2- Fuel Cycle options for Innovative Nuclear Energy Systems

Focus on fast neutron spectrum reactors and on waste management

M.Salvatores

Joint IAEA-ICTP Workshop on
Physics and Technology of Innovative Nuclear Energy Systems for Sustainable Development
20-24 August 2018
ICTP, Miramare - Trieste, Italy

IAEA
International Atomic Energy Agency
Atoms for Peace

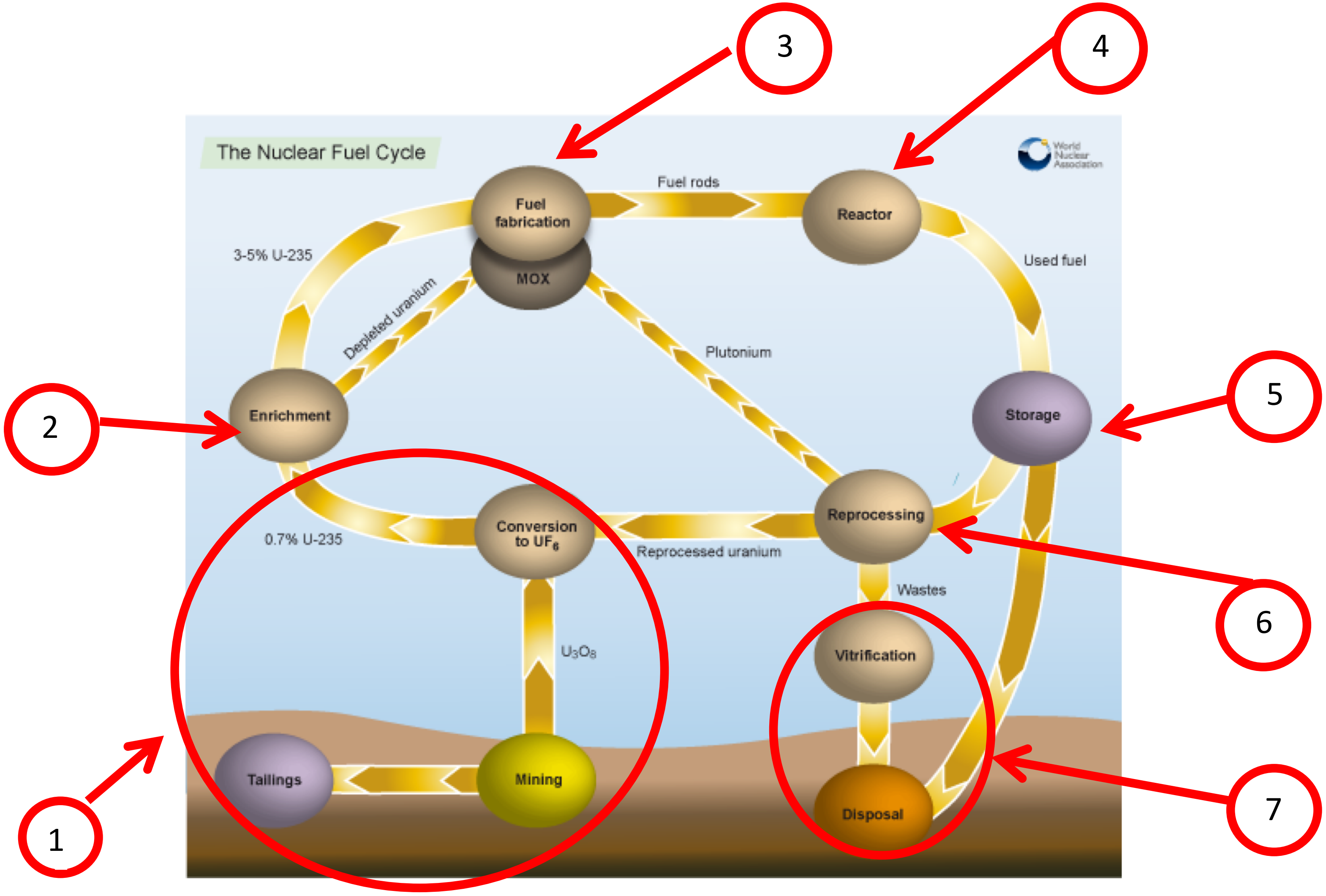
Nuclear Fuel Cycles

- Many of the central issues associated with nuclear power are tied primarily to the choice of fuel cycle. Resource limitations, non-proliferation, and waste management are primarily fuel cycle issues.

- The fuel cycle provides the mass flow infrastructure that connects the energy resources of uranium and thorium ore through the nuclear power plants to the eventual waste management of the nuclear energy enterprise.

- Natural resources include fuels (uranium and thorium), materials of construction, and renewable resources (such as water for cooling purposes). Wastes may include mill tailings, depleted uranium, spent nuclear fuel (SNF) and high level (radioactive) waste (HLW), other radioactive wastes, releases to the environment (air and water), and non-nuclear wastes.

- Multiple technical facilities are deployed in the fuel cycle. In a simplified fuel cycle schematic, there are ***7 major fuel cycle facilities.***


The Nuclear Fuel Cycle
World Nuclear Association
3
4
Fuel fabrication
MOX
Fuel rods
Reactor
Used fuel
3-5% U-235
Depleted uranium
Plutonium
2
Enrichment
Storage
5
0.7% U-235
Conversion to UF6
Reprocessed uranium
Reprocessing
6
Wastes
U3O8
Vitrification
Tailings
Mining
Disposal
7
1

The preferred choice or choices of fuel cycles and reactors depends upon the requirements for sustainability, safety, and economics

.

Four generic fuel cycles span the space of feasible conversion of ore resources to energy.

- ***Once through***. The fuel is fabricated from e.g. uranium, irradiated, and stored to allow for reduction of heat, then directly disposed of as a waste. Light Water Reactors (LWRs) in the United States currently use this fuel cycle.

- ***Partial recycle***. Some fraction of the SNF is processed, and some fraction of the actinide material is recovered from recycle, and new fuel is fabricated.
The fuel is returned to the reactor one-two times

- ***Full fissile recycle***. All SNF is processed for recovery and recycle of plutonium (and/or ^{233}U). The SNF is repeatedly processed and recycled. Minor actinides and fission products are sent to the waste stream from the processing operation.

An example of this is the traditional Liquid Metal Fast Breeder Reactor (LMFBR) fuel cycle.

- ***Full-actinide recycle***. All SNF is processed, and all actinides are multiply recycled.

- ***Other options are available***: e.g. a better utilization of Uranium but avoiding recycle

Spent fuel management options as of today

1. Spent fuel disposal
2. Spent fuel reprocessing and Pu recovery

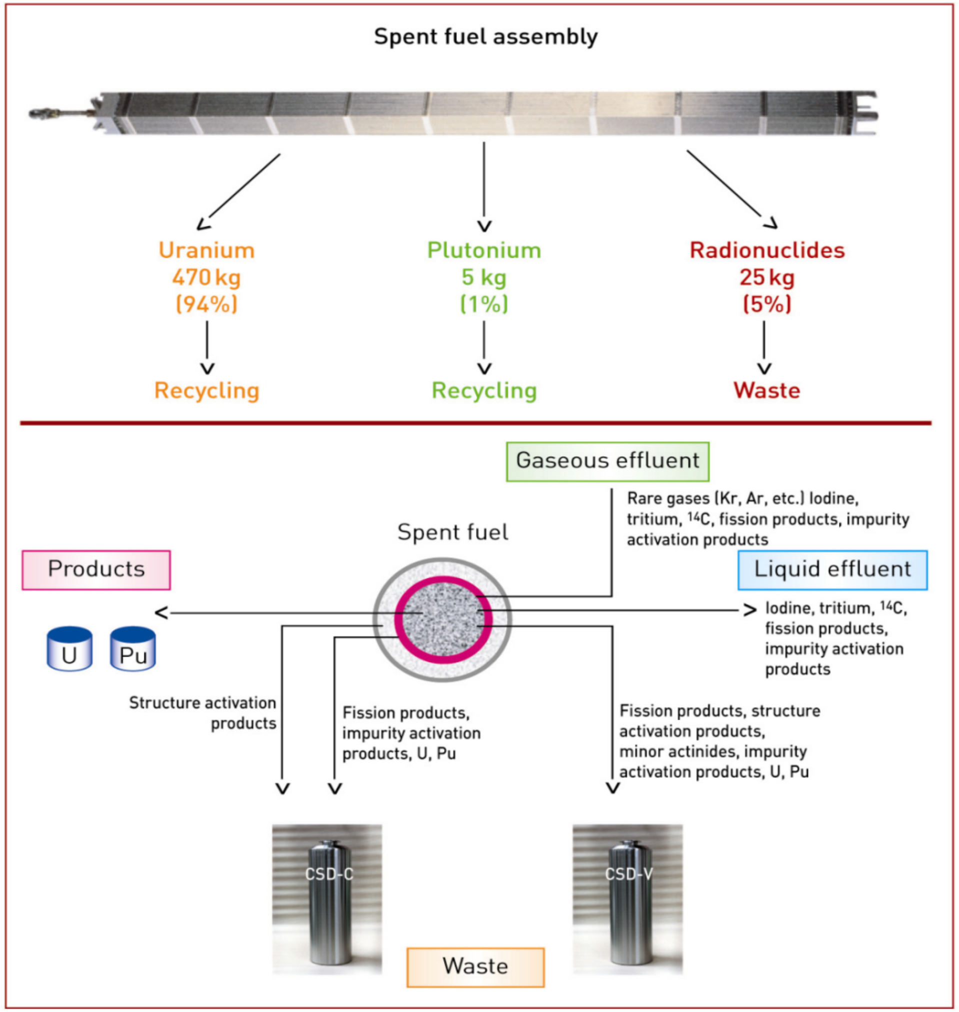


Figure 1 : spent UOX fuel content

Innovative fuel cycles. Focus on waste management: 3 major scenarios to implement P&T (partitioning and transmutation)

a) Sustainable development of nuclear energy with waste minimisation.
One type of reactor, one fuel type, one reprocessing process (homogeneous TRU recycling)

b) „Double strata“ fuel cycle: 1) commercial reactors with Pu utilisation 2) separate MA management. Two separate fuel cycles.

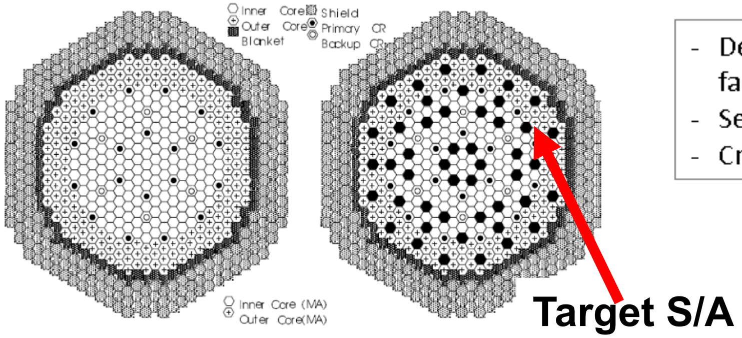
➔ The two previous scenarios imply the continuous use of nuclear energy, the stabilisation of the TRU stocks in the fuel cycle and the minimisation of wastes in a repository.

c) Reduction of TRU stockpiles (e.g. as a legacy from the past operation of power plants)

➔ All three scenarios go beyond the strategy of „once-through“ („open“) fuel cycle (i.e. the final storage of irradiated fuel), and imply fuel reprocessing.

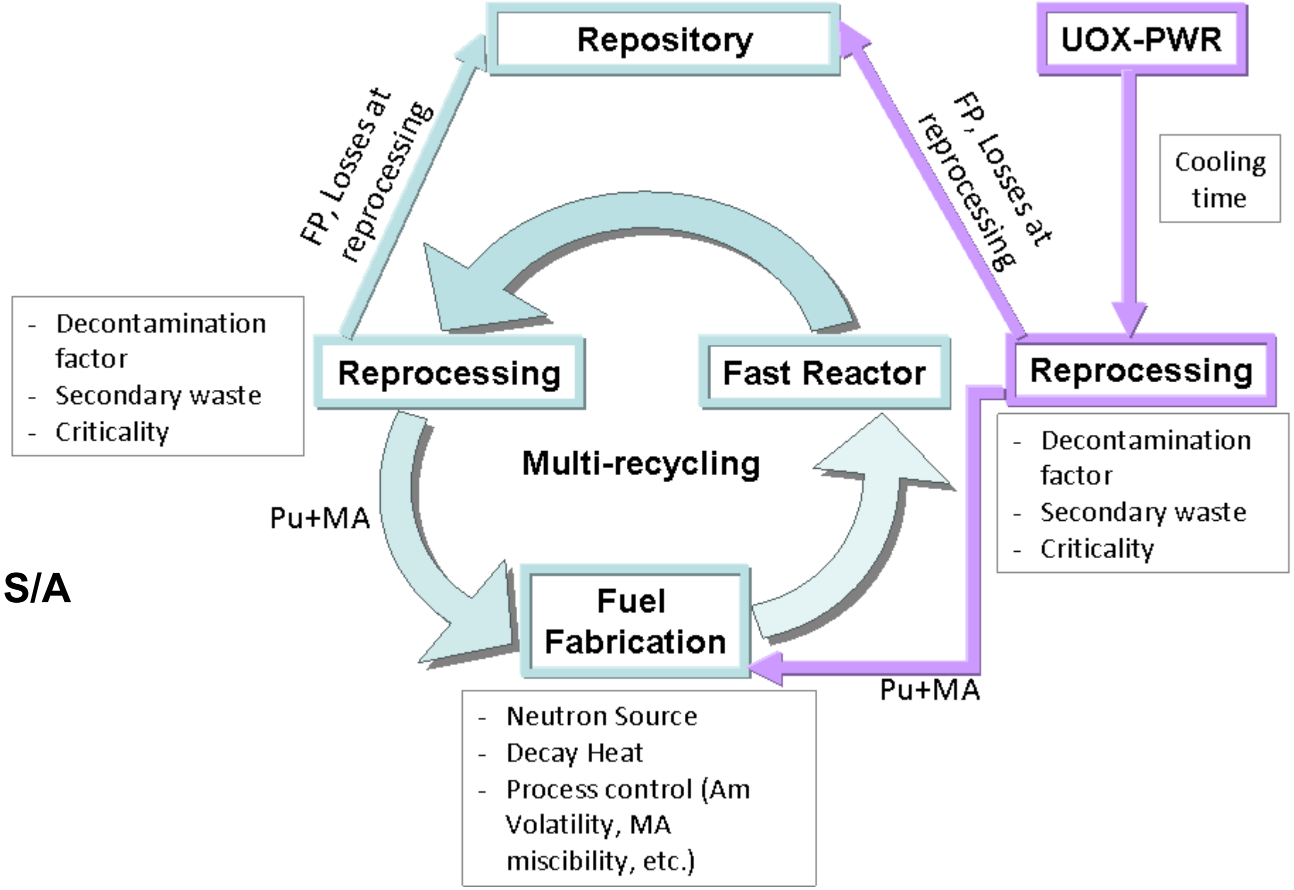
Scenario a): *Sustainable development of nuclear energy for electricity production and waste minimization*

Homogenous TRU recycling in a critical fast reactor. The fuels are standard mixed oxide or dense fuels (metal, nitride, carbide), with MA content of a few percent (e.g. definitely < 5-10%). Also Heterogeneous recycling using MA targets



Fast reactor core for homogeneous TRU recycle

Fast reactor core for heterogeneous TRU recycle



- Decontamination factor
- Secondary waste
- Criticality

- Decontamination factor
- Secondary waste
- Criticality

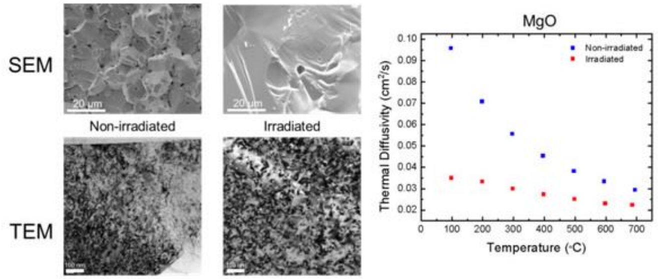
- Neutron Source
- Decay Heat
- Process control (Am Volatility, MA miscibility, etc.)

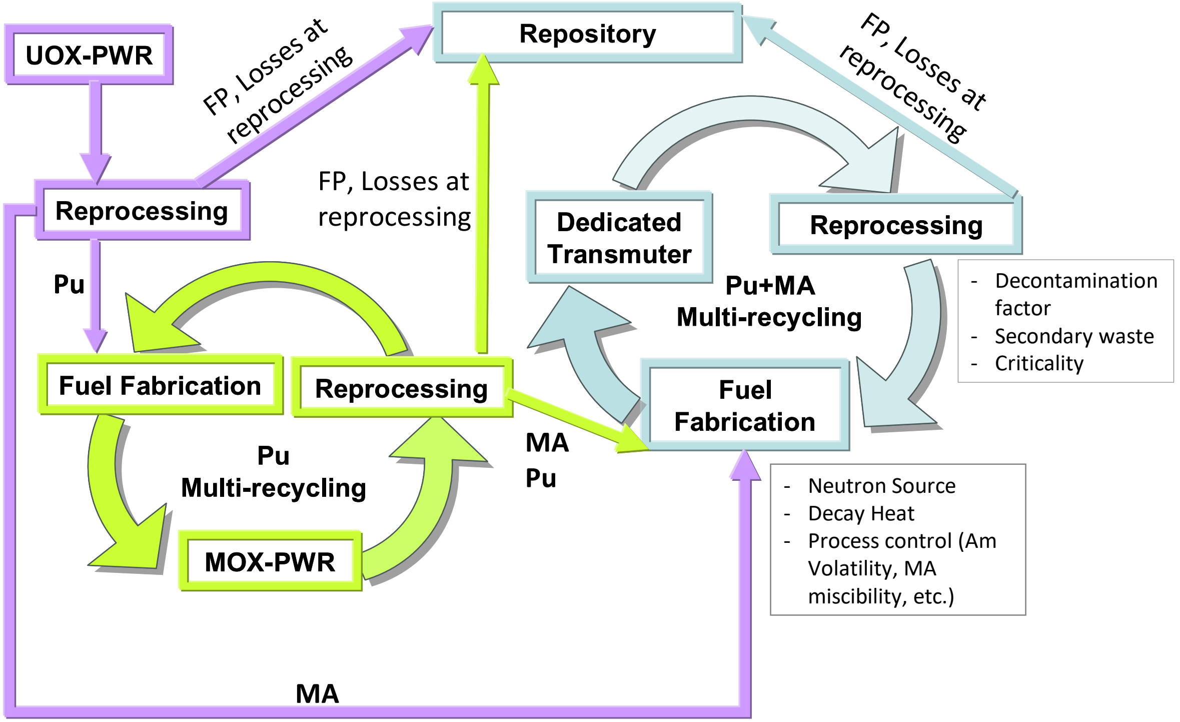
Scenario b): Reduction (elimination) of MA inventory (pure waste management objective)

The objective is to reduce drastically the MA inventories, while Pu is still considered a resource.

Need separation of Pu from MA, to be kept together, or separation of Cm from Am, and Cm storage.

To maximise consumption: a U-free fuel (inert matrix) in an external neutron source-driven system, ADS with conversion ratio CR=0. A “critical” burner FR with CR ~ 0.5 or less, can also be envisaged.





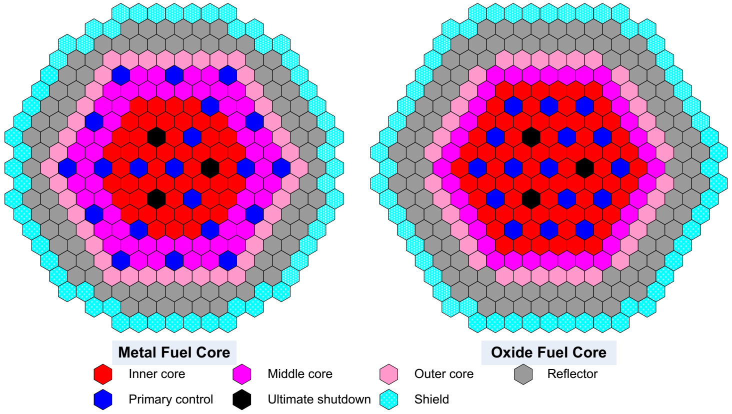
- Decontamination factor
- Secondary waste
- Criticality

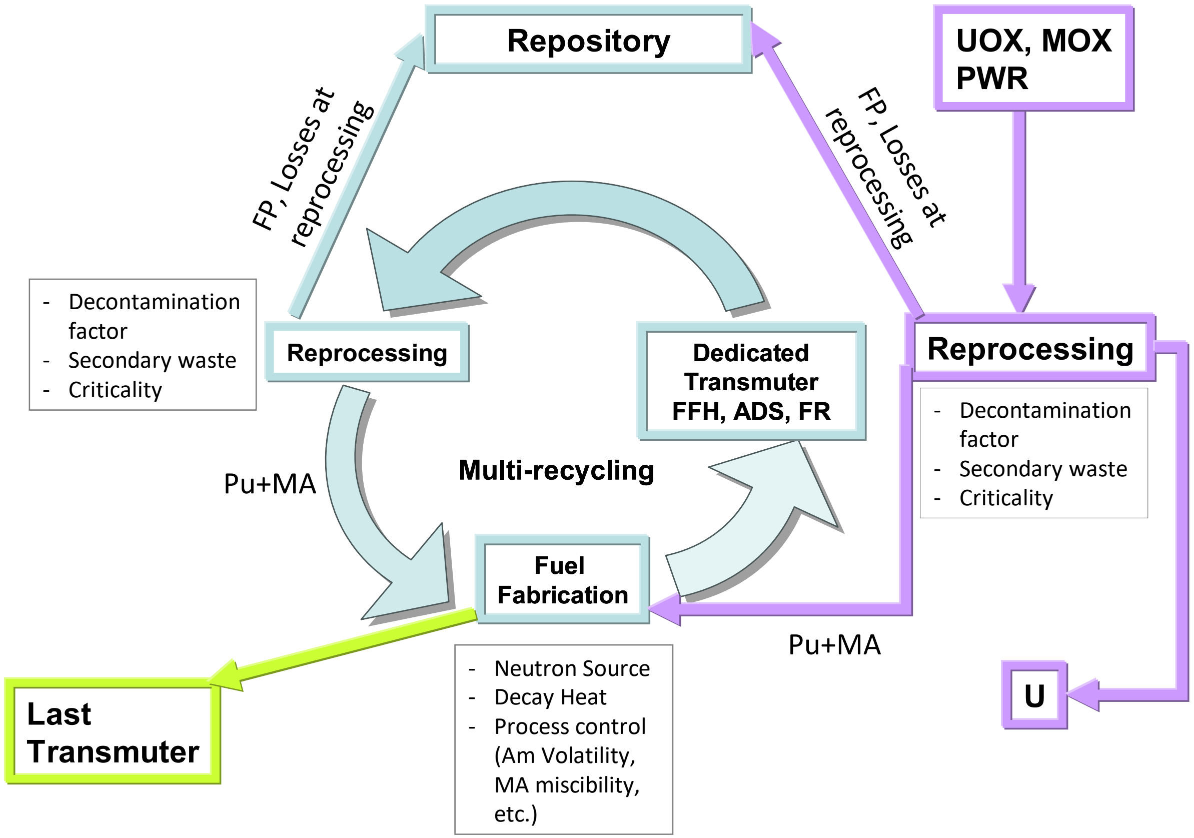
- Neutron Source
- Decay Heat
- Process control (Am Volatility, MA miscibility, etc.)

Scenario c): Reduction (elimination) of TRU inventory as unloaded from LWRs

The ratio MA/Pu is ~0.1. As for reprocessing, grouped TRU recovery without separation of Pu from MA.

To maximise consumption: a U-free fuel (inert matrix) in an external neutron source-driven system, ADS with conversion ratio CR=0. A “critical” burner FR with CR ~ 0.5 or less, can also be envisaged





Repository

UOX, MOX PWR

FP, Losses at reprocessing

FP, Losses at reprocessing

- Decontamination factor
- Secondary waste
- Criticality

Reprocessing

Dedicated Transmuter FFH, ADS, FR

Reprocessing

- Decontamination factor
- Secondary waste
- Criticality

Pu+MA

Multi-recycling

Fuel Fabrication

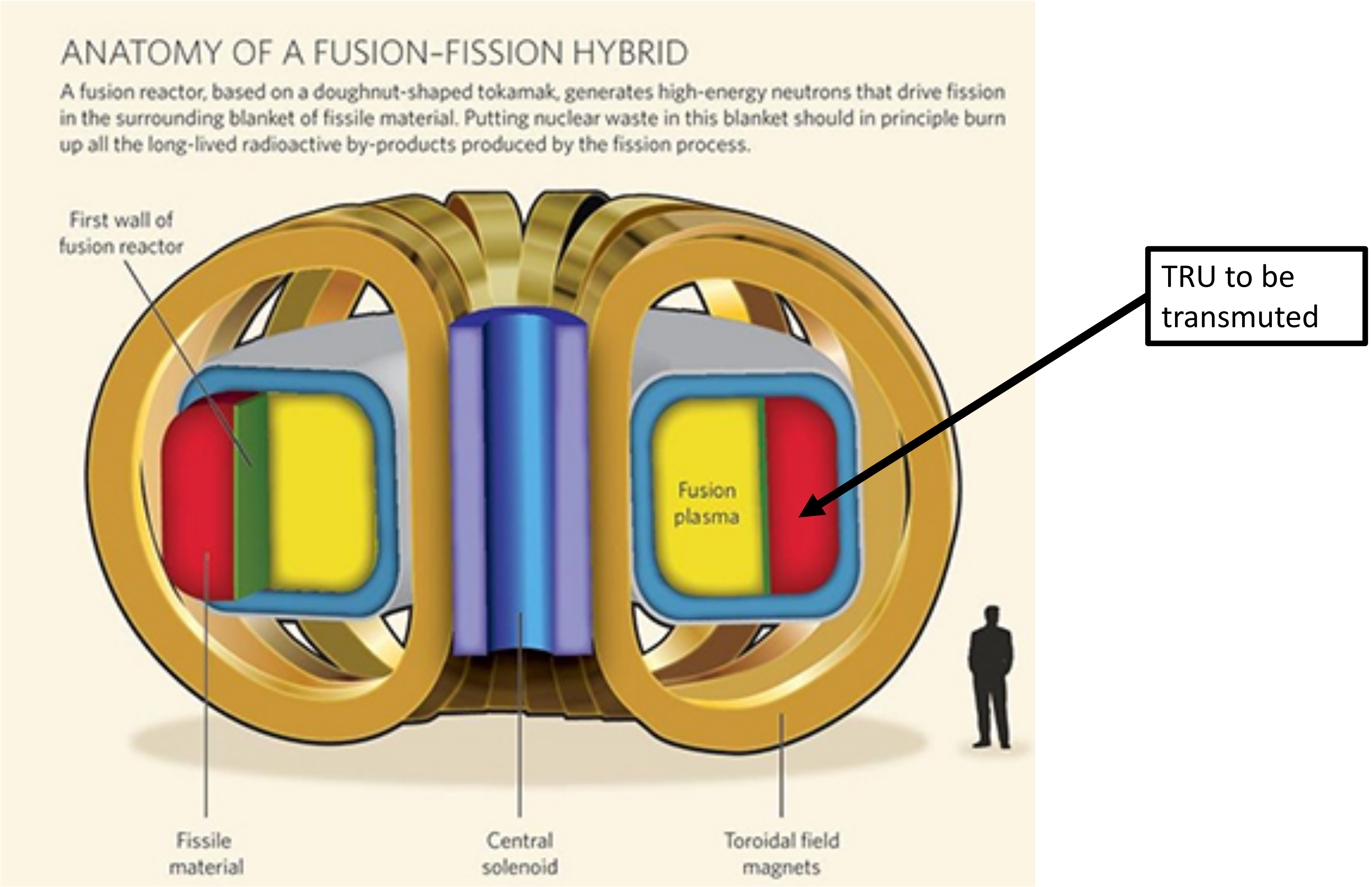
Pu+MA

U

Last Transmuter

- Neutron Source
- Decay Heat
- Process control (Am Volatility, MA miscibility, etc.)

There are innovative alternatives to critical fast reactors or ADS for MA or TRU reduction (elimination), e.g.:



ANATOMY OF A FUSION-FISSION HYBRID

A fusion reactor, based on a doughnut-shaped tokamak, generates high-energy neutrons that drive fission in the surrounding blanket of fissile material. Putting nuclear waste in this blanket should in principle burn up all the long-lived radioactive by-products produced by the fission process.

TRU to be transmuted

Innovative fuel cycles. Potential benefits of P&T

In principle, P&T offers significant potential benefits to the fuel cycle:

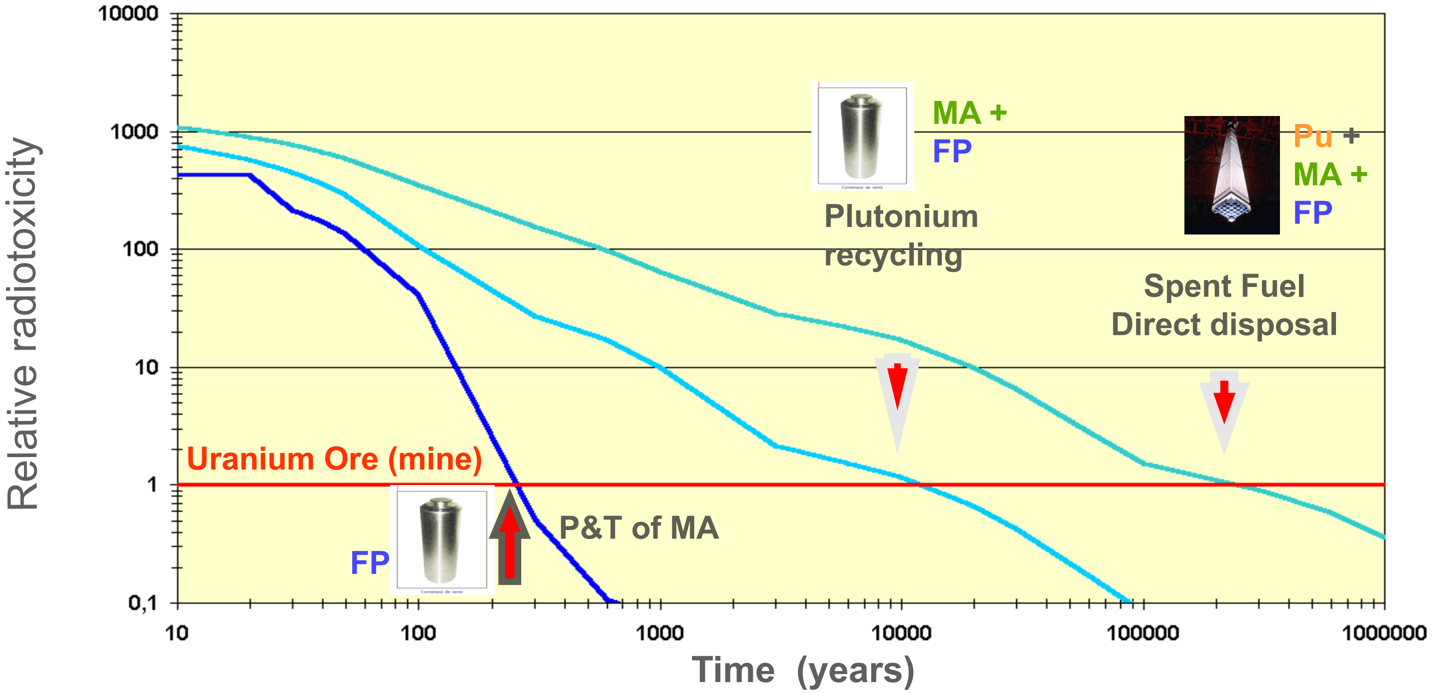
-***Reduction of the potential source of radiotoxicity*** in a deep geological storage („intrusion“ scenario)

-***Reduction of the heat load and high level waste volume***: larger amount of wastes can be stored in the same repository

-If TRU are not separated (e.g. in the homogeneous recycling in a Fast Neutron Reactor), ***improved proliferation resistance*** is expected

- ➢**Results of impact studies in the USA, in Japan and in Europe**
- ➢**However, still a debated issue between P&T and Waste Management Communities: which are the “good” metrics?**
- ➢**A comparative analysis has been performed by the OECD-NEA**

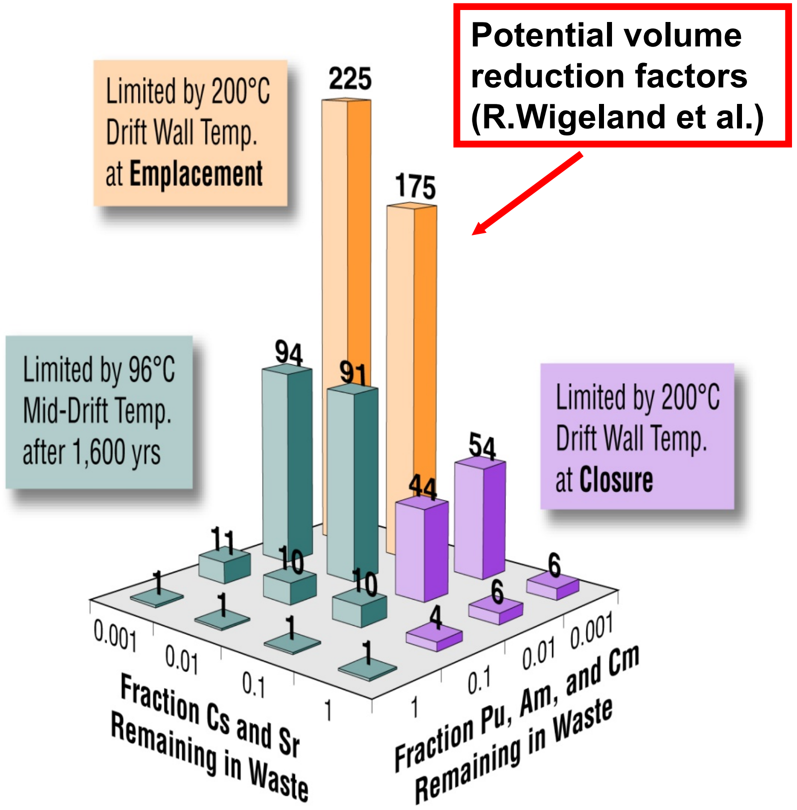
Impact of P&T: 1) Radiotoxicity of ultimate waste



Recycle of all actinides in fast reactors provides a significant reduction in the time required for radiotoxicity to decrease to that of the natural uranium ore used for the LWR fuel
From 250,000 years down to about 400 years if 0.1% actinide loss to wastes

Impact of P&T: 2) Heat load reduction. A US study

- **Plutonium, americium, caesium, strontium, and curium are primarily responsible for the decay heat that can cause repository temperature limits to be reached**
- **Large gains in repository space are possible by processing spent nuclear fuel to remove those elements**



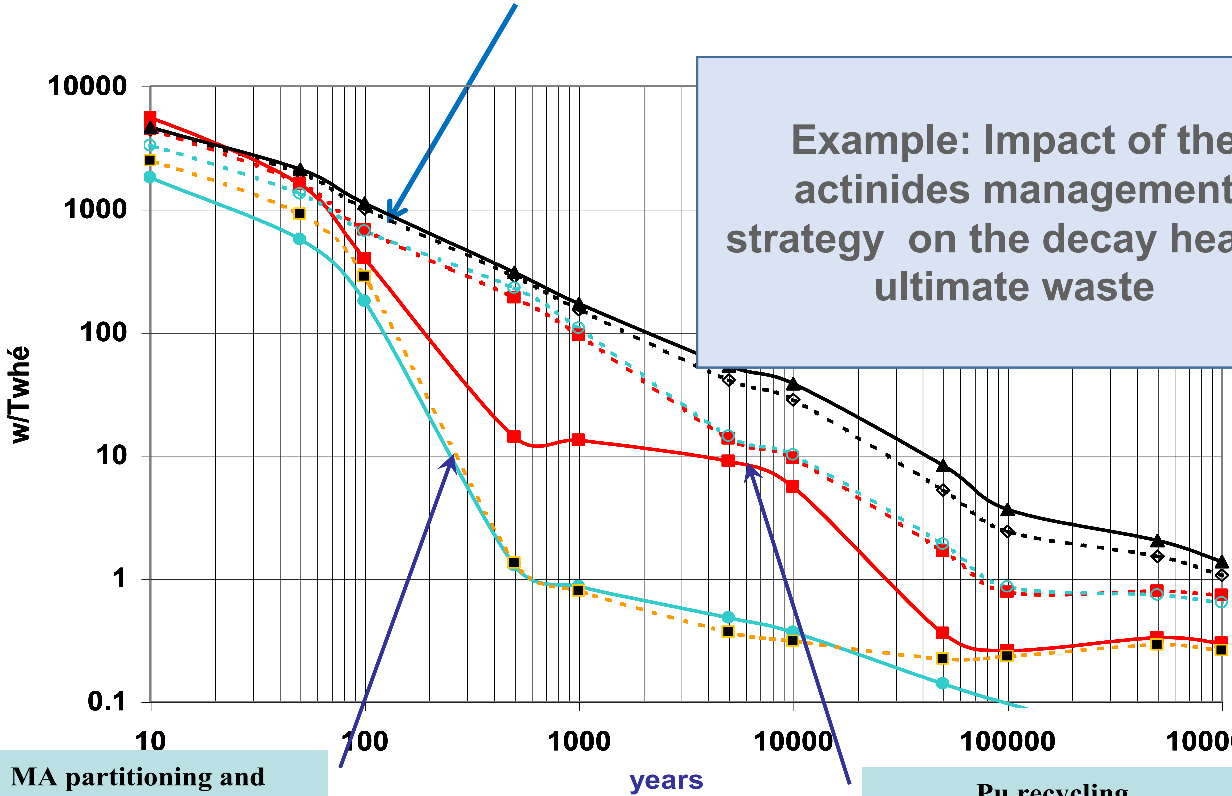
Potential volume reduction factors (R.Wigeland et al.)

Similar studies in Europe and Japan with consistent conclusions

Example: Impact of the actinides management strategy on the decay heat of ultimate waste

Spent fuel direct disposal

Pu +
MA +
FP



MA partitioning and transmutation

FP

Pu recycling
no MA partitioning

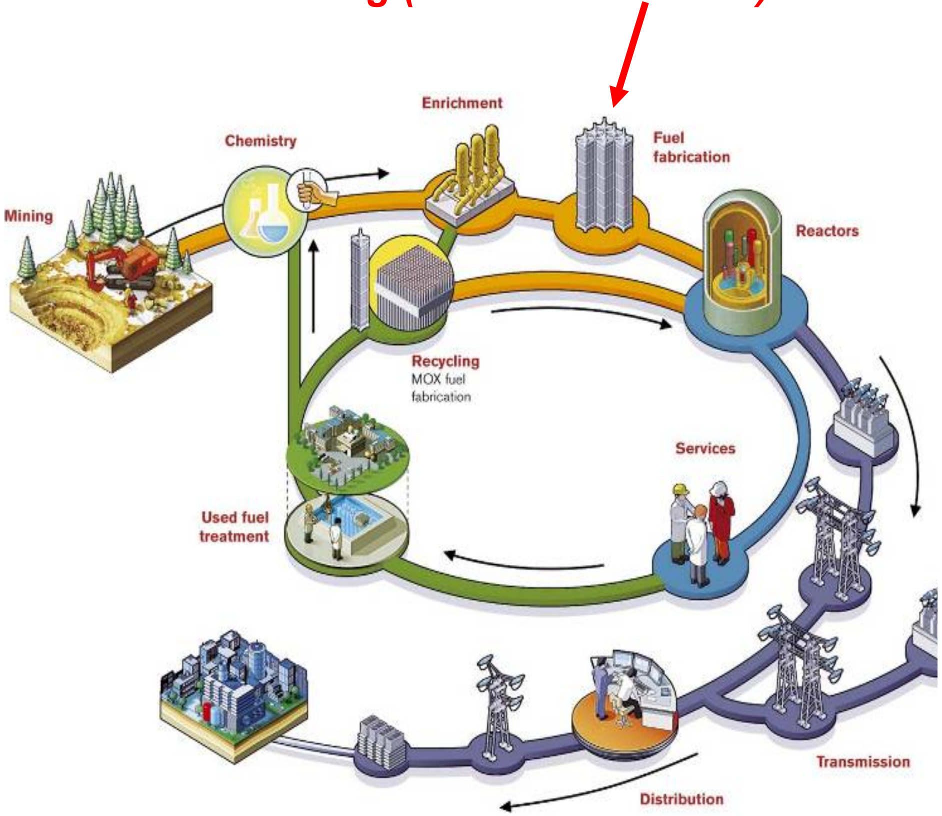
MA +
FP

Innovative fuel cycles. Some feasibility issues

Feasibility issues of the different fuel cycle options indicated previously can arise when considering not only the transmuter reactor core feasibility but also the associated fuel cycle.

Case of decay heat and neutron production after post-irradiation cooling (at fuel fabrication):

Reactor type	PWR		FR		
Fuel type Parameter	MOX (Pu only)	Homog TRU recycle	Pu only	Homog. TRU recycle, CR=1 and MA/Pu~0.1	Homog.TRU recycle, CR=0.5 and MA/Pu~1
Decay heat	1	x3	x0.5	x2.5	x38
Neutron source	1	x8000	~1	x150	x4000



Alternative fuel cycle options

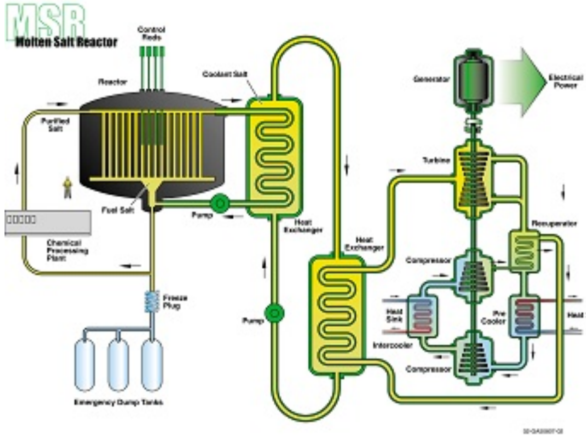
Alternative fuel cycles are under investigations. We will briefly outline three alternatives:

- **The use of Molten Salts Reactors (MSR)**
- **The deployment of small modular reactors (SMR)**
- **An option to make a better use of Uranium without recycling: the Travelling wave Reactor of TerraPower (TWR)**

a) Molten Salt Reactor (MSR) technology was partly developed, including two demonstration reactors, in the 1950s and 1960s in the USA (Oak Ridge National Laboratory). The demonstration MSRs were thermal-neutron-spectrum graphite-moderated concepts.

Since 2005, R&D has focused on the development of fast-spectrum MSR concepts (MSFR) combining

- the generic assets of fast neutron reactors (extended resource utilization, waste minimization)
- with those relating to molten salt fluorides as fluid fuel and coolant (low pressure and high boiling temperature, optical transparency) .



As for the fuel cycle, the main MSR concept is to have the fuel dissolved in the coolant as fuel salt, and ultimately **to reprocess that online**. Thorium, uranium, and plutonium all form suitable fluoride salts that readily dissolve in the $LiF\text{-}BeF_2$ (FLiBe) mixture, and thorium and uranium can be easily separated from one another in fluoride form.

b) Small Modular Reactors (SMRs), have been investigated, with power levels between 10 and 300 MWe.

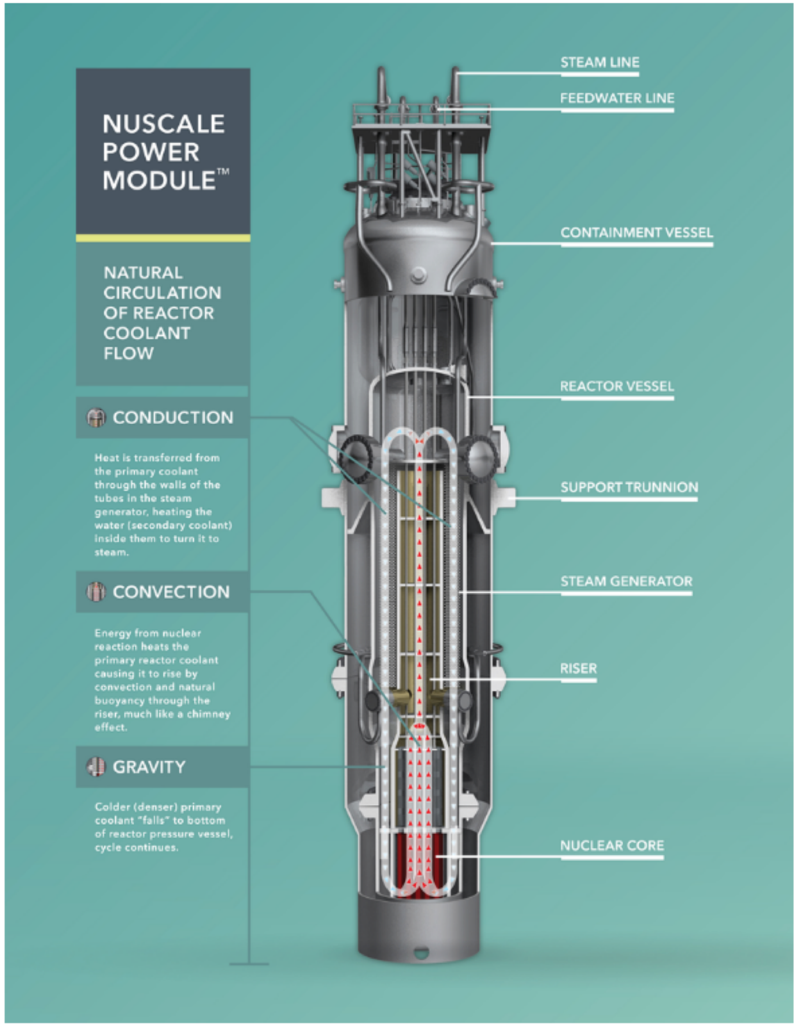
An example among many, is the NUSCALE project in the USA:
it is an Integral Pressurized Water Reactor (IPWR) based
on light water reactor technology of ~60MWe.

Each NuScale Power Module includes the containment,
reactor vessel, steam generators, and pressurizer.

The company claims it can shut down and continue cooling itself
indefinitely in the event of a catastrophe.

The devices are intended to be kept in a below-ground pool,
to absorb the shock of earthquakes, with a concrete lid
over the pool.

In the event that AC power is lost for normal cooling systems,
the pool water begins to absorb heat and boil



NUSCALE POWER MODULE™

NATURAL CIRCULATION OF REACTOR COOLANT FLOW

CONDUCTION

Heat is transferred from the primary coolant through the walls of the tubes in the steam generator, heating the water (secondary coolant) inside them to turn it to steam.

CONVECTION

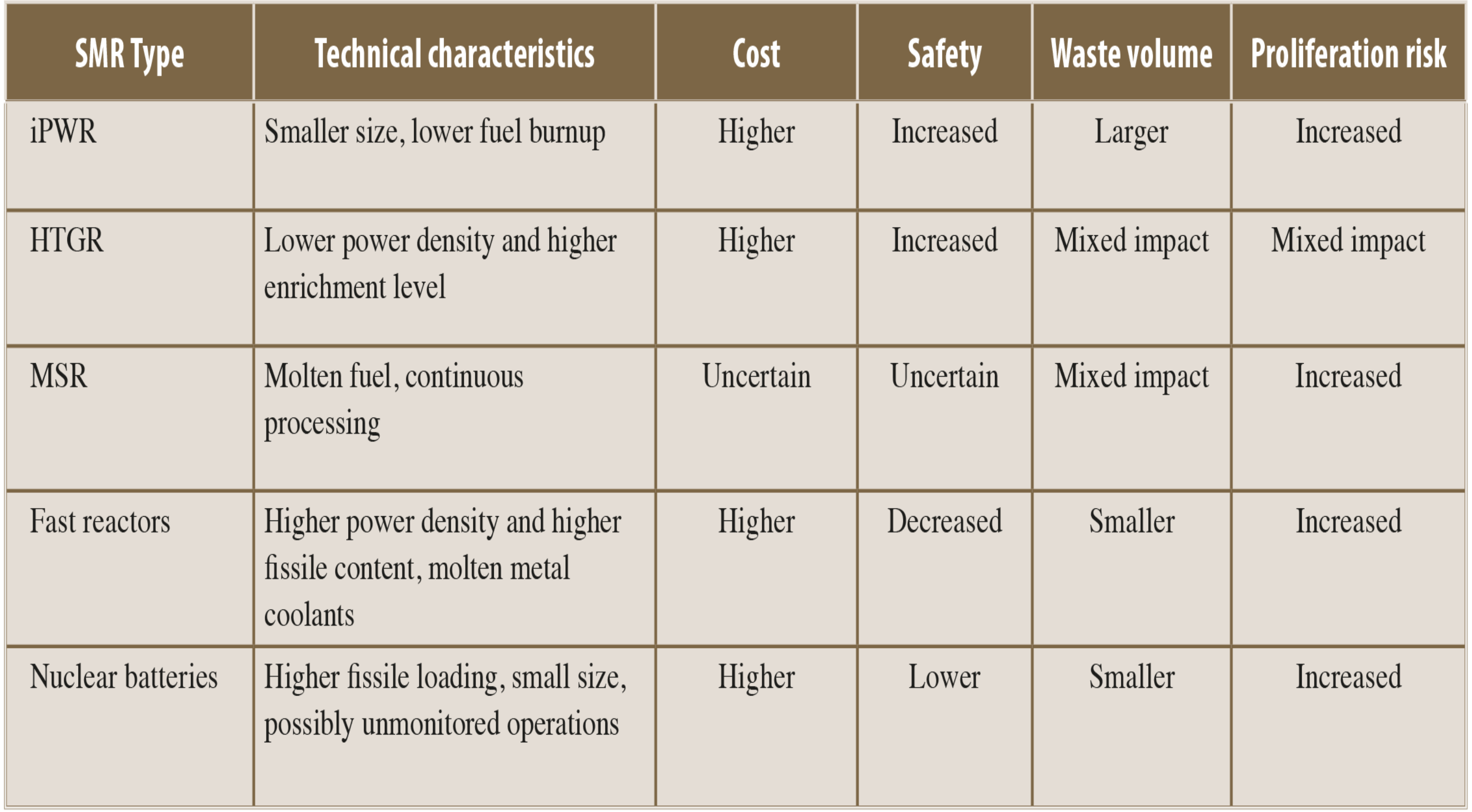
Energy from nuclear reaction heats the primary reactor coolant causing it to rise by convection and natural buoyancy through the riser, much like a chimney effect.

GRAVITY

Colder (denser) primary coolant "falls" to bottom of reactor pressure vessel, cycle continues.

As for the potential problems with nuclear energy identified e.g. in a MIT study — safety enhancement, proliferation resistance, decreased generation of waste, and cost reduction —it turns out that each of these priorities can drive the requirements on the reactor design in different, sometimes opposing, directions. This is ***the case also for SMRs***

Trade-offs between desired features and focusing on any one goal might make other goals more difficult to achieve:



SMR Type	Technical characteristics	Cost	Safety	Waste volume	Proliferation risk
iPWR	Smaller size, lower fuel burnup	Higher	Increased	Larger	Increased
HTGR	Lower power density and higher enrichment level	Higher	Increased	Mixed impact	Mixed impact
MSR	Molten fuel, continuous processing	Uncertain	Uncertain	Mixed impact	Increased
Fast reactors	Higher power density and higher fissile content, molten metal coolants	Higher	Decreased	Smaller	Increased
Nuclear batteries	Higher fissile loading, small size, possibly unmonitored operations	Higher	Lower	Smaller	Increased

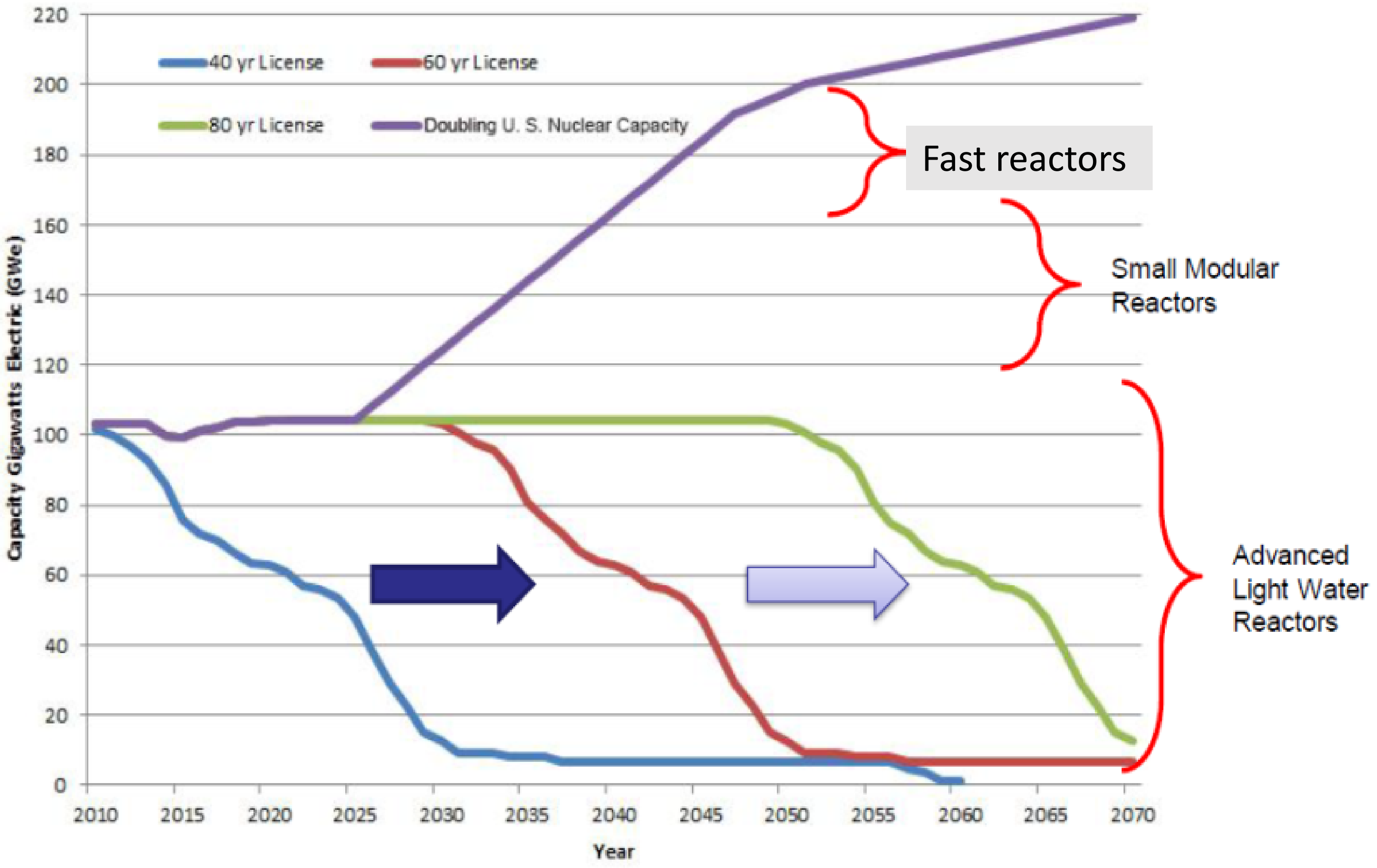
ENERGY

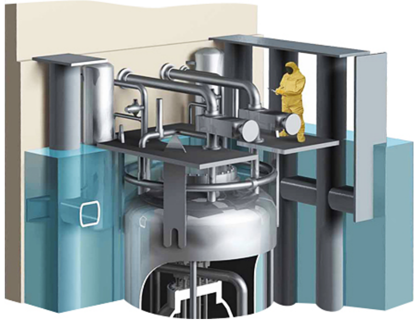
Nuclear Energy

Nuclear Power Capacity needed to meet Clean Power Goals

However, one can make the hypothesis that a (large) number of SMR will be deployed. In the case of the USA, the previous scenario(s) will be modified e.g. as indicated here

…but impact on resources!





NuScale Power Module (NuScale)

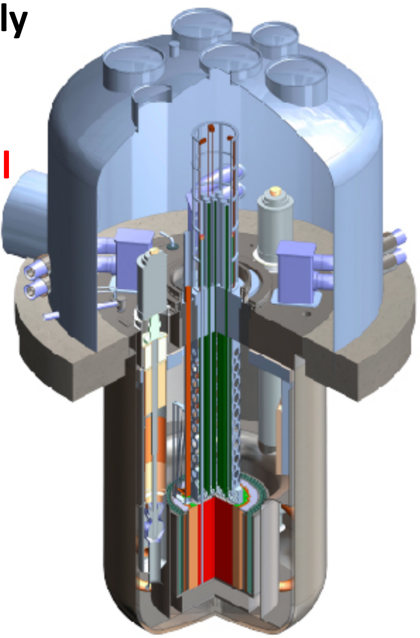
c) A better Uranium utilization will have an obvious impact on the resources availability issue and it will imply a different fuel cycle. This would be the case if the newly proposed Travelling Wave Reactor of TerraPower would be deployed on a large scale:

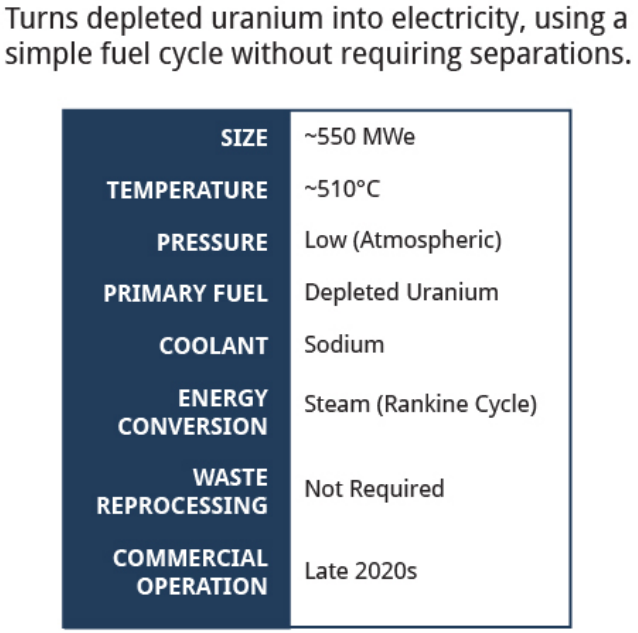
In fact, TerraPower, LLC has developed the Traveling Wave Reactor (TWR) which is a near-term deployable and is presented as a truly sustainable energy solution that is globally scalable for the indefinite future.

The fast neutron spectrum allows up to a ~30-fold gain in fuel utilization efficiency when compared to conventional light water reactors utilizing enriched fuel.

On a country level, this represents:

1) **no reprocessing plants need to be built,**
2) **a reduced number of enrichment plants need to be built,**
3) **reduced waste production results in a lower repository capacity requirement and reduced waste transportation costs and**
4) **less uranium ore needs to be mined or purchased since natural or depleted uranium can be used directly as fuel.**





Turns depleted uranium into electricity, using a simple fuel cycle without requiring separations.

SIZE	~550 MWe
TEMPERATURE	~510°C
PRESSURE	Low (Atmospheric)
PRIMARY FUEL	Depleted Uranium
COOLANT	Sodium
ENERGY CONVERSION	Steam (Rankine Cycle)
WASTE REPROCESSING	Not Required
COMMERCIAL OPERATION	Late 2020s

Conclusions

- Innovative fuel cycles and reactor concepts can potentially help the optimization of waste management and improve resources utilization

- However, fuel cycle issues are essential in order to assess the feasibility and the economy of a specific strategy:

  - Fuel reprocessing with very small losses in the TRU recovery is mandatory (e.g. 99.9% recovery of any TRU isotope)

  - Build-up of higher mass actinides (Cm, Bk, Cf isotopes) can be a heavy burden at fuel handling, fuel fabrication etc., with a potential impact on reactor availability and fuel cycle optimization. This should be investigated in practical applications.

- Multi-recycle is a key feature of any future fuel cycle: any once-through approach will open crucial issues related to resources availability