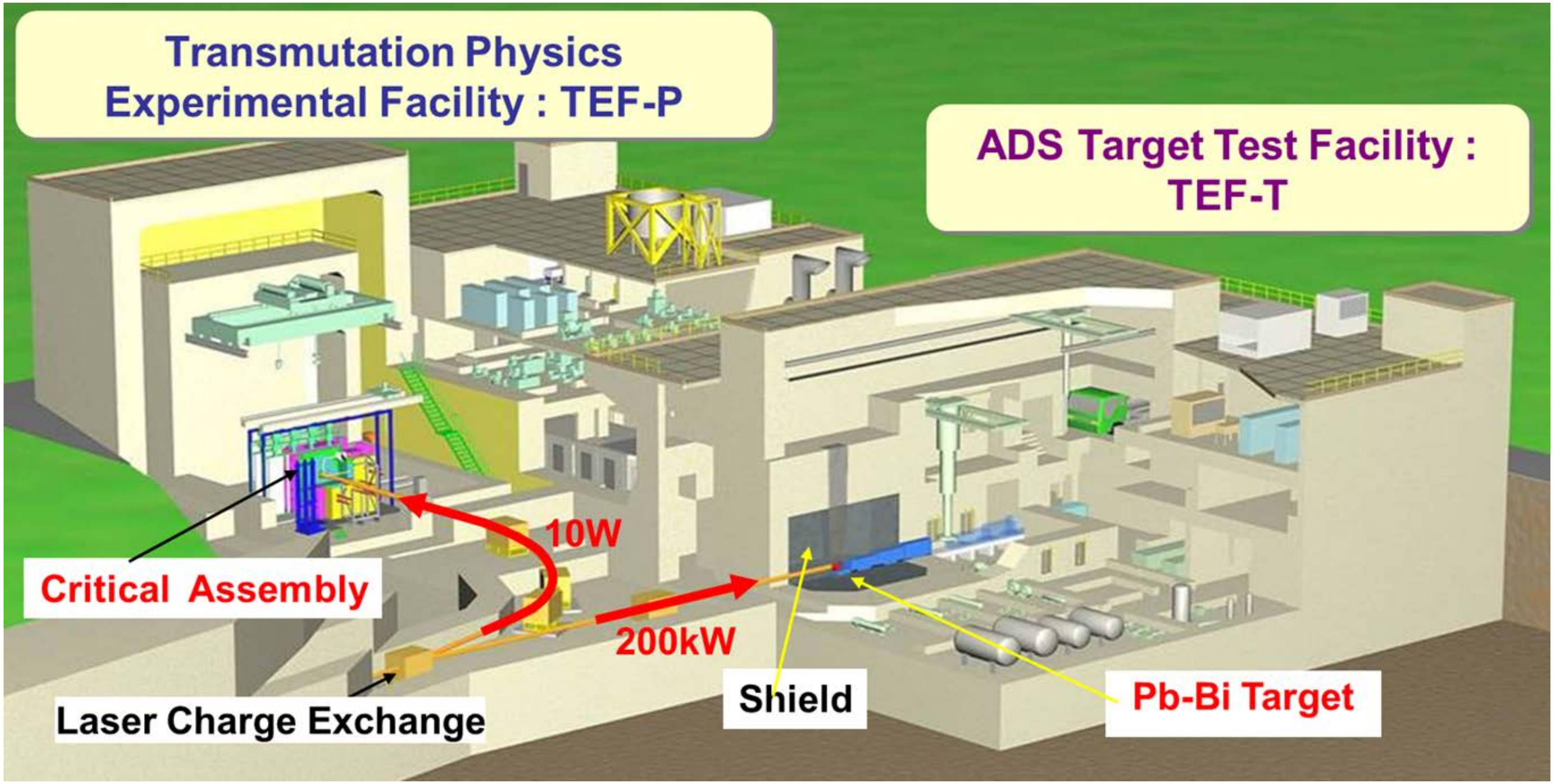
This fuel composition would not be acceptable for critical reactor

ADS: more suitable for dedicated transmuter

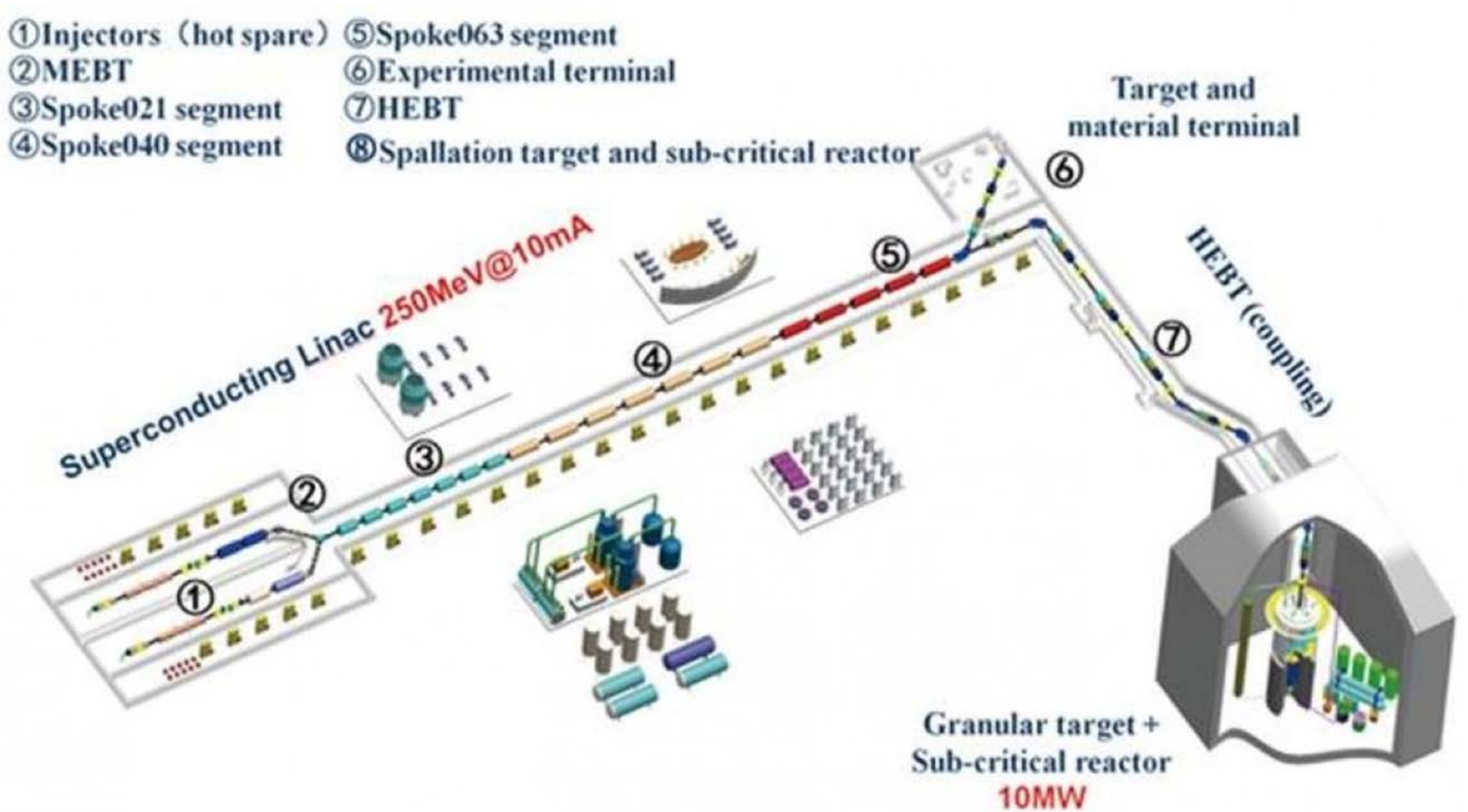


ADS Projects in the World

JPARC, Japan


Transmutation Physics
Experimental Facility : TEF-P
ADS Target Test Facility :
TEF-T
10W
Critical Assembly
200kW
Shield
Pb-Bi Target
Laser Charge Exchange

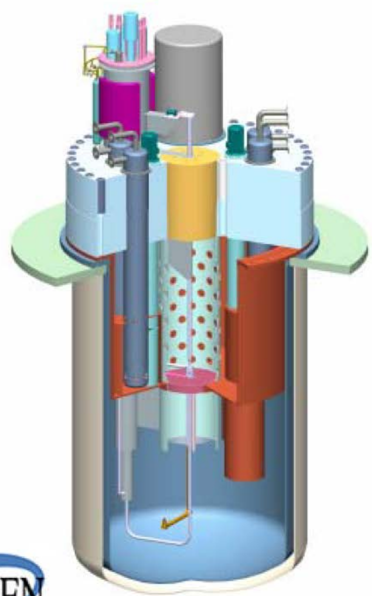
CIADS, China


①Injectors（hot spare）
②MEBT
③Spoke021 segment
④Spoke040 segment
⑤Spoke063 segment
⑥Experimental terminal
⑦HEBT
⑧Spallation target and sub-critical reactor
Target and material terminal
Superconducting Linac 250MeV@10mA
HEBT (coupling)
Granular target + Sub-critical reactor
10MW

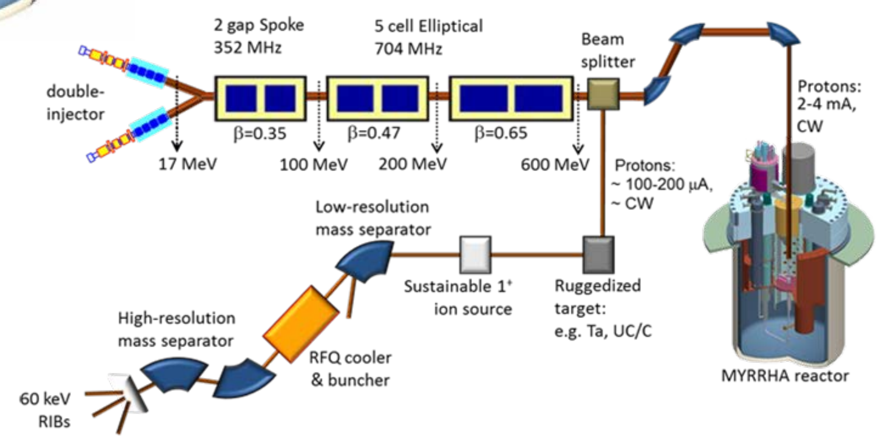
MYRRHA (Belgium)

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



PAL

Thank You for your attention!!