Future prospects for the transition to a closed fuel cycle

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Current status of closed fuel cycle

Currently, most power reactors operate in an open fuel cycle. Only a few dozen nuclear reactors (about 40) in countries with advanced nuclear power programs operate in a closed fuel cycle that utilizes reprocessed spent fuel. However, the number of these reactors continues to grow, and even some countries that do not yet operate a closed fuel cycle are considering making the transition to one.

For now, the Czech Republic belongs to the first group. Today our fresh fuel consumption is about 55 – 75 t HM/year which contains about 3 t of fissile material (U-235).

The spent nuclear fuel is stored in spent fuel intermediate storage facilities located at the Dukovany and Temelín NPP sites until it could be transferred to the planned deep underground repository.

This strategy is in line with the current national concept of spent fuel management, but in conjunction with the construction of new reactors and the further development of nuclear energy, it is time to open up the debate as to whether it would not be appropriate to close the fuel cycle in the future, make better use of nuclear fuel and thus significantly reduce the overall production of spent fuel and postpone the need to build a deep underground repository.



Photo: Courtesy ČEZ a.s.

Why to close the fuel cycle of LWR – What would it get us

In general terms, it is about better use of nuclear fuel. (By about 25 %)

- The main reason is to significantly reduce the volume and quantity of spent fuel and high-level waste for long term final disposal. (About 5 times)
- Another reason is to reduce the total long-term radiotoxicity of the disposed waste. (About 10 times)
- Short- and medium-term benefit is that the need to build a deep geological repository could be postponed.

However, a prerequisite is having a nuclear reactor able to use (approved to use) MOX fuel.

Spent fuel composition

Depending on the initial enrichment of the uranium fuel, the composition of the spent UOX fuel is approximately as follows:

Spent nuclear fuel



94- 96% U

1% Pu and other transuranium elements 0,1 %

3-5% Fission products

Current and projected spent fuel balance in the Czech Republic

Light water reactor spent fuel contains about 1 % plutonium and about 96 % uranium, of which about 0,8 % is U-235 and about 0,4 % is U-236. The remainder is fission products and so-called minor actinides (Np, Am, Cm).

year	2017	2018	2019	2020	2025	2030	2035	2040
Arisings of tHM	60	85	61	70	56	70	102	100
Cumulative amount of tHM in storage	1895	1980	2041	2111	2483	2849	3181	3551
Approximate amount of Pu (t) in tHM	18	19	20	21	25	29	32	36

Source: Nuclear Energy Data

This means that now (in 2026) we have almost 27 tons of plutonium in spent fuel and in 2035 we will store over 30 tons of plutonium, with about 1 ton of plutonium being added every year thereafter. The commissioning of new reactors will then multiply the annual plutonium production even more.

LWR spent fuel reprocessing technology

The current PUREX hydrometallurgical technology is suitable for spent oxide fuel from light-water reactors.

This process is based on dissolving the fuel in nitric acid and then gradually extracting uranium and plutonium from the nitrate solutions using an organic extractant—tributyl phosphate (dissolved in kerosene) .

The process yields:

- Uranium product
- Plutonium product (or, after processing to reduce the risk of plutonium misuse, a mixture of uranium and plutonium products)
- High-level waste (so-called high-level raffinate) — a mixture of fission products and minor actinides (Np, Am, Cm)



Photo: Courtesy ORANO

Uranium from reprocessing can be stored as low-level waste, or it can be further re-enriched at an enrichment plant to produce new RepU (ERU) uranium fuel.

Plutonium, when mixed with depleted (or natural) uranium, is used to produce MOX mixed uranium-plutonium fuel.

Technical aspects

Reduction of spent fuel volume and HLW

From about 8 fuel assemblies, 1 MOX fuel assembly can be obtained (and also 1 RepU fuel assembly - i.e. uranium fuel prepared by re-enrichment of uranium obtained from reprocessing.)

In addition to the new MOX fuel assemblage, the reprocessing will produce 3 containers of vitrified HLW, 2 containers of intermediate compacted metallic waste and some cemented LLW containing the originated from sludge and rinse water.



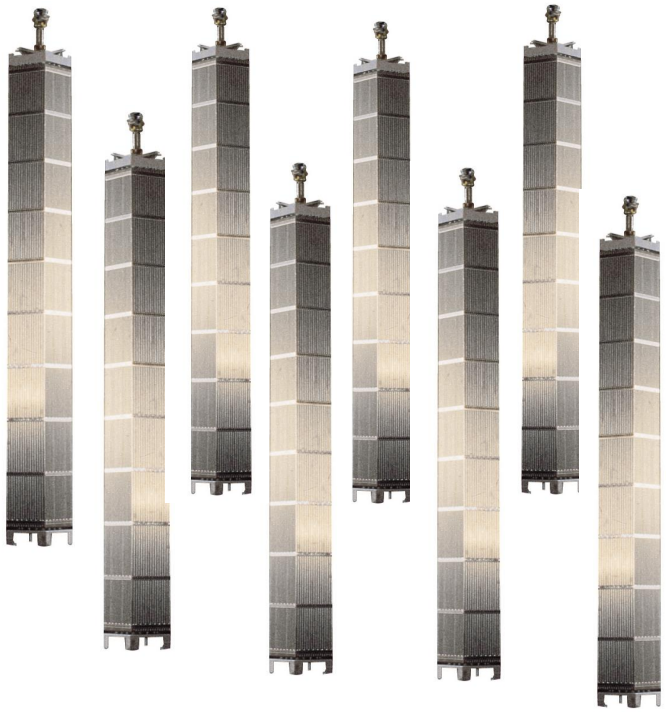


Photos: Courtesy ORANO

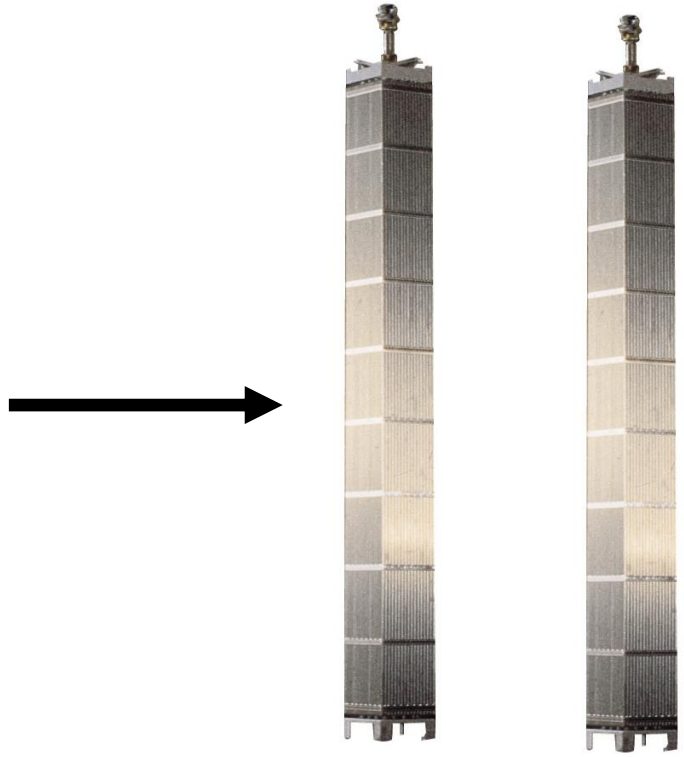
Technical aspects cont.

Approximate balance:

8 assemblies of SNF UOX



1 MOX + 1 RepU + 3 UC-V + 2 UC-C





Vitrified HLW



Compacted MLW

HLW volume reduction by 5

LWR SNF is reprocessed after about 10 years of cooling, when its initial radioactivity and heat generation from the decay of short-lived fission products have been significantly reduced.

Spent fuel reprocessing plants – current status

Spent fuel reprocessing plants

- France: ORANO - La Hague, capacity 1700 t/year
- RF: ROSATOM - Ozersk (Chelyabinsk), 400 t/year, Zheleznogorsk, 250 t/year
- India: Trombay, PREFRE - Tarapur, KARP - Kalpakkam, about 300 t/year
- Japan: JNFL - Rokkashomura, 800 t/year - planned capacity, operational in March 2027
- China: 200 t/year, Gansu, CNNC – Lianyungang, 800 t/year – under construction, start-up planned for 2030
- USA: ORANO and SHINE – planned capacity about 100 t/year – under preparation, probably in Janesville, early 2030s



La Hague

MOX fuel fabrication

ORANO – MELOX plant (Marcoule)

- In operation since 1995
- Current approved capacity: 195 t HM/year
- Production in 2008: 126 t HM
- Current approx. production: 150 t HM



ROSATOM – Mining and Chemical Combine (Zheleznogorsk)

- MOX production for BN-800 (Beloyarsk 4)



MOX plant of Japan Nuclear Fuel at Rokkasho-Mura – about 130 t HM, construction finalized in 2027, full operation in 2030.

Re-enrichment of uranium – fabrication of RepU

The re-enrichment of uranium from reprocessing is carried out on a special enrichment lines, separate from the enrichment of natural uranium, due to the presence of slightly radioactive uranium isotope U-236.

Until recently, re-enrichment was carried out only at the TENEX Group's plants in Seversk and Zheleznogorsk.

Now, a RepU line is also in operation at the URENCO plant in Almelo, and ORANO is also significantly expanding its Georges Bessee II enrichment complex in Pierrelatte.





Countries with the largest number of reactors and their fuel cycles

Note: *In principle, all new light-water reactors can be operated in part with MOX uranium-plutonium fuel. New Gen III+ reactors approved for the European Union must be capable of burning MOX fuel in at least 30% of their core volume (a requirement under the EUR standard).*

USA: 94 reactors, all with an open fuel cycle, but a closed fuel cycle is now planned

China: 64 reactors, preparing to implement a closed fuel cycle

France: 57 reactors, uses a closed fuel cycle

Russia: 36 reactors, uses a closed fuel cycle

Japan: 33 reactors (originally 52) – 15 in operation, 10 preparing to start up, will once again use a closed fuel cycle

South Korea: 26 reactors, all with an open fuel cycle

India: 25 reactors, uses a closed fuel cycle

Existing experience with MOX and RepU

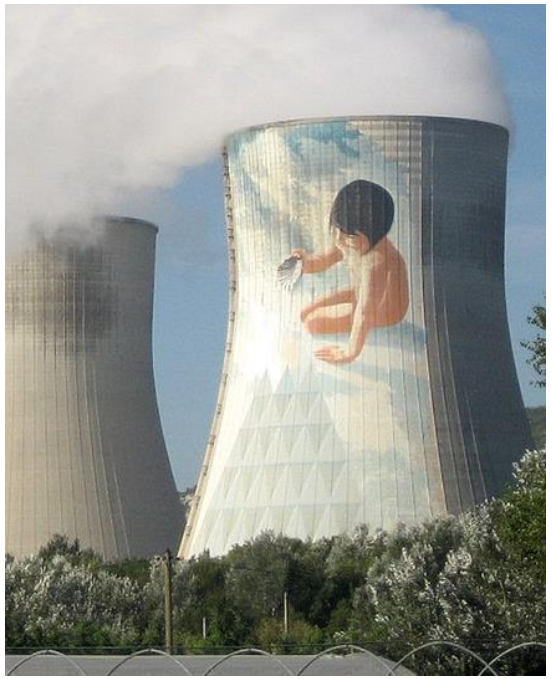
Use of MOX fuel LWR

- 22 reactors in France
- 2 reactors in Belgium
- 10 reactors in Germany (including 2 BWRs - Gundemmingen NPP)
- 3 reactors in Switzerland
- 5 reactors in Japan
- 1 reactor in the Netherlands, 1 reactor in USA, 1 reactor in RF

Other type reactors in India (exper.), Russia (BN-800), China (exper.), …

Use of RepU fuel

- several reactors in France
- 3 reactors in Belgium
- 1 reactor in the UK (Sizewell)
- 1 reactor in Sweden (BWR Oskarsham)
- 1 reactor in the Netherlands
- 6 reactors on Germany (1 BWR – NPP Grundemmingen)
- 3 reactors in Switzerland



Note:
Unit 2 (900 MWe) at Cruas-Meysse NPP operated by EDF has been using a complete zone with recycled re-enriched uranium (RepU) since February 2024.

APR 1000 and MOX or RepU fuel

Currently, there are no plans to use MOX fuel in the APR1000 reactors at EDU II, and Korea has no experience with a closed fuel cycle.

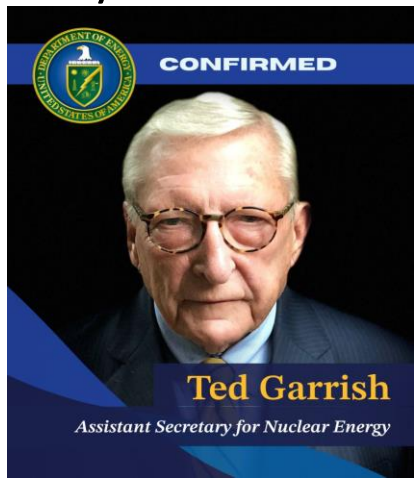
However, the APR1000 meets the requirements of the EUR, and calculations performed by KHNP show that both its core and control system would allow the use of MOX fuel.

This means that it would be possible to burn MOX fuel in the APR1000 in the future.

From the perspective of reactor control systems, RepU fuel is even easier to use than MOX fuel.

The Republic of Korea developed its nuclear program with significant assistance from the United States. It is possible that it will be influenced by the U.S.'s new approach to the fuel cycle in the future.

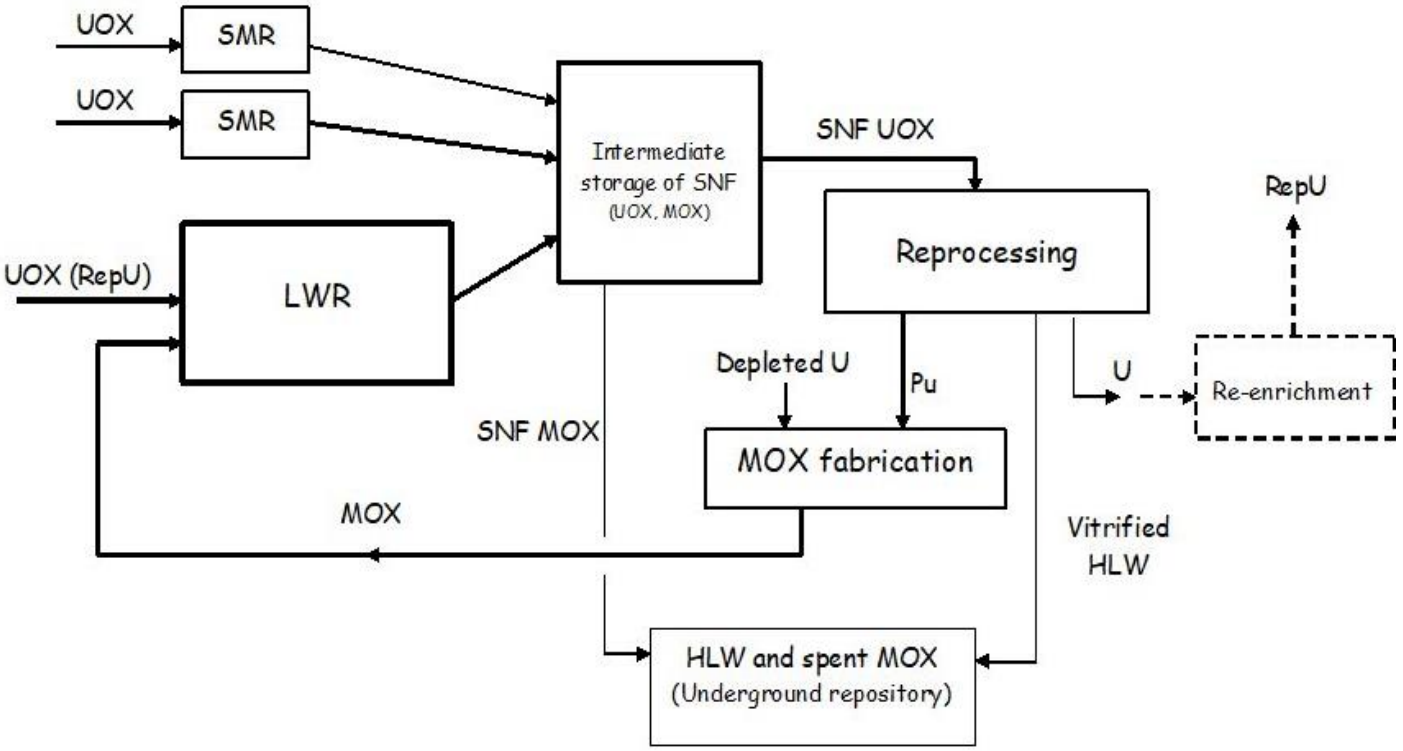
Ted Garrish: „Used fuel is an incredible untaped resource in the United States.“ In 2026, the US-DOE provided $19 million for the development of spent nuclear fuel recycling technologies.



Possibility of integrating SMR into the PWR fuel cycle

The SMR fuel cycle as is practically not discussed in the individual proposals (including Rolls- Royce SMR), usually only the type of fuel is mentioned - this basically implies its fabrication and then in some cases the methods and principles of fuel exchange in the reactor are discussed.

Thus, the issue of SMR spent fuel could probably only be addressed in conjunction with the LWR fuel cycle *(or, where there will be FRs, the FR fuel cycle).*



Political and legislative aspects

There are as yet no legislative or contractual barriers to reprocessing the fuel from the new reactors and it is difficult to see how they could arise.

Similarly, there are no obstacles to reprocessing fuel supplied for existing VVER reactors by Westinghouse and Framatome.

There is a formal legislative barrier concerning the choice of the reprocessing of fuel supplied from the Soviet Union and subsequently from the Russian Federation.

According to the Intergovernmental Agreement from 1994 and the Amendment from 1999, any reprocessing of Russian fuel should take place in the Russian Federation. The Agreement is still in force, automatically renewed every two years, with a one-year notice period. *(However, the government may either try to change it in the future, or simply terminate it.)*

Economical aspects

When assessing the economic aspects, it is necessary to consider not only the cost of fresh uranium fuel, and the cost of reprocessing and fabrication of MOX fuel, but it is necessary to take into account the reduction in the consumption of fresh UOX, the reduction in the amount of spent fuel disposed of, including HLW, and above all the delay in the need to build a deep repository.

The main benefit from the closure of the fuel cycle should accrue to the State that is responsible for the final disposal of the nuclear waste.

The costs incurred by the operator in connection with the use of MOX and RepU should be compensated, for example, by not paying a charge on the nuclear account for the electricity generated by the incineration of MOX.

Conclusion

What would be the main benefit of using MOX (and RepU) in our new reactors

- With the gradual reprocessing of our SNF to MOX, the short to medium term benefit would be to delay the need to build a deep repository for decades.
- The amount of future SNF (spent MOX and vitrified HLW) would be reduced in mass and volume to about 25% the equivalent uranium SNF.
- The overall long-term radiotoxicity of the SNF including HLW would also be reduced.

- However, the use of MOX and RepU also has disadvantages for NPP operator.
- Even fresh MOX fuel is radioactive, which puts additional handling requirements on the operator.
- MOX is still slightly more expensive than fresh uranium fuel.
- The operator should be compensated for all of this if the operator is not wholly owned by the state.

MOX makes it possible to keep plutonium inventories in balance.

The transition to a closed fuel cycle is the path to the further development of nuclear energy.

We try to recycle just about everything — we should recycle spent nuclear fuel as well.

Thank you for your attention.