Energy Efficiency of Accelerator Driven Sub-critical Reactors for Nuclear Waste Transmutation

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Overview

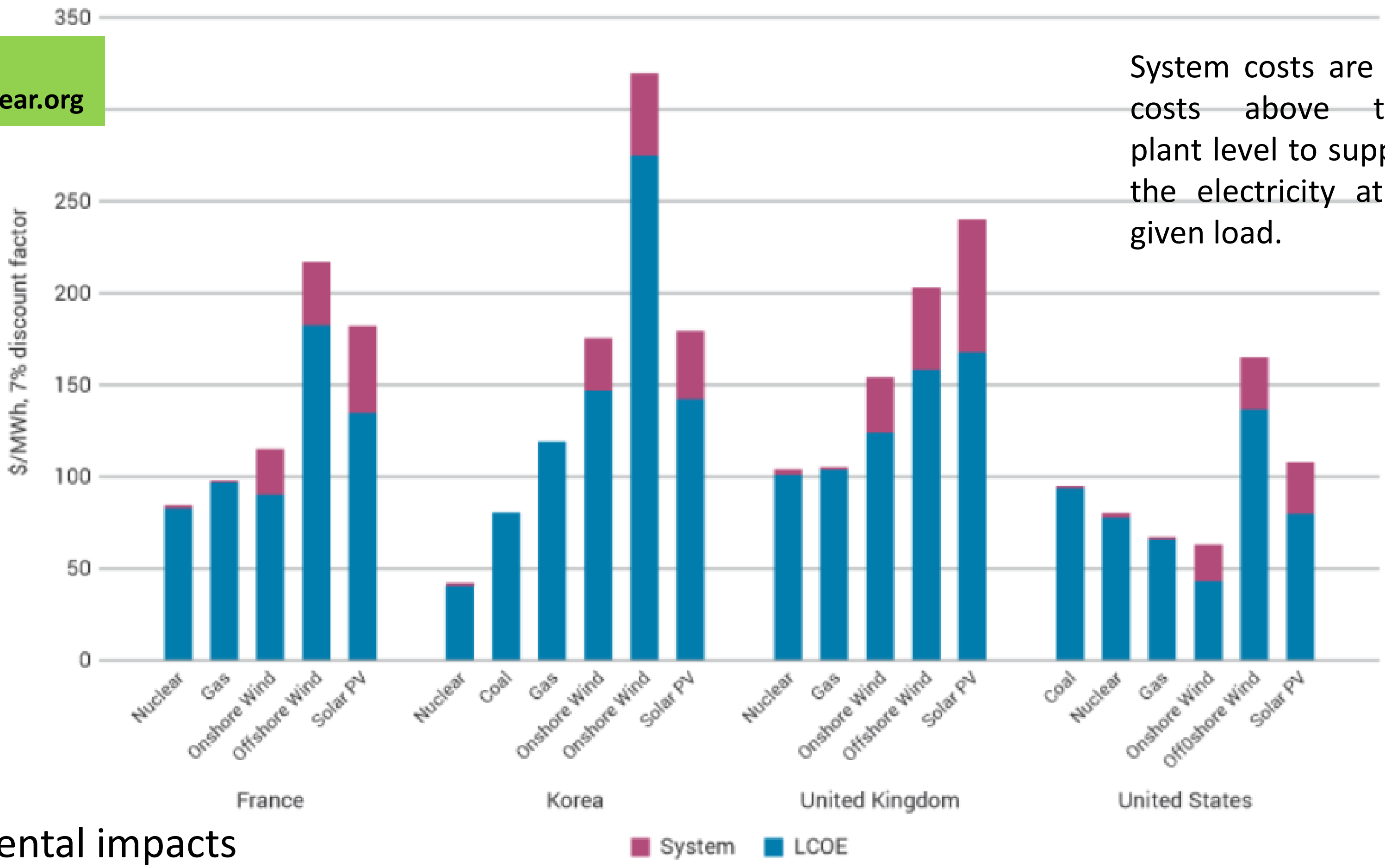
- Nuclear energy and internalizing the external costs.

- Calculation of the nuclear fuel cycle cost:
  - Corrected thermal efficiency of ADSR
  - Corrected capacity factor of ADSR

- Summary: the LCOE for ADSR and conclusion.

Nuclear energy competitiveness

- ☐ Cost reduction is the common goal of power plants. For instance, in matter of nuclear energy, this can be achieved by improving the efficiency of the plants as well as its reliability. Are advances in the fuel cycles the key factor to reduce the costs of nuclear energy?



Comparative LCOEs and System Costs in Four Countries (2014 and 2012)*

Source: http://www.world-nuclear.org

System costs are all costs above the plant level to supply the electricity at a given load.

- ☐ Safety
- ☐ Environmental impacts

Internalizing the external costs

- In the context of external energy goals, internalizing the external costs is crucial:

Ex: No carbon taxation → No incentive for energy producers to switch to other sources.

- Definition: “*An* *<u>external cost</u>, also known as an externality, arises when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group.*” **[1]**

  Air pollution is a typical example of this.

- The costs of waste disposal are very difficult to estimate: this is a multi-dimensional problem.

- Also, as mentioned in **[2]**, “*the most important fact to keep in mind in considering any estimate of the cost of alternative fuel cycles is the high degree of uncertainty about key components of each cycle*”.

Calculation of the Nuclear Fuel Cycle Cost

$$LCOE = \frac{\sum_t \left(\frac{\mathrm{Investment}_t + \mathrm{O\&M}_t + \mathrm{Fuel}_t + \mathrm{Carbon}_t + \mathrm{Decommissioning}_t}{(1+r)^t} \right)}{\sum_t \left(\frac{\mathrm{Electricity}_t}{(1+r)^t} \right)}$$ [3]

- *t* : the year in which the electricity is produced and the expenses are made.
- *r* : annual discount rate
- $\mathrm{Investment}_t$: investment cost in the power plant in the year t
- $\mathrm{O\&}M_\mathrm{t}$: operations and maintenance cost in the year t
- Fuel_t : fuel costs in year t
- $\mathrm{Carbon}_\mathrm{t}$: carbon cost in the year t
- $\mathrm{Decommissionnong}_\mathrm{t}$: decommissionning cost in the year t
- $\mathrm{Electricity}_\mathrm{t}$: amount of electricity produced in the year t (in MWh)

❑ The *LCOE ($/MWh)* represents the price that has to be paid to produce electricity, taking into account all costs of the fuel cycle, including the back-end, i.e the waste disposal.

❑ This is a standard measure for comparison of different fuel cycles and different technologies.

Main specifications of the model plant

Capacity factor	**85 %**
Durability	40 years
Discount rate	7.6 %
…	

- Disposal costs include transportation and packaging.
- Reprocessing costs include storage, transportation and vitrification.
- The cost of direct disposal is based on theoretical studies and concepts that are not yet given international consensus.

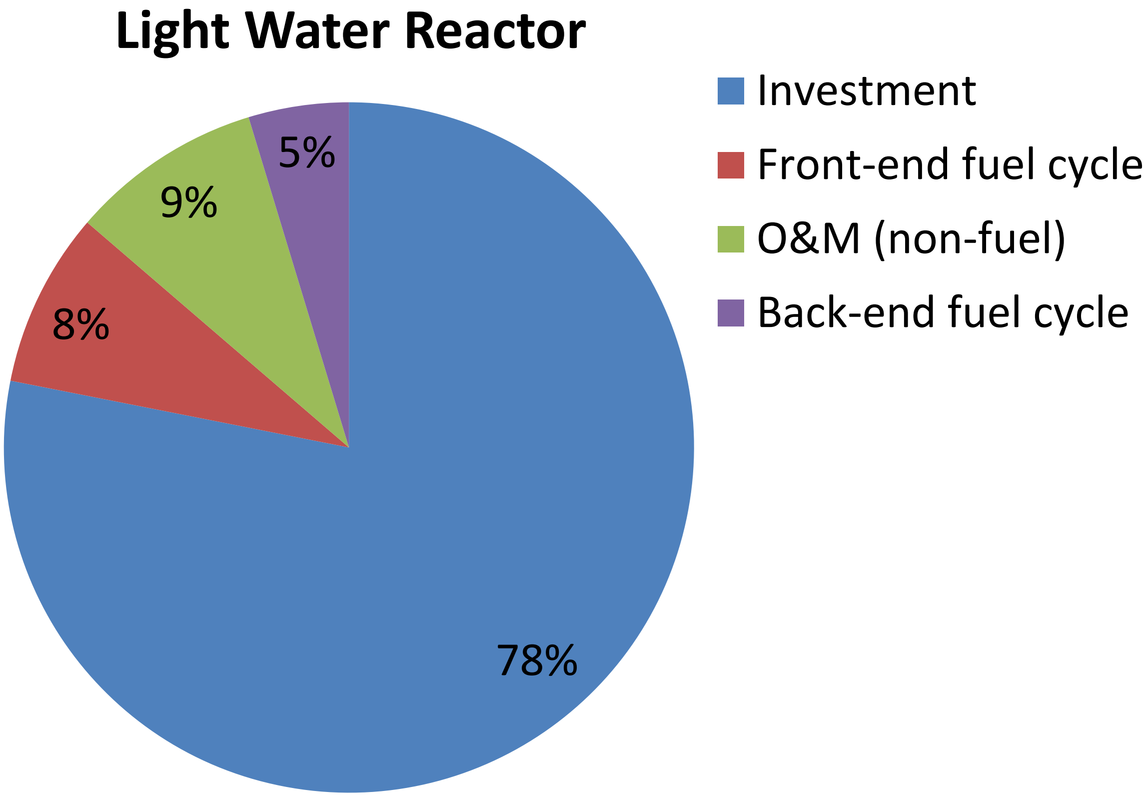
For more details about the assumed model, see [MIT 2011 study: “The Future of Nuclear Fuel Cycle” **[2]].**

The LCOE for the Fast Reactor Recycle

❑ Light Water Reactor burning fresh UOX fuel.

❑ The most important factor in the Front End Fuel Cycle is the enrichment (not the cost of raw uranium). Scarcity is not yet a problem ...

7.6 % discount rate



The back-end fuel cycle is composed of the costs of :

- Reprocessing
- Disposing of the separated HLW
- Charge paid for the separated transuranics

❑ The LCOE calculated at the back-end of the fuel cycle is strongly dependent on the discount rate.

The nuclear fuel cycle accounts for ~ 13 % of the total power generation costs.

Impact of the Accelerator on LCOE

$$LCOE = \frac{\sum_t \left(\frac{\text{Investment}_t + \text{O\&M}_t \boxed{+ \text{Fuel}_t +} \text{Carbon}_t + \text{Decommissioning}_t}{(1+r)^t} \right)}{\sum_t \left(\frac{\boxed{\text{Electricity}_t}}{(1+r)^t} \right)}$$

- All parameters in the above formula change by adding an accelerator to an already existing reactor: the investment cost should increase by roughly 10%.

  The cost of the 1.4 MW SNS linac is estimated to be 0.7 B$.

- The saving potentially comes from the back-end fuel: we assume that the ADSR is **a net burner**. In the best case scenario, most of the offending radioisotopes, i.e the minor actinides are eliminated, yielding a reduction in the volume of the waste disposal facility. This is reflected as a saving in the cost of the Fuel.

- The amount of electricity produced with an ADSR is lower than with a fast reactor concept.

The main question to answer is whether the costs of deploying the external source of neutrons will be offset by a reduction of the costs of the nuclear waste disposal?

Energy efficiency parameters

$$\text{Electricity}_t(\text{MWh}) = \mathbf{C} \times \Delta t(h) \times \boldsymbol{\eta_{th}} \times P_{th,c}(MW)$$

- C is the capacity factor of the plant defined as the ratio of the plant's actual output to its maximum possible output: for an ADSR, one key parameter to determine C is the reliability of the accelerator.

- η_{th} is the thermal efficiency of the power plant: for an ADSR, the power drained by the accelerator lowers the overall efficiency of the installation.

☐ If we define C_0 and η_{th0} as the uncorrected capacity factor and uncorrected thermal efficiency, i.e without an accelerator, then the electricity produced by an ADSR writes:

$$\text{Electricity}_{t,ADS} = \frac{\mathbf{C}}{\mathbf{C_0}} \times \frac{\boldsymbol{\eta_{th}}}{\boldsymbol{\eta_{th0}}} \times \text{Electricity}_{t0}$$

Corrected thermal efficiency of ADSR

We evaluate the overall efficiency of an ADSR by adding the cost of the accelerator beam:

❑ First, one shows that:

$$\boxed{P_{th}(MW) = E_f(MeV) \times I(A) \times \frac{\mathrm{N}_0}{\nu} \times k_1 S + (P_{dh})}$$

where $E_f(MeV) \sim 200\ MeV$; I is the beam current, ν is the number of neutrons produced per fission (~2-3), N_0 is the number of neutrons per proton (n/p) and S is /

$$S = 1 + k_2 + k_2 k_3 + k_2 k_3 k_4 + \cdots + k_2 k_3 \ldots k_p + \cdots$$

k_i is the multiplication factor of the generation i.

❑ It results:

$$\boxed{\frac{\eta_{th}}{\eta_{th0}} = 1 - \frac{E_p}{E_f} \times \frac{\nu}{N_0} \times \frac{1}{k_1 S} \times \frac{1}{\eta_{acc}\, \eta_{th0}}}$$

$$\eta_{th} = \frac{P_{el,c} - P_{acc,grid}}{P_{th,c}} \quad ;$$

η_{acc} is the wall-plug efficiency of the accelerator.

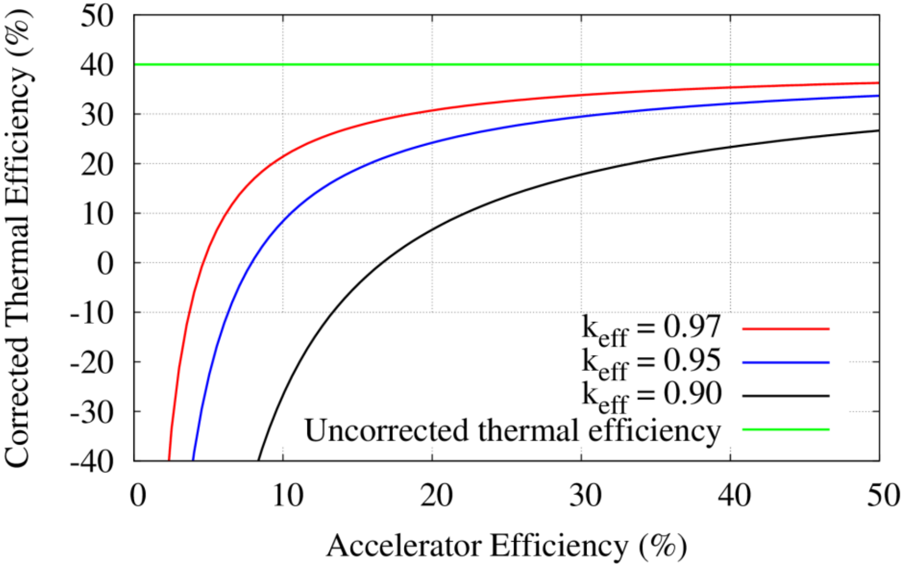
➨ **The first generation of neutrons (k_1) has the same energy efficiency impact as the wall-plug efficiency of the accelerator.**

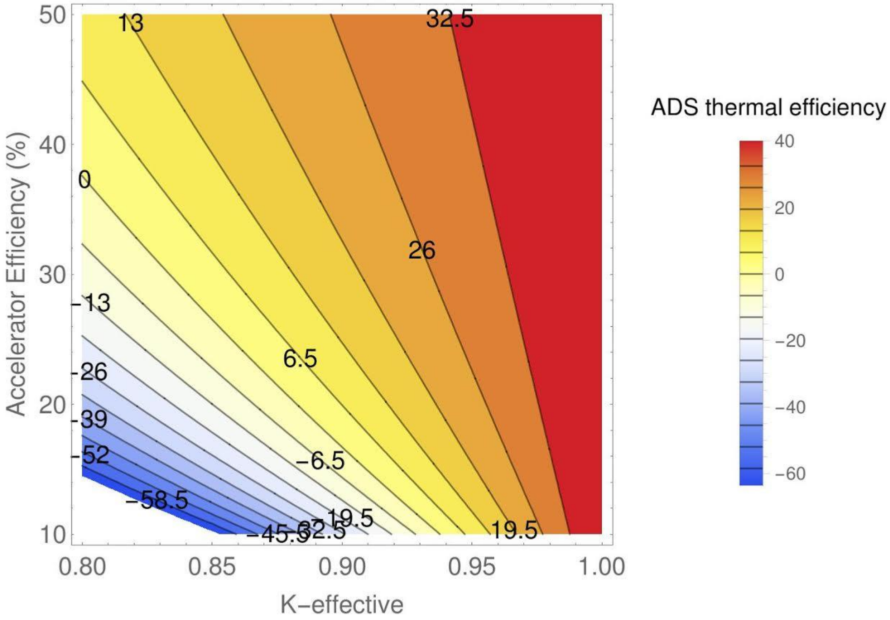
Corrected thermal efficiency of ADSR

- ☐ Assuming the list of parameters in the table below and $k_i = k_{eff}\ \forall\, i$, this yields:

Uncorredted thermal efficiency	40 %
Proton energy E_p (GeV)	1
Energy released per fission E_f (GeV)	0.208
Neutrons per proton N_0 (lead target)	20
Neutrons per fission ν	2.5

$$\boxed{\eta_{th} \approx \eta_{th0} - 0.6\,\frac{1-k_{eff}}{k_{eff}}\,\frac{1}{\eta_{acc}}}$$ **[4]**





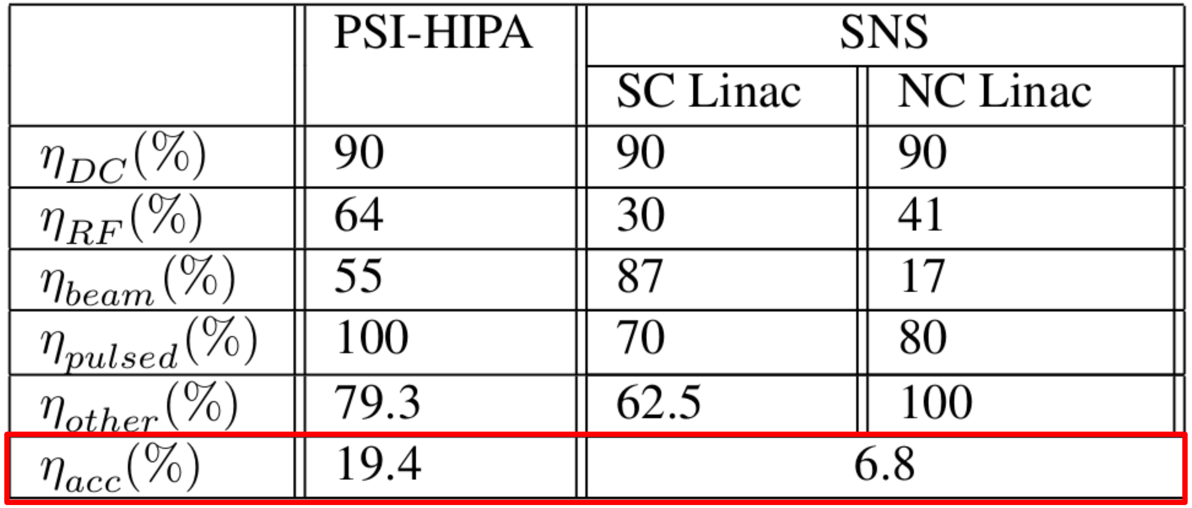
The wall-plug efficiency of the accelerator has a major impact on the economics of the system.

Accelerator efficiency: where does it stand today?

- The wall-plug efficiency of an accelerator is given by:

$$\boxed{\eta_{acc} = \eta_{AC \to DC} \times \eta_{DC \to RF} \times \eta_{RF \to beam} \times \eta_{other}}$$

where $$\eta_{other} = \frac{AC}{AC + magnet + cryo + coffee + \cdots} \to 100\ \%$$ for high power



	PSI-HIPA	SNS	
		SC Linac	NC Linac
$\eta_{DC}(\%)$	90	90	90
$\eta_{RF}(\%)$	64	30	41
$\eta_{beam}(\%)$	55	87	17
$\eta_{pulsed}(\%)$	100	70	80
$\eta_{other}(\%)$	79.3	62.5	100
$\eta_{acc}(\%)$	19.4	6.8	

The projected accelerator efficiency for an ADSR lies in the range [20% : 30%].

Corrected capacity factor of ADSR

- ☐ Capacity factor is the main strength of the nuclear industry compared to other energy sources:

Period	Nuclear	Hydropower	Wind	Solar Photovoltaic	Coal
2014	91.7%	37.3%	34.0%	25.9%	61.0%
2015	92.2%	35.9%	32.5%	28.6%	54.6%

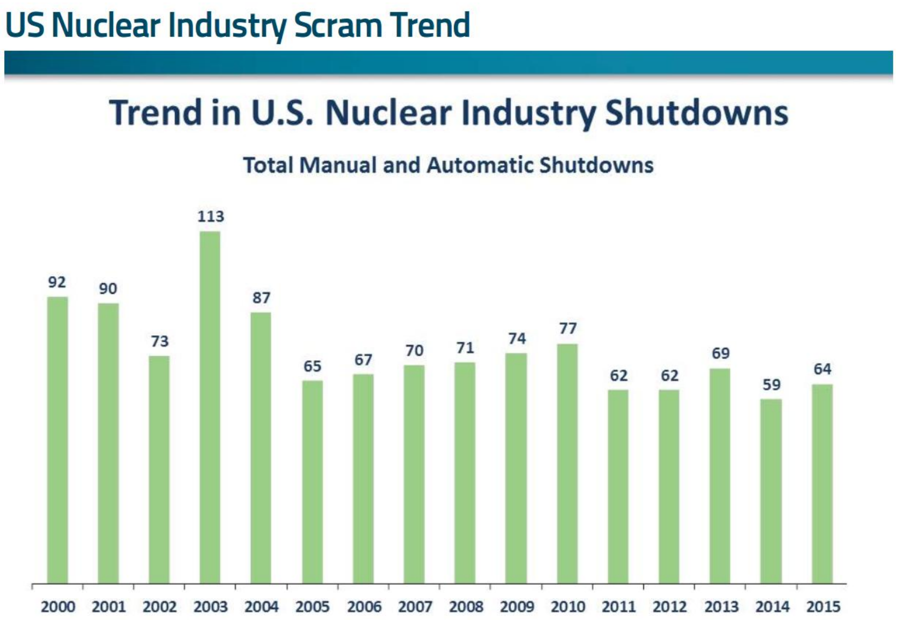
Capacity Factors for Utility Scale Generators in the USA [data from US Energy Information Administration].
(Record reached in 2015)

- ☐ Let's assume that the accelerator has N well separated beam trips during the operation period T, long enough to induce a reactor shut-down lasting Δt_{bt}. Then the corrected capacity factor of the plant writes:

$$\boxed{\frac{C}{C_0} = 1 - \frac{N \times \Delta t_{bt}}{T}}$$

- ☐ **It is particularly difficult to estimate the time required to reach the nominal power of the reactor after a scram. Multi-dimensional problem but vital for ADSR.**

Corrected capacity factor of ADSR

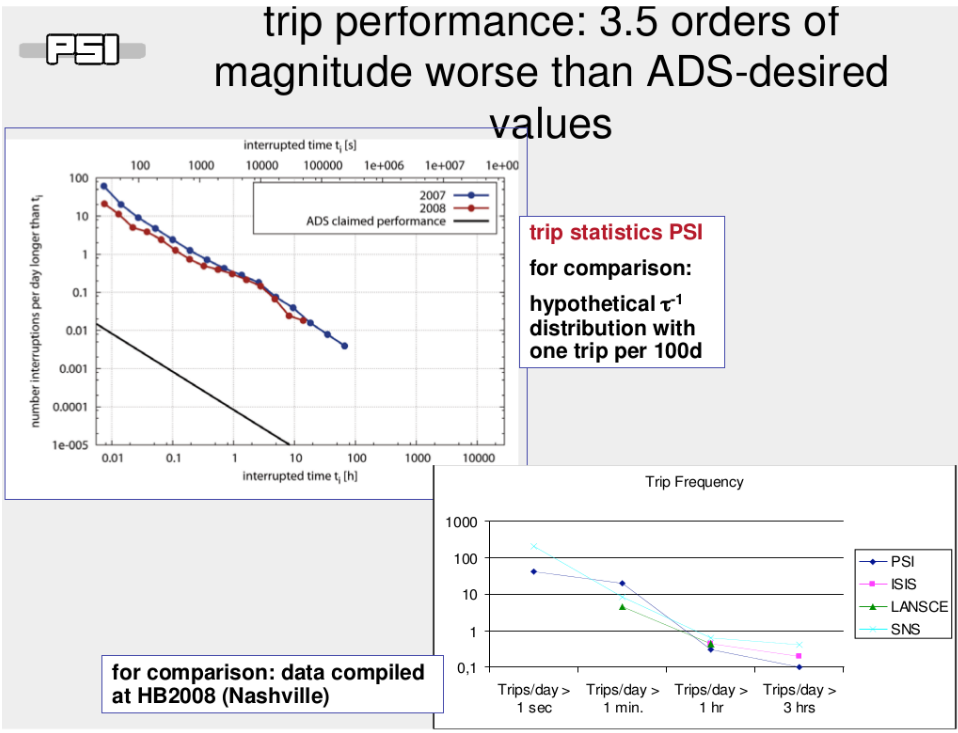


US Nuclear Industry Scram Trend

Trend in U.S. Nuclear Industry Shutdowns

Total Manual and Automatic Shutdowns

Source: Nuclear Energy Institute (NEI).



trip performance: 3.5 orders of magnitude worse than ADS-desired values

trip statistics PSI

for comparison:

hypothetical τ^{-1} distribution with one trip per 100d

for comparison: data compiled at HB2008 (Nashville)

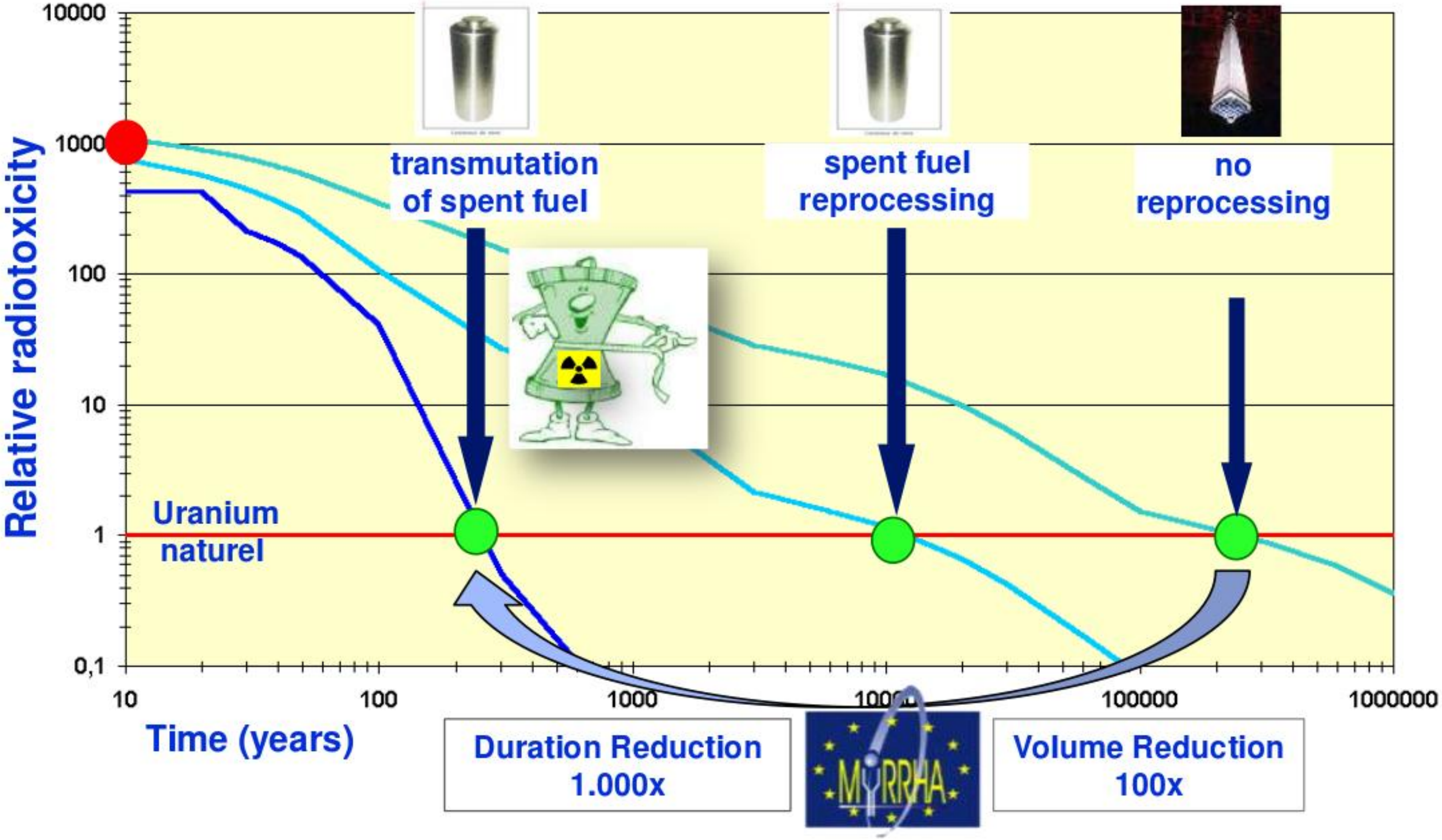
Courtesy Mike Seidel, PSI.

With the current state of the art in terms of reliability, an ADS system will never work.

Fuel parameters

Courtesy of MYRRHA

$$LCOE = \frac{\sum_t \left(\frac{\text{Investment}_t + \text{O\&M}_t \boxed{+ \text{Fuel}_t +} \text{Carbon}_t + \text{Decommissioning}_t}{(1+r)^t} \right)}{\sum_t \left(\frac{\text{Electricity}_t}{(1+r)^t} \right)}$$



The burden of the radioactive waste can be reduced by two orders of magnitude through reprocessing and transmutation.

Fuel parameters

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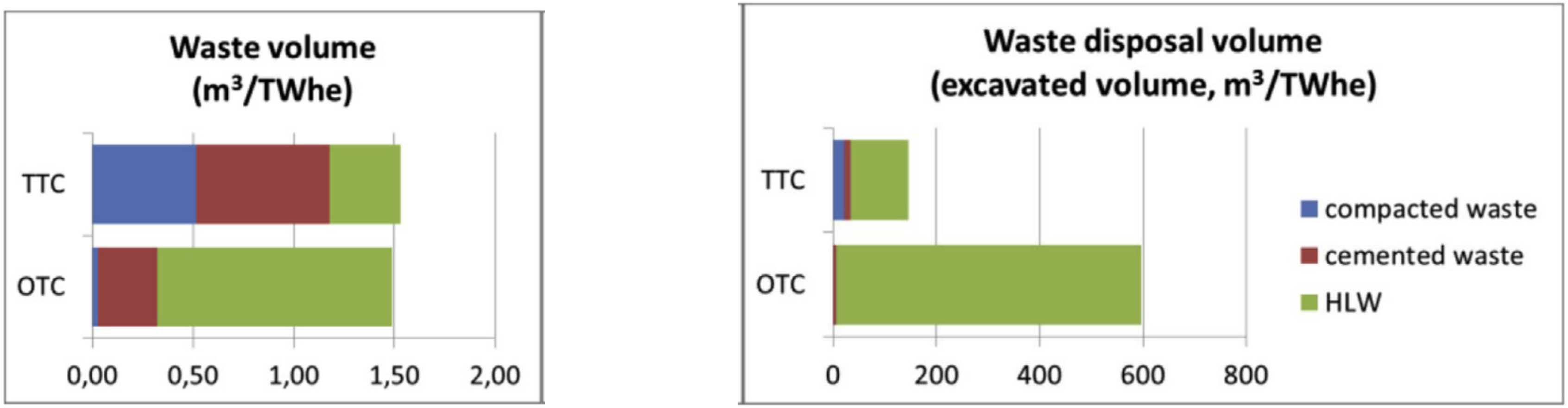


Comparison of the waste volumes for the TTC and the OTC [5].

- ☐ The total quantities of waste to deal with are almost the same in all different fuel cycles. However, the types of waste are changed: HLW reduce considerably, which allows more compact wasteforms. **This has a major impact on reducing the volume of the repository.**

- ☐ In all studies, the cost of the spent nuclear fuel management represents a small fraction of the total LCOE.

Summary: the LCOE for ADSR

$$\boxed{\boldsymbol{LCOE = \frac{C_0}{C} \times \frac{\eta_{th0}}{\eta_{th}}\ LCOE^{min}}}$$

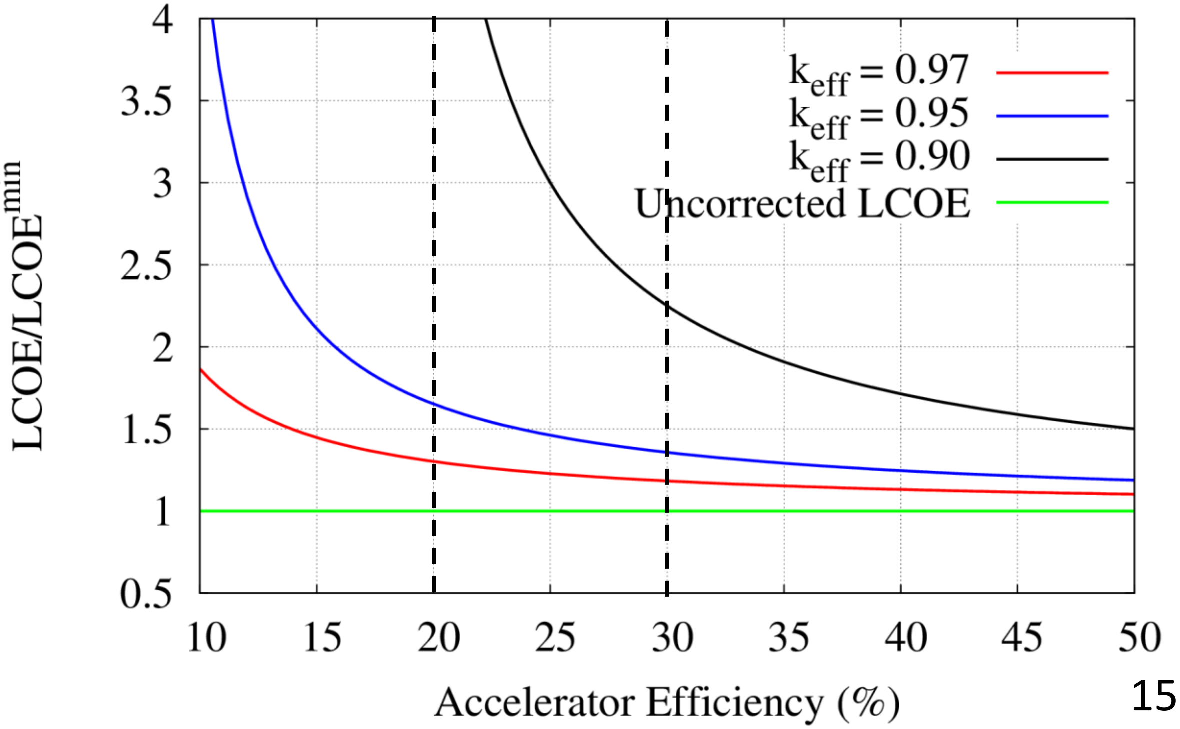
where one assumed

- an order of magnitude reduction in the footprint of the waste repository.
- 10% increase in the investment as well as the O&M costs

yielding $LCOE^{min} \approx LCOE_{fast\ critical\ reactor}$

The (achievable) supplemental cost of ADSR (on the LCOE) lies in the range 20% to 70% in comparison with fast critical reactors.

Strong dependence on $\boldsymbol{k_{eff}}$ and $\boldsymbol{\eta_{acc}}$.



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CONCLUSION:

❑ **The additional costs of the ADSR fuel cycle compared to the OTC are not offset by the reduction of the costs of the nuclear waste disposal**: this is mainly due to the effects of the discount rate on the long term expenses: since the strategy of waste disposal is implemented over a long period of time, any small discount rate decreases the contribution to the LCOE.

❑ OTC with direct storage is cheaper. However, this solution requires more time for the spent fuel to become stable than any empire or state has ever lasted (**Roman empire lasted 2214 years versus 300 000 years for the waste**).

Conclusion

- It is often affirmed that the cost of disposing of high level waste after reprocessing and transmutation will be less than the cost of disposing of it directly, i.e OTC. However, the basic conclusion from what preceded is that, even if the cost of reprocessing were zero, the conclusion that **reprocessing is uneconomic** remains the same. Same conclusion in a 2003 MIT study and 2012 CEA study **[6]**.

- Low-cost is the main driver for modern economic decision making. **However, the cost of the associated risks of the different technologies is not necessarily taken into account.**

- Impacts on the environment and on future generations are very different depending on the strategy: the economic comparison between the different approaches should not be the only driver for decision making.

- **The accelerator wall-plug efficiency, its reliability as well as the effective multiplication factor are the key parameters for competitiveness with other advanced fuel cycle technologies.**

References

[1] “External costs, Research results on socio-environmental damages due to electricity and transport”, European commission, EUR 20198 (2003).

[2] “The Future of Nuclear Fuel Cycle”, An Interdisciplinary MIT Study (2011).

[3] “The Economics of the Back End of the Nuclear Fuel Cycle”, OECD-NEA Report No. 7061, OECD-Nuclear Science (2013).

[4] M. Haj Tahar, F. Méot and S. Peggs, “Energy Efficiency of High Power Accelerators for ADS Applications”, IPAC 2016, TUPOY044.

[5] Ch. Poinssot et al, “Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles”, Energy 69 (2014).

[6] “REPORT ON SUSTAINABLE RADIOACTIVE WASTE MANAGEMENT”, CEA (2012).