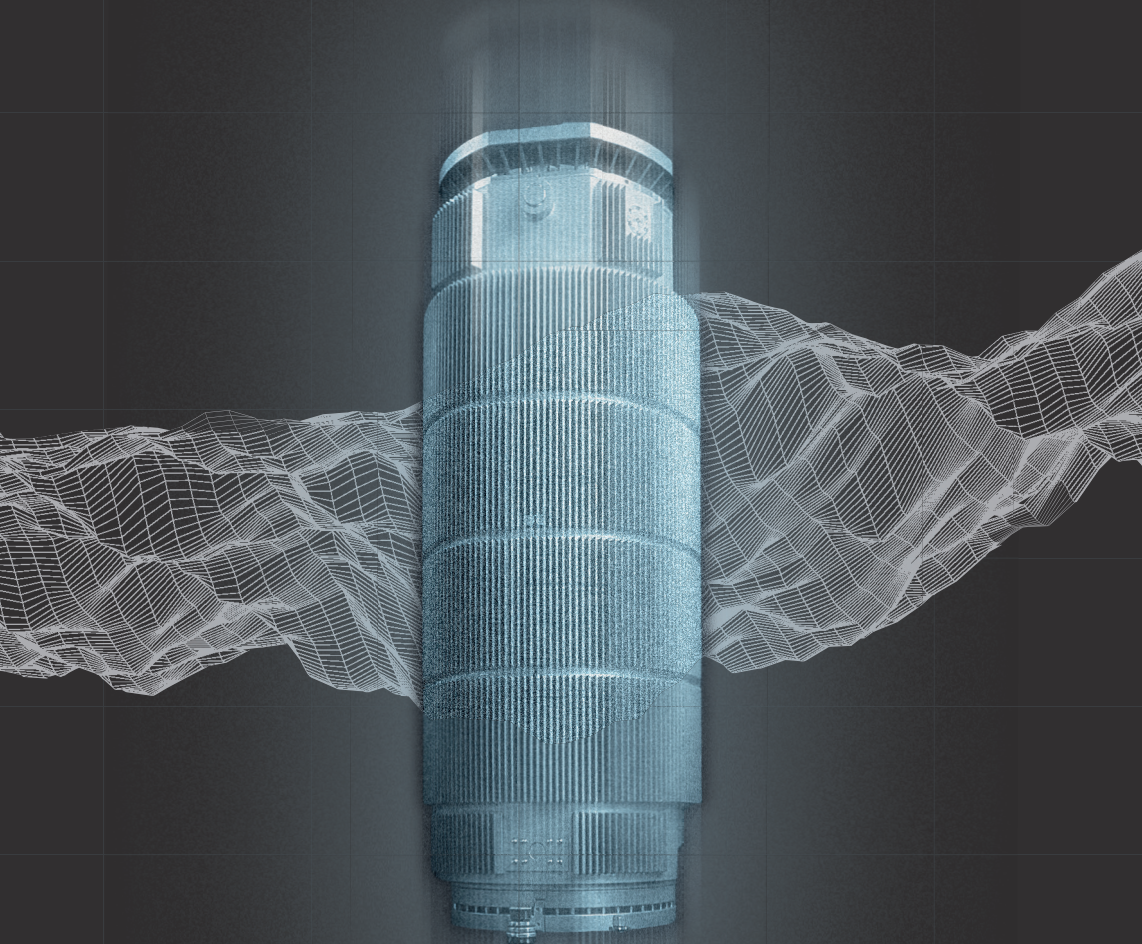




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Sustainable NFC

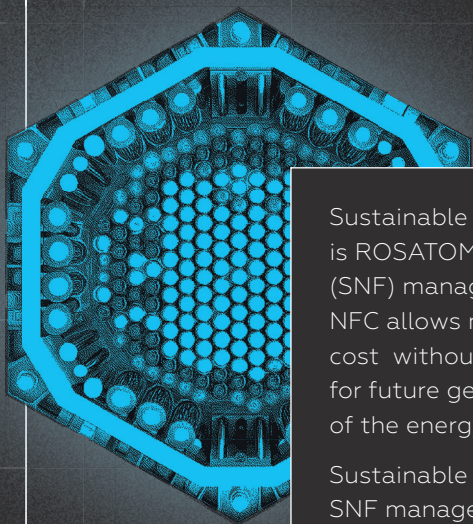
15 questions and answers about
Sustainable Nuclear Fuel Cycle by ROSATOM





[01]

What is Sustainable Nuclear Fuel Cycle by ROSATOM?



Sustainable Nuclear Fuel Cycle (Sustainable NFC) is ROSATOM's integrated offer in spent nuclear fuel (SNF) management for its foreign costumers. Sustainable NFC allows minimization of SNF lifecycle management cost without imposing the problem of its accumulation for future generations and to maximize the use of the energy potential of nuclear materials.

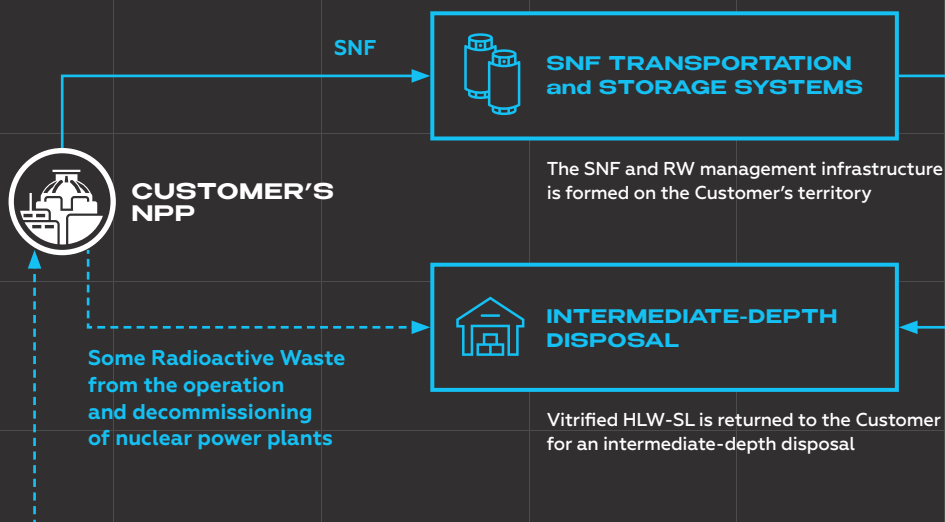
Sustainable NFC solutions are based on the centralized SNF management system and the fast neutron reactors fleet in the Russian Federarion.

Sustainable NFC

Sustainable NFC allows implementing an integrated process of SNF management: SNF is removed from the NPP site and reprocessed, the «short-lived» fraction of radioactive waste is placed in casks. After technical storage required to reduce the residual heat generation, «short-lived» fractions of radioactive waste are returned to the Customer's country for intermediate-depth disposal.

An example of the Sustainable NFC

CUSTOMER'S
TERRITORY

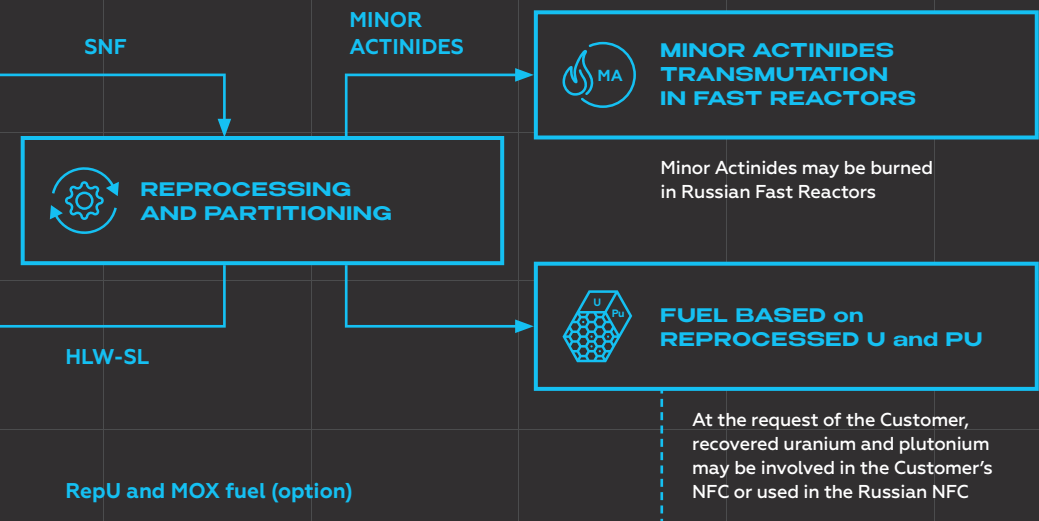


Sustainable NFC combines the following solutions:

- SNF reprocessing with fractionation (partitioning) of a «short-lived» fraction of high level radioactive waste (HLW-SL), its vitrification and technological storage in casks for subsequent return to the Customer's country ([see question No.2](#));
- casks for the transportation and storage of SNF/HLW-SL ([see questions Nos.4-6](#));
- intermediate-depth borehole disposal of HLW-SL in the casks in the Customer's country ([see question No. 7](#));
- nuclear fuel made of reprocessed uranium (RepU-fuel) and uranium-plutonium fuel (U-Pu fuel) for reactors in the Russian Federation or in the Customer's country (if technically possible and economically feasible); ([see questions Nos. 8-10](#)).
- it is also planned to supplement the list of services with the transmutation of minor actinides in fast neutron reactors in the Russian Federation ([see question No. 11](#)).

TERRITORY OF THE RUSSIAN FEDERATION

The spent nuclear fuel is sent to the Russian Federation for reprocessing. SNF is reprocessed, radioactive waste is fractionated (partitioned) to HLW-SL and minor actinides



How are SNF reprocessing and RW partitioning performed?

[02]

SNF reprocessing is a set of chemical and technological operations designed to remove fission products from the fuel and to recover valuable nuclear materials (uranium and plutonium, which together account for roughly 97% of the SNF mass) for subsequent reuse.



In the Russian Federation, PUREX (Plutonium-Uranium Recovery by Extraction) technology is used, which has been significantly upgraded for efficient management of radioactive waste.

For example, plans call for separating a “short-lived” fraction of high level radioactive waste (HLW-SL), whose activity is dominated by Cesium (Cs) and Strontium (Sr) isotopes ([see question No. 7](#)).



In the longer term, the aim is to separate minor actinides such as Americium (Am), Neptunium (Np) and Curium (Cm) ([see question No. 11](#)).

Separating radioactive waste into such fractions is referred to as radioactive waste fractionation (partitioning).

SNF reprocessing with radioactive waste fractionation is a key element of the Sustainable NFC. It allows recovering and reusing valuable nuclear materials obtained from SNF and to produce radioactive waste that can be isolated in a manner that is as safe and efficient as possible.

Can all SNF types be reprocessed?

[03]

From a technological standpoint, yes.

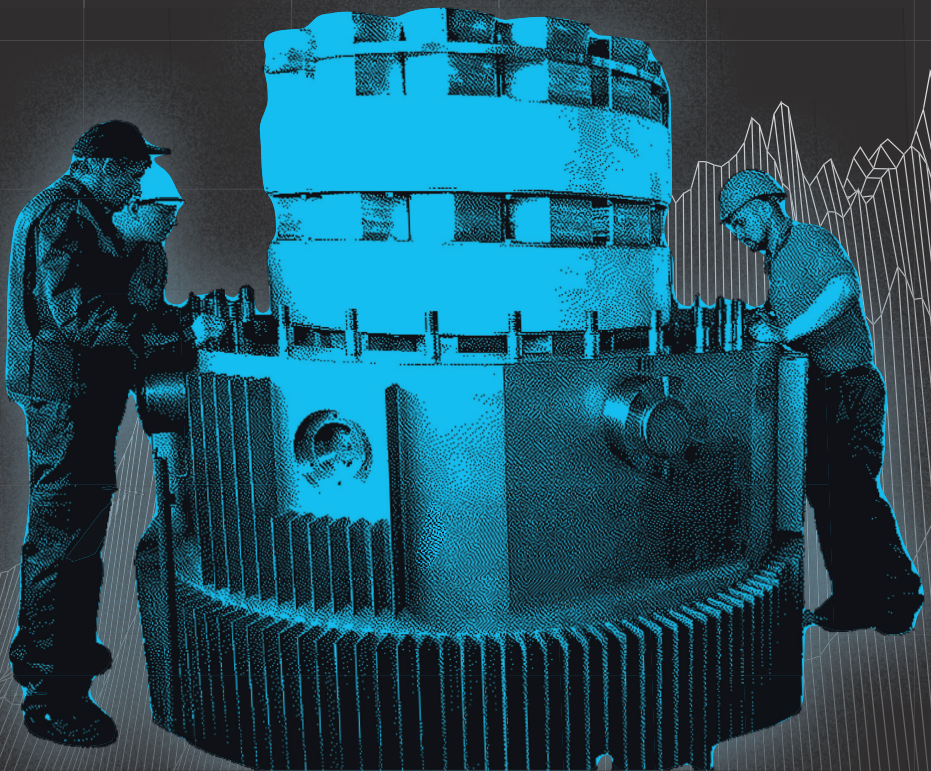
ROSATOM has experience in reprocessing of all SNF types ever manufactured in the USSR and the Russian Federation, including uranium–zirconium, uranium–beryllium and uranium–molybdenum types of fuel. However, today reprocessing in Russia focuses mainly on SNF from LWRs, since the main production lines are configured for this type of fuel.

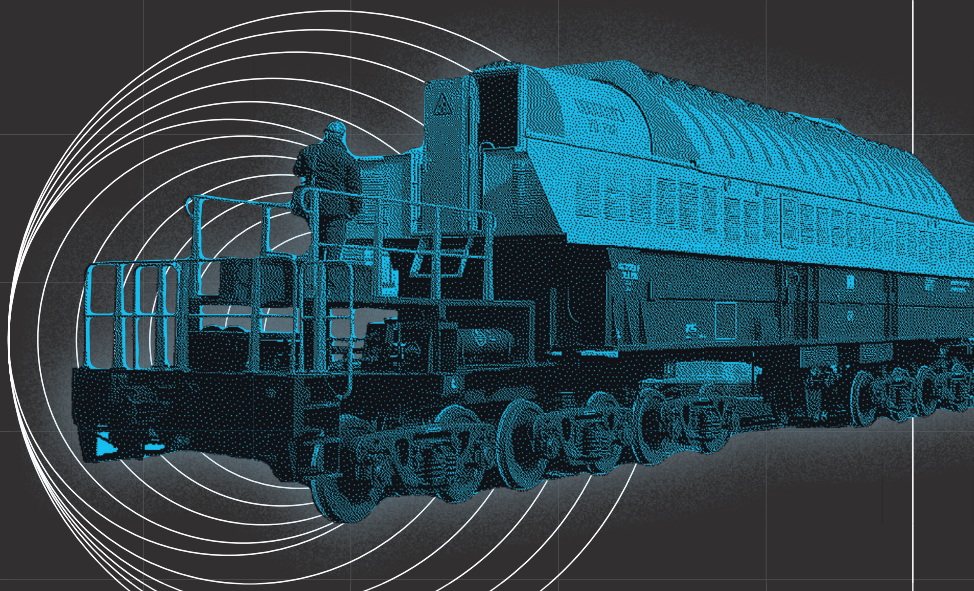
In principle, all SNF types can be reprocessed, but a feasibility study is required.

Sustainable NFC

[04]

What solutions for storage and transportation of SNF and RW from SNF reprocessing are provided under Sustainable NFC?





ROSATOM's solutions are standardized — the same equipment can be used for long-term storage of SNF in the Customer's country, for transportation to the Russian Federation, for return shipments, for storage and/or final isolation of the «short-lived» fraction (HLW-SL) in the Customer's country.

The SNF transportation and storage system bases on two types of casks ([see question No. 5](#)):

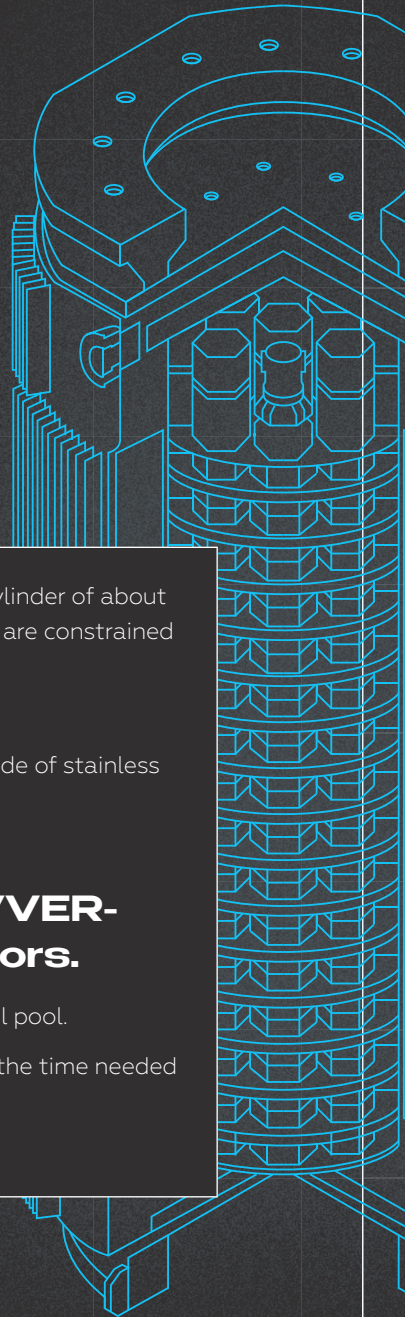
- transport casks;
- long-term storage casks.

The casks are placed in dedicated casks storage facilities (CSF) that provide heat removal and safe storage conditions ([see question No. 6](#)).

The system also allows for the use of rail transporters and ships equipped for handling operations and for maintenance.

[05]

What cask solutions does ROSATOM offer?



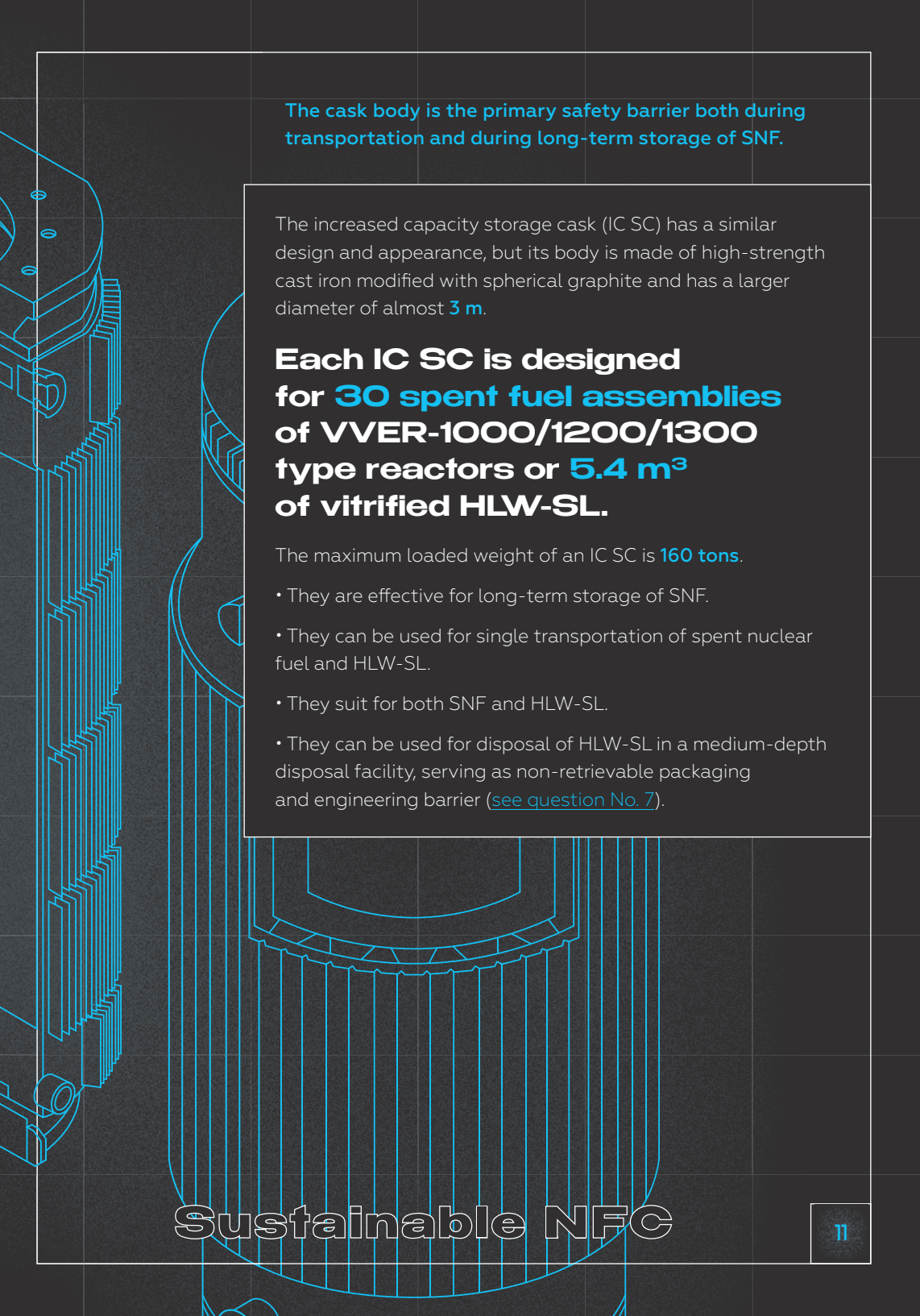
In simple terms, a transport and transfer cask (TTC) is a cylinder of about **2.5 metres** in diameter and **6 metres** high. Its dimensions are constrained by civil engineering structures of an NPP.

The maximum loaded weight of a TTC is **~117 tonnes**.

Its surface is finned to improve heat removal, with fins made of stainless steel.

Each TTC is designed to hold 18 spent fuel assemblies of VVER-1000/1200/1300 type reactors.

- They are used to remove SNF from the reactor spent fuel pool.
- Can provide SNF interim storage for 3–5 years, which is the time needed to accumulate transport batches for shipment.
- They are effective for repeated transport operations.



The cask body is the primary safety barrier both during transportation and during long-term storage of SNF.

The increased capacity storage cask (IC SC) has a similar design and appearance, but its body is made of high-strength cast iron modified with spherical graphite and has a larger diameter of almost **3 m**.

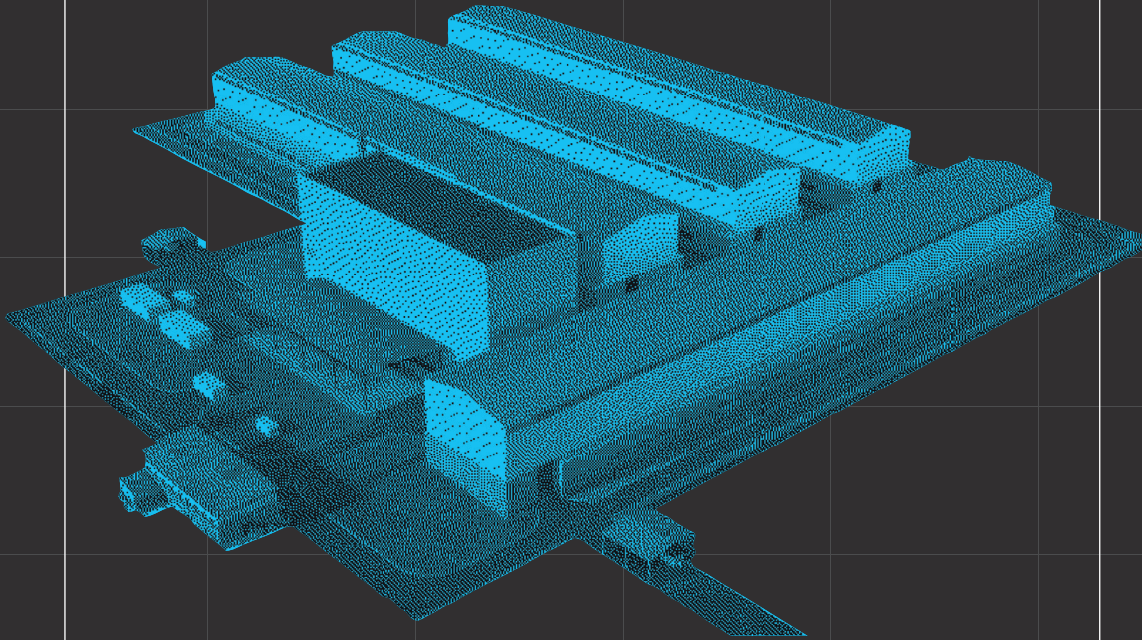
Each IC SC is designed for 30 spent fuel assemblies of VVER-1000/1200/1300 type reactors or 5.4 m³ of vitrified HLW-SL.

The maximum loaded weight of an IC SC is **160 tons**.

- They are effective for long-term storage of SNF.
- They can be used for single transportation of spent nuclear fuel and HLW-SL.
- They suit for both SNF and HLW-SL.
- They can be used for disposal of HLW-SL in a medium-depth disposal facility, serving as non-retrievable packaging and engineering barrier ([see question No. 7](#)).

[06]

What is the
Cask Storage Facility
and how long can
SNF and RW be
stored there?

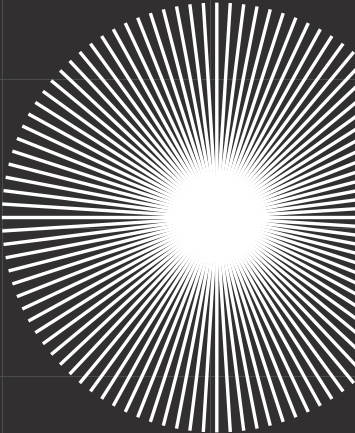


Cask Storage Facility (CSF)
is a basic infrastructure facility
built on the Customer's site
and designed for long-term storage
of casks (TTC/IC SC) loaded
with SNF / HLW-SL.

Up to 60 years of safe SNF storage in CSF (and longer for HLW-SL)

Such a facility typically includes:

- An initial start-up complex, or storage pad, where SNF casks can be stored for 3-5 years, providing enough time to build up transport batches for SNF shipment to reprocessing.
- A SNF handling unit, where SNF is reloaded from a TTC to an IC CS. The unit is needed in case of deferred SNF processing solution. At this stage, the SNF is prepared for long-term storage. The use of IC SC roughly halves the number of casks required for long-term SNF storage.
- Storage modules are buildings that remove residual heat and protect against climatic and external impacts during long-term storage. They can accommodate IC SC with SNF or with HLW-SL if commissioning of a medium-depth disposal facility is delayed.



ROSATOM has developed a reference design for a CSF that can be tailored to Customer requirements and built in stages, in line with market conditions and national SNF management policies.

What should be done with RW arising from SNF reprocessing?

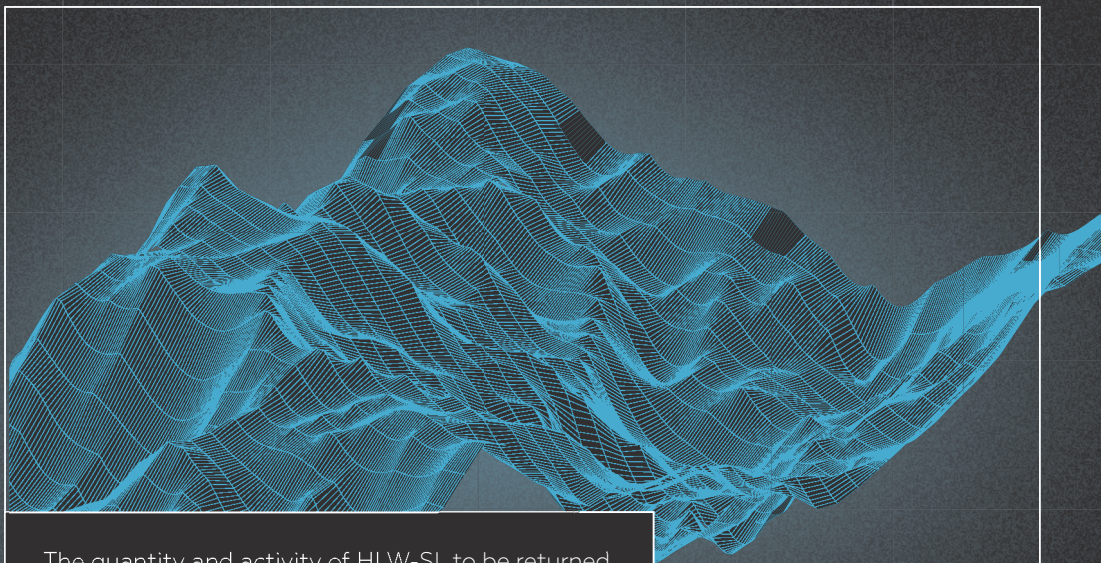
The «short-lived» fraction of high-level waste (HLW-SL) is subject to return to the Customer. It can be disposed of safely and cost-effectively in geological conditions available in almost any country that is planning or already operates NPPs, both large and small capacity.

The activity of HLW-SL is dominated by Cesium-137 and Strontium-90, each with a half-life of about 30 years.

Studies by the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE RAS) have confirmed that HLW-SL fraction can be safely disposed of in medium-depth facilities, for example in boreholes up to 100 m deep.

ROSATOM offers to develop, in the Customer's country, a disposal facility complex designed to accommodate all RW generated over the entire life of an NPP – including operational and decommissioning waste – as well as the HLW-SL returned after SNF reprocessing.

This avoids the need for an expensive deep geological repository, with its complex site selection and safety analysis requirements, and allows the Customer to significantly reduce SNF management costs.



The quantity and activity of HLW-SL to be returned to the Customer's country are determined using a dedicated methodology based on equivalence between the activity of the imported SNF and that of the returned HLW-SL.

Under the equivalence principle, the dose equivalents of the imported SNF and the returned HLW-SL as well as the nuclear fuel produced using the regenerated materials and supplied to the NPP of the SNF reprocessing Customer (in case a respective decision is taken) must match.

Dose factors for each isotope are based on officially approved recommendations issued by Rostechнадзор, the Russian nuclear regulator.

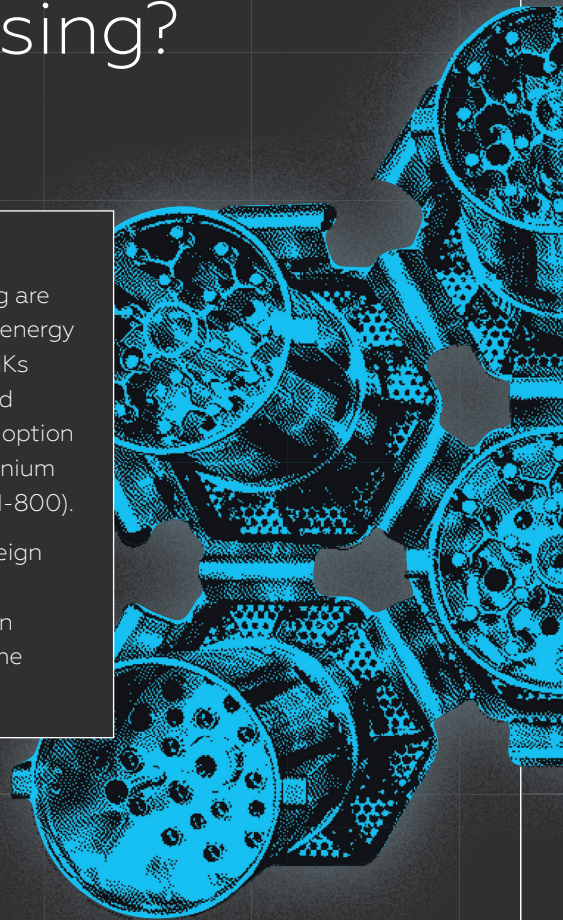
In practice, this principle is implemented by agreeing on a calculation methodology for the amount of HLW-SL to be returned, depending on the characteristics of the original SNF – including initial enrichment, burnup and cooling time.

[08]

What should be done with U and Pu recovered from SNF reprocessing?

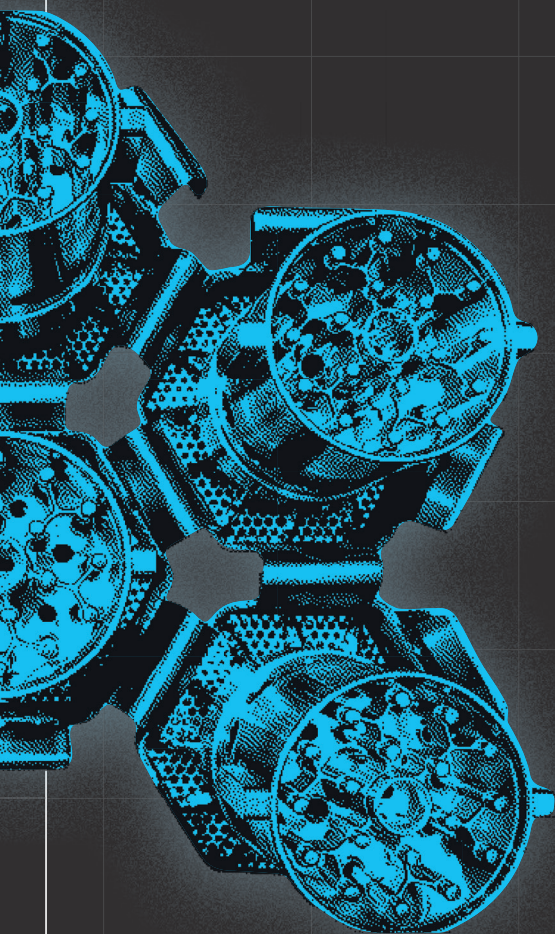
In the Russian Federation, uranium and plutonium recovered from SNF reprocessing are reused efficiently thanks to a multi-reactor energy system based on operation of VVERs, RBMKs and fast neutron reactors. Thus, reprocessed uranium is used in RBMK reactors, with the option to use it in VVERs in the future, while plutonium is used in fast neutron reactors (such as BN-800).

Uranium and plutonium recovered from foreign SNF can also be reused within the Russian NFC. By request of the Customer, the option of returning valuable nuclear materials to the Customer's NFC can be considered.



[09]

Can plutonium be used in fuel for VVER reactors?



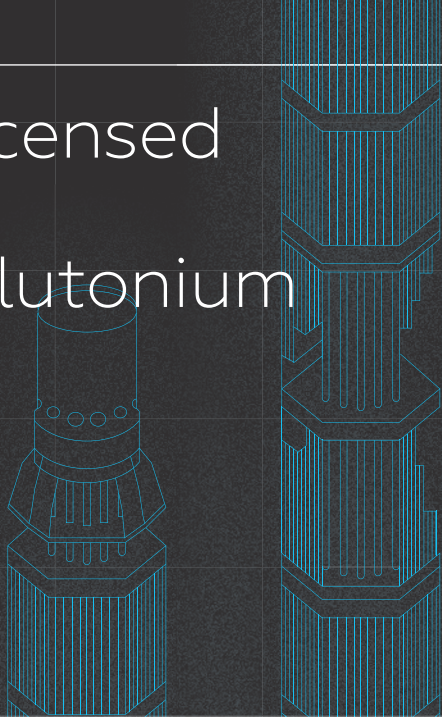
Yes, but its use must be feasible.

When deciding whether to load uranium-plutonium fuel into VVER type reactors, it is also necessary to consider the need for additional protective measures at the NPP (minimizing staff contact with fuel, using reinforced casks, etc.) and to license the plant to operate using the new fuel type.

The energy potential of plutonium is better realized in fast neutron reactors than in thermal neutron reactors. This is due to specific features of fast neutron reactor operation and of plutonium's interaction with fast spectrum neutrons.

How is NPP licensed to operate on uranium-plutonium fuel?

[10]

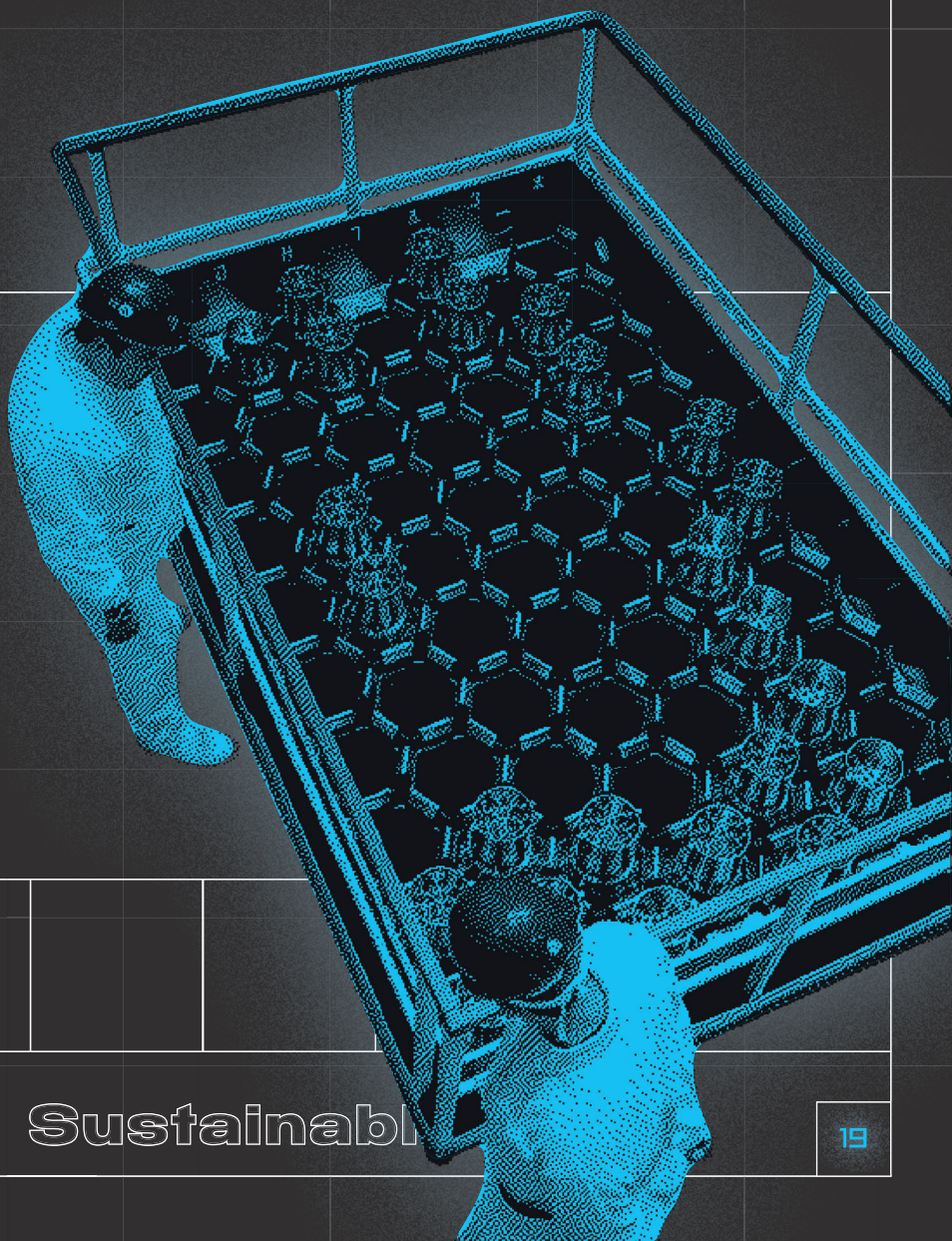
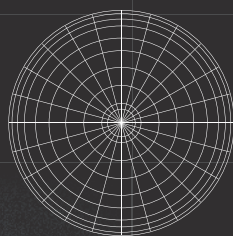


From a licensing perspective, uranium-plutonium fuel is a new type of fuel. Its use requires a programme of measures to demonstrate that it can be used safely in a specific reactor

Key stages include:

1. Calculations and simulation of fuel behavior in various conditions, supported by experimental data.
2. Tests in research reactors and pilot loading of small batches into power reactors.
3. Adapting the plant's fuel-handling systems to ensure unloading and transport of the fuel with minimal staff exposure.
4. Adjustment of reactor control and protection systems depending on the characteristics of the new fuel.

**The scope and nature
of the measures depend
on the reactor design
and the specific type
of uranium-plutonium fuel.**



Sustainable

[11] What are the minor actinides and how should they be managed?

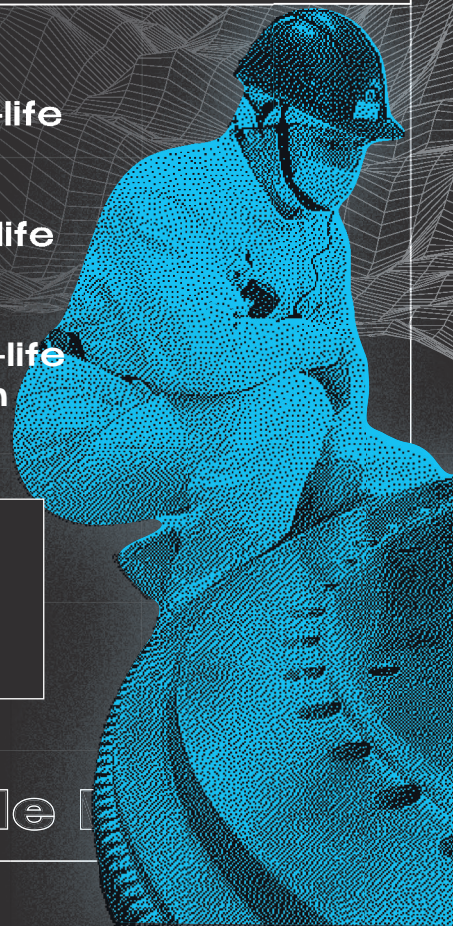
Minor actinides include americium (Am), neptunium (Np) and curium (Cm) which are the products of transmutation (conversion of one chemical element into another) of uranium and plutonium. In total they account for less than 0.1% of SNF, yet together with their decay products they determine the long-term radiological activity and heat release of SNF or RW from SNF reprocessing after about 300 years of storage.

432 years — the half-life of isotope ^{241}Am

2.1 years — the half-life of isotope ^{237}Np

15.6 years — the half-life of isotope ^{247}Cm

Their volume and radiological hazard can be reduced by converting them into other elements under neutron or proton irradiation — a process known as burning or transmutation.

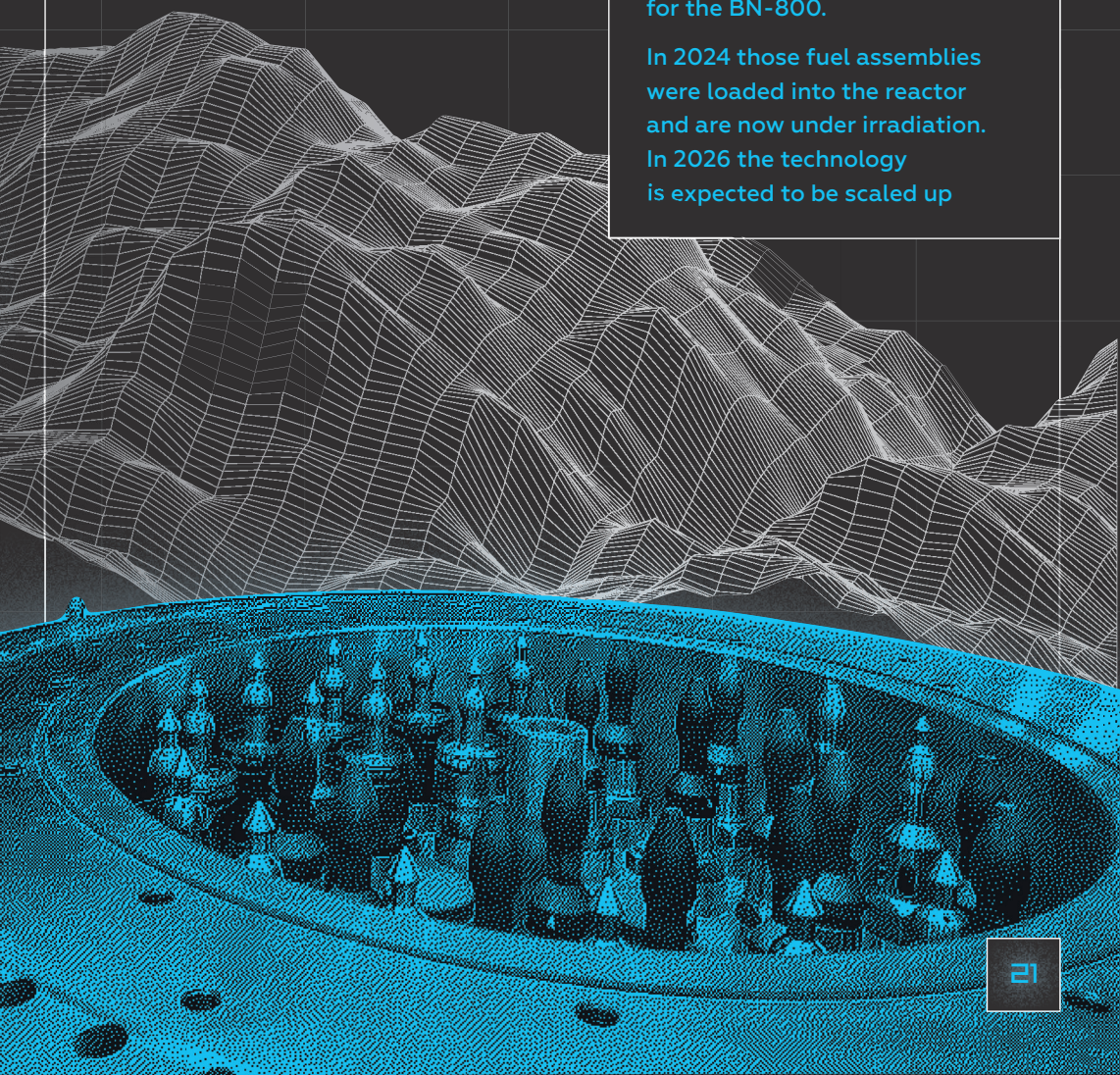


In the Russian Federation, minor actinides are transmuted in fast neutron reactors such as BN-600 and BN-800, new and advanced reactors including BN-1200M, BREST-300 and SVBR are also to be used for transmutation.

Americium and neptunium are transmuted on an industrial scale. Curium can be aged for 30 years until it naturally decays into plutonium, suitable for reuse as nuclear fuel.

In 2023, for the first time in the world, ROSATOM's industrial-scale equipment manufactured serial MOX fuel assemblies containing americium (0.9%) and neptunium (0.6%) for the BN-800.

In 2024 those fuel assemblies were loaded into the reactor and are now under irradiation. In 2026 the technology is expected to be scaled up



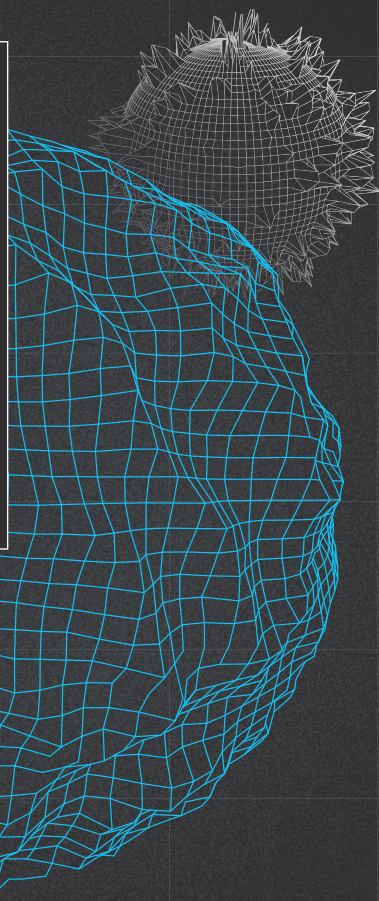
Do ROSATOM's spent fuel management solutions have a proven track record?

[12]

Absolutely.

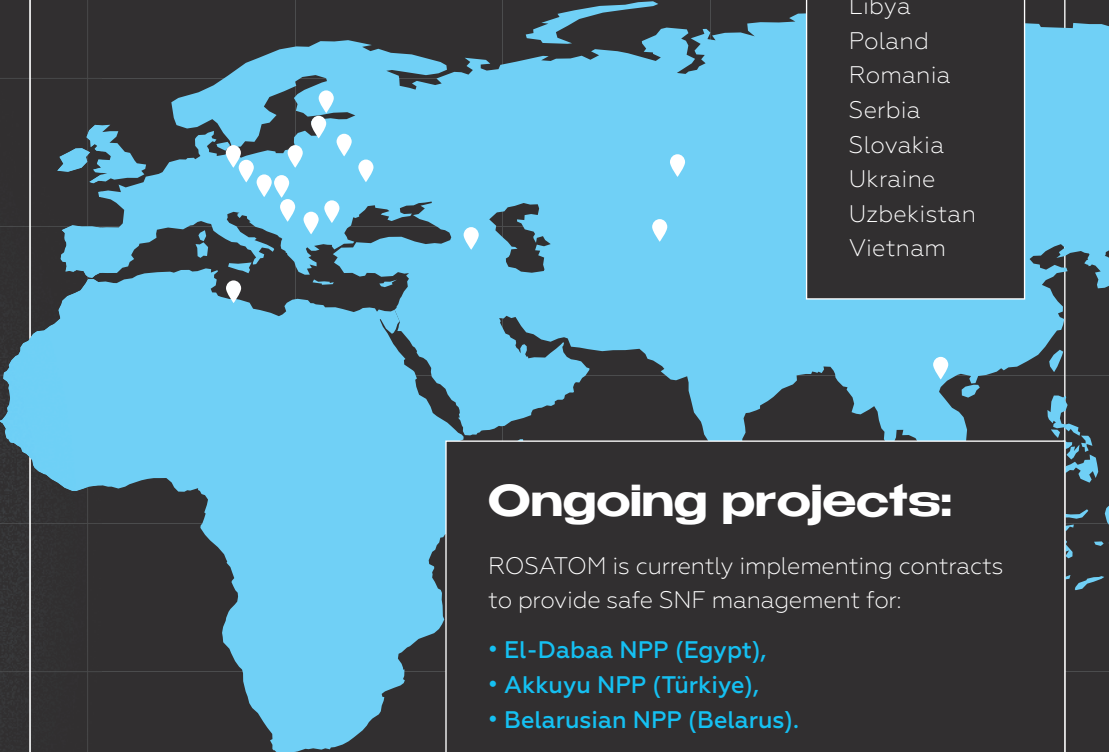
SNF reprocessing to ensure environmentally acceptable management of fission products with reprocessed nuclear materials returned to the NFC is the basis of the Russian Federation's national SNF management policy.

The Russian Federation operates a centralized SNF management system, and at two ROSATOM sites industrial-scale technologies for reprocessing and/or interim technological storage of SNF are already in place at two ROSATOM sites.



The Russian nuclear industry has significant experience in organizing shipment, reprocessing and other services in the field of SNF management for foreign NPPs and research reactors with Customers from the following countries:

Armenia
Belarus
Bulgaria
Czech Republic
Finland
Germany
Hungary
Kazakhstan
Latvia
Libya
Poland
Romania
Serbia
Slovakia
Ukraine
Uzbekistan
Vietnam



Ongoing projects:

ROSATOM is currently implementing contracts to provide safe SNF management for:

- El-Dabaa NPP (Egypt),
- Akkuyu NPP (Türkiye),
- Belarusian NPP (Belarus).

Under these contracts, Russian-designed NPPs are provided with the equipment and solutions necessary to ensure safe SNF and RW management throughout the entire lifecycle of the NPPs.

Sustainable NFC is an adjustable solution.

Whatever the size of the reactor fleet or the maturity of SNF management infrastructure in the Customer's country, the Sustainable NFC can be assembled to meet specific needs of each Customer as much as practical.

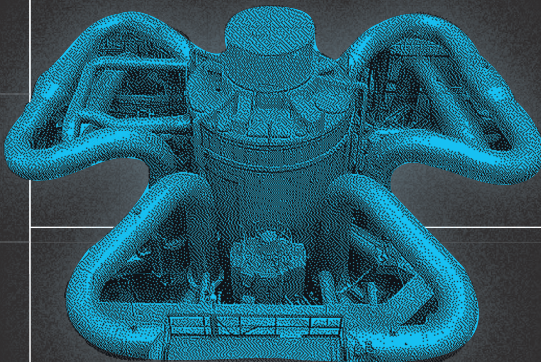
Sustainable NFC relies on reference solutions and advanced technologies, including:

- proven radiochemical solutions that enhance the efficiency and environmental performance of SNF reprocessing;

- RW fractionation, which allows to separate specific groups of elements and isotopes;

- RW medium-depth disposal technologies, including those within a single complex of disposal facilities for all RW generated throughout the NPP lifecycle;

- Generation IV fast neutron reactor systems that ensure feasible use of plutonium recovered from SNF reprocessing and reburning of minor actinides.



Sustainable NFC is cost-effective.

In an open fuel cycle, where SNF is sent for direct disposal without prior reprocessing, the Customer's costs include not only ongoing expenditures for long-term SNF storage, but also future costs of constructing an expensive deep geological repository – from site selection and safety analysis, public acceptance to construction, operation and monitoring of the disposal facility over a long period.

Adopting the Sustainable NFC removes the need to build such a facility. Even taking into account the cost of SNF transportation and reprocessing, implementing the Sustainable NFC does not increase the cost of electricity generation at an NPP as compared with the open fuel cycle. Additional savings come from the possibility of reusing valuable nuclear materials in the NFC.

Sustainable NFC with the open fuel cycle for a specific project can be carried out as part of a feasibility study ([see question No. 14](#)).

Sustainable NFC supports the UN Sustainable Development Goals



• Goal 7: Affordable and clean energy.

Sustainable SNF management increases attractiveness of nuclear energy as a clean and reliable source of energy.



• Goal 9: Industry, innovation and infrastructure.

The use of advanced technologies and engineering solutions at all stages of the SNF management lifecycle.



• Goal 12: Responsible consumption and production.

SNF reprocessing allows to reuse valuable nuclear materials.



• Goal 15: Life on land.

Minimizing the volume of waste sent for disposal.



• Goal 17: Partnership for the goals.

International cooperation with Customers at all stages of product development.

[14]

How can the Sustainable NFC be implemented in my country?

Regardless of the size of the reactor fleet or the current stage of development of the SNF management infrastructure, the following steps are recommended:

1. Feasibility study.

Analysis of international experience in the field of SNF management and its applicability to the situation in national context.

Comparison of SNF management options according to the selected parameters, starting with its unloading from the reactor core into the cooling pools, ending with the disposal of radioactive waste from SNF reprocessing.

Based on the results, recommendations are developed on the most optimal national SNF management option and the actions required to implement it.

2. National strategy for the management of SNF and RW.

Development or update of the national strategy for the management of SNF and RW, taking into account the results of the Feasibility Study.





3. Intergovernmental Agreement.

Conclusion of an intergovernmental agreement on cooperation in the field of SNF management with the Russian Federation in the development of the national strategy for SNF and RW management.

4. Foreign trade contracts for safe SNF management.

The conclusion and implementation of a foreign trade contract for safe SNF management with an authorized organization of the Russian Federation. The contract scope is defined on a case-by-case basis and may include: creation of a basic infrastructure for SNF/RW management in the country, shipment of SNF to the Russian Federation, its reprocessing, technological storage and return of HLW-SL to the Customer's country in a form that does not require a disposal in a deep geological facility. At the customer's request, and where feasible, the contract may also cover management of valuable nuclear materials recovered during SNF reprocessing.

[15]

What export options are available for sending SNF for reprocessing?

Scenario 1: Shipments as the spent fuel pool fills up.

- If there is a direct rail connection exists, SNF is shipped using Russian casks and railway transporters.
- In case of multimodal logistics (river/ sea plus rail), an NPP site needs to have a storage pad to be constructed (a start-up complex of the cask storage facility (CSF, [see question No. 6](#)) together with sufficient fleet of transport and transfer casks (TTC), typically 16-24 pieces (for a 2-4-unit NPP).

Scenario 2: Deferred shipments

- In case of complex logistics (for example, where transit through third countries is required) or where political decisions favour long-term SNF storage, a CSF needs to be constructed with SNF handling unit and storage modules, equipped with increase capacity storage casks (IC SC) and transport and transfer casks (TTC).

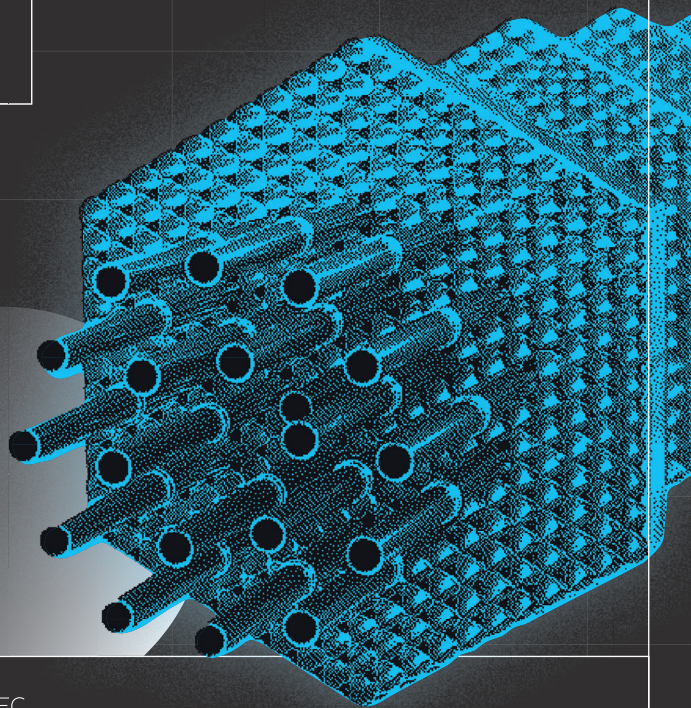
Both scenarios require the construction of an intermediate HLW-SL disposal facility ([see question No. 7](#)). It is recommended to integrate this facility with other national facilities aimed for disposal of operational waste and waste from NPP decommissioning to manage all the waste produced during NPP lifecycle at a single complex.

The preparation of the first SNF shipment to the Russian Federation for reprocessing may take up to 10 years, so preparation should start well in advance.

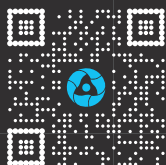
List of abbreviations

- **BN-600, BN-800** — fast neutron reactors with the sodium coolant
- **BREST-300** — natural safety fast neutron reactor with the lead coolant
- **CSF** — cask storage facility for casks loaded with SNF/HLW-SL
- **HLW-SL** — the «short-lived» fraction of high-level radioactive waste; mainly Sr-90 and Cs-137
- **IC SC** — increased capacity storage cask
- **MOX** — nuclear fuel containing several types of oxides of fissile materials, mainly — plutonium and uranium oxides
- **NFC** — nuclear fuel cycle
- **NPP** — nuclear power plant
- **PUREX** — Plutonium-Uranium Recovery by Extraction: technology for SNF reprocessing
- **RW** — radioactive waste
- **RBMK** — high-power channel-type light water reactor
- **REMIX** — nuclear fuel fabricated from plutonium and uranium recovered from SNF
- **SFA** — spent fuel assembly
- **SNF** — spent nuclear fuel
- **SVBR** — fast neutron reactor with the lead-bismuth coolant
- **TTC** — transport and transfer cask
- **U-Pu fuel** — uranium-plutonium fuel, for example, MOX fuel
- **VVER** — conventional light water reactor by ROSATOM

TENEX, JSC



- A leading global supplier of NFC products, successfully representing Russian nuclear industry on international markets for more than 60 years.
- Integrator of ROSATOM's international sales of goods and services related to the management of SNF and RW from its reprocessing.
- A company authorized by the Government of the Russian Federation to conclude international contracts related to the import of foreign reactors SNF to the Russian Federation for reprocessing.



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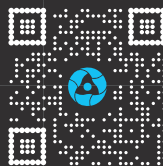
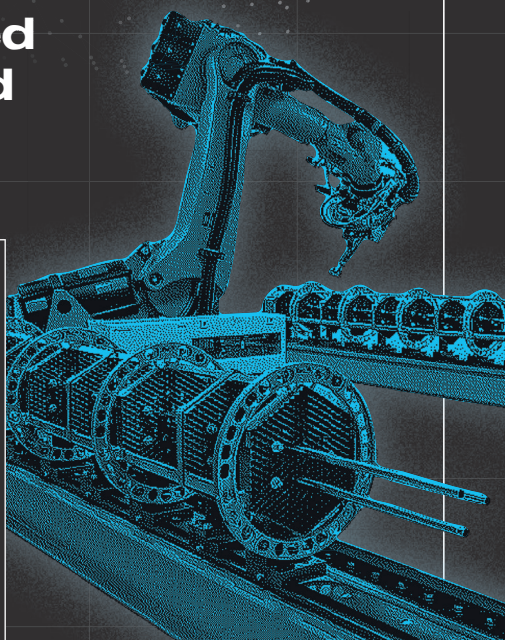
TENEX, JSC is your gateway to cutting-edge solutions for SNF management and NFC closure.

TVEL, JSC

Currently, every sixth power reactor outside the Russian Federation is powered by fuel manufactured by TVEL, JSC.

- One of the world's largest nuclear fuel manufacturers and an exclusive fuel supplier for all Russian NPPs, naval and research reactors, as well fuel components for NPPs and research reactors.

- Actively develops and introduces new nuclear fuel solutions to the global market, including fuel from regenerated uranium, accident-tolerant fuels, various types of plutonium-containing fuels, and high-density fuel for fast reactors, and others. The company also provides related services, including support in the process of fuel licensing by Customer's national regulator, operation support and fuel performance analysis, etc.



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Sustainable NFC



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