ROSATOM

SUSTAINABLE NUCLEAR FUEL CYCLE

ROSATOM State Corporation
product line

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Preface

Today, sustainable development became firmly established as one of the modern trends in the global economy. More and more companies organize their operation while striving to meet the evolving needs of people without detriment to the posterity and the planet's ecosystem. ROSATOM is also committed to this principle. Currently, Rosatom is the only company in the world that can offer a full line of services throughout the nuclear fuel cycle: from uranium mining, its enrichment and nuclear fuel fabrication to SNF packaging, transportation, reprocessing and recovered materials utilization. We develop all these components within the sustainability logic.

One of the Rosatom products meeting the sustainable development goals is the Sustainable Nuclear Fuel Cycle. Its objective is to handle spent nuclear fuel effectively and to use its reprocessing products rationally.

This product, along with the construction and operation of NPPs, will allow our customers to ensure clean energy production without leaving a nuclear legacy to the next generations. The solutions included into the Sustainable NFC are based on advanced technologies, such as SNF reprocessing with HLW partitioning, plutonium-containing fuel for fast neutron reactors, and minor actinide transmutation. I am confident that this product is a new stage in the development of the nuclear industry, which is the basis of the entire global low-carbon energy balance.

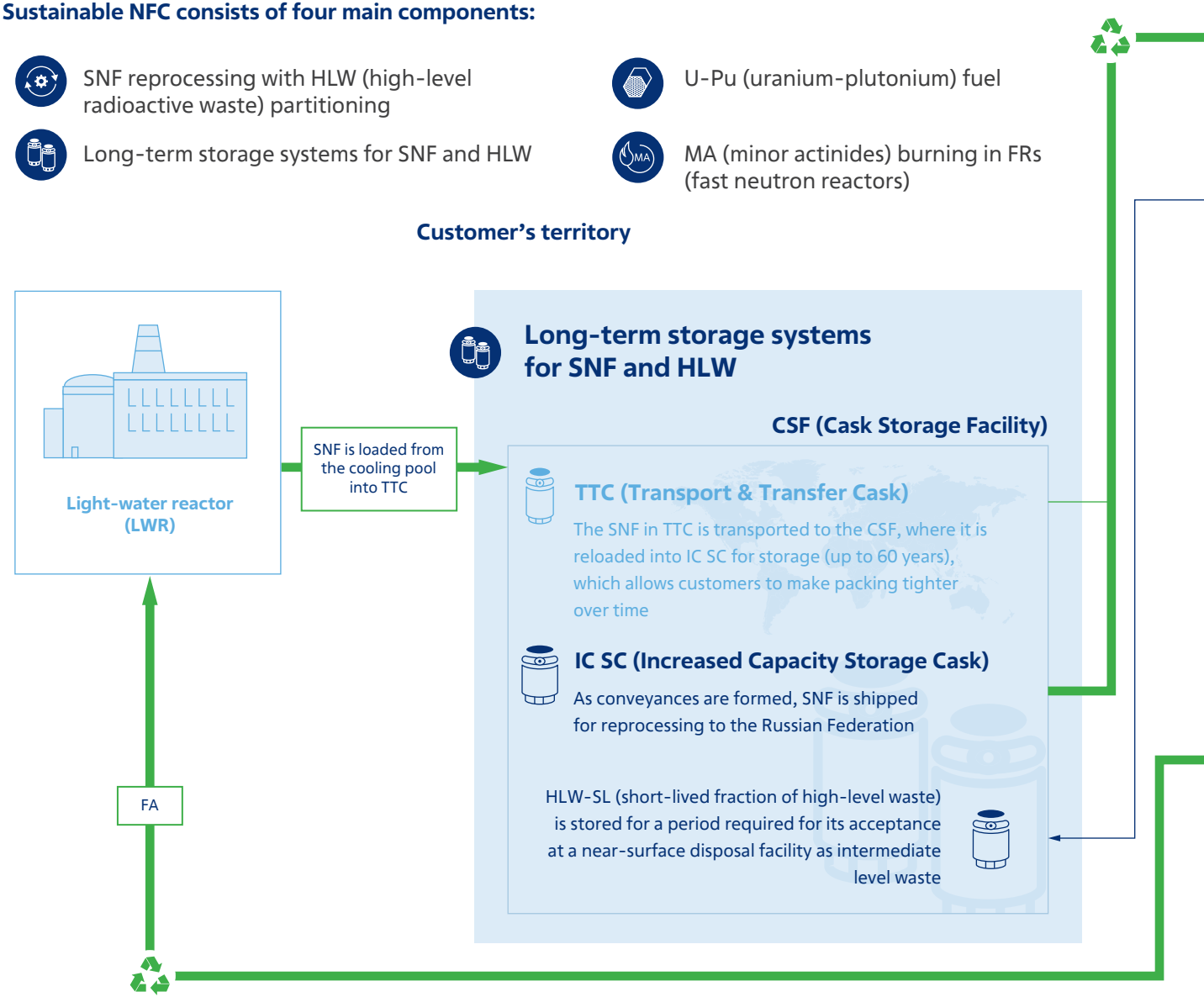
ALEKSEY LIKHACHEV
DIRECTOR GENERAL
OF ROSATOM STATE ATOMIC ENERGY CORPORATION

Sustainable Nuclear Fuel Cycle

The Sustainable Nuclear Fuel Cycle (Sustainable NFC) is a new product of ROSATOM State Corporation, which makes management of spent nuclear fuel (SNF) and its reprocessing products efficient and stable.

Sustainable NFC consists of four main components:

- SNF reprocessing with HLW (high-level radioactive waste) partitioning
- U-Pu (uranium-plutonium) fuel
- Long-term storage systems for SNF and HLW
- MA (minor actinides) burning in FRs (fast neutron reactors)



Territory of the Russian Federation

SNF reprocessing and HLW partitioning

SNF in IC SC

IC SC's neutron shielding is dismantled, the inner basket is replaced with a basket for HLW

HLW-SL in IC SC

HLW-SL is solidified, stored in the Russian Federation, and then returned to the customer

SNF reprocessing with HLW partitioning

MA

Minor actinides burning in FRs

Separation of Np, Am, Cm

Np and Am are included in the composition of fuel for FRs

Cm is stored until it decays to Pu, which is supplied to the fuel fabrication facility

RepU

Pu

SNF

MA Fuel Assemblies

Pu

U-Pu fuel

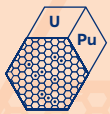
Additional purifying, enrichment and fuel fabrication

U-Pu fuel

RepU fuel

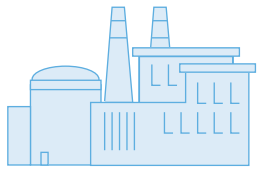
RepU/U-Pu fuel fabrication

For LWRs



For FRs

U-Pu fuel



Fast reactor NPP (FRs)

Fuel made of recovered nuclear materials is supplied to the customer. At the customer's request, Pu can be utilized in Russian FRs.

See p. 15 for terms and abbreviations

Sustainable NFC is a tailor-made product for each client based on unified solutions with reference

SNF reprocessing with HLW partitioning

- Radiochemical reprocessing of SNF with reprocessed uranium and plutonium recovering
- HLW partitioning with isolation of HLW-SL; returning HLW-SL to the customer
- Interim storage of long-lived fractions of HLW and temporarily unclaimed regenerated nuclear materials with the possibility of its use and transmutation

Long-term storage systems for SNF and HLW

- Development of infrastructure for interim SNF and HLW storage, long-term storage and/or final disposal of HLW-SL on the territory of the customer's country
- SNF transfer for reprocessing to the Russian Federation
- Interim storage of SNF in the Russian Federation until its reprocessing and HLW-SL until its return to the customer

U-Pu fuel

- Production and supply of fuel based on reprocessed uranium and plutonium
- Ensuring maximum recycling of nuclear materials in existing reactors

Minor actinides burning in FRs

- Separation of americium, neptunium, curium from HLW
- Fabrication of americium burnout elements (ABE) enabling placement of minor actinides in the reactor core
- Irradiation of the ABEs in FRs
- ABEs reprocessing with HLW conditioning

Sustainable NFC is chosen to:

MINIMIZE THE VOLUME AND RADIOACTIVITY OF WASTE
to be finally isolated at the deep geological repository and in some cases to exclude the need to construct such a facility

MAXIMIZE THE USE OF THE ENERGY POTENTIAL
of nuclear materials by its recycle

OPTIMIZE THE COSTS
of nuclear fuel cycle

PROVIDE A SUSTAINABLE MODEL
of production and consumption by permanently resolving the issue of SNF accumulation

Flexibility of Sustainable NFC:

allows client to obtain
exact set of solutions
to satisfy its specific needs

CASES

	Components demanded in the case
OPERATING NPPS WITH RESTRICTIONS FOR MODERNIZATION	
CONSTRUCTION OF THE FIRST NPP IN THE COUNTRY	
NUCLEAR PHASE-OUT	
ACTIVE DEVELOPMENT OF NUCLEAR POWER	

* based on RepU

SNF reprocessing with HLW partitioning

SNF reprocessing with HLW partitioning is a key element of a Sustainable NFC, which allows extracting and using valuable materials from SNF, minimize the amount of RW and isolate them as safely and efficiently as possible.

ROSATOM's institutes have over 100 years of experience in the development of applied radiochemistry and 50 years of experience in commercial SNF reprocessing. This experience has allowed ROSATOM to create solutions that fully meet modern environmental requirements, particularly in terms of secondary RW minimization. In addition, ROSATOM's enterprises involved in SNF reprocessing strictly comply with requirements for nonproliferation of nuclear fissile materials.

The volume of the customer's SNF transfer for reprocessing, as well as conditions of the HLW-SL return for isolation, is agreed with the customer, taking into account the readiness of its infrastructure.

300 000 Years

a minimum period of SNF radioactivity reduction to the level of uranium ore, if the SNF is disposed off without reprocessing

300 Years

a time of HLW-SL radioactivity reduction to the level of uranium ore

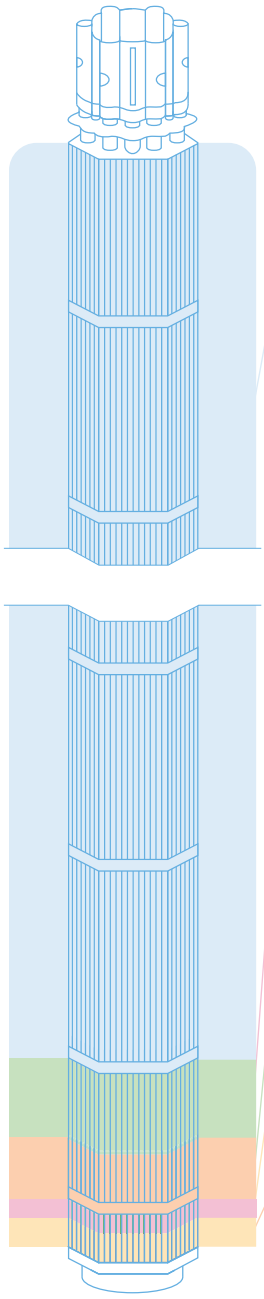
30 Years

an expected cooling time of HLW-SL before its shipment to the customer for subsequent disposal

5 times

reduction in volume of conditioned HLW containing only the short-lived fraction (implemented in the Sustainable NFC) compared to the volume of HLW that includes all fission products after SNF reprocessing

Fractions at SNF reprocessing



URANIUM - 96%

Used in the production of fuel for thermal neutron reactor (TR) NPPs after purification and enrichment.

Raw material for LWR fuel (instead of fresh U)

SHORT-LIVED FRACTION (HIGH LEVEL Cs, Sr) - 2.5%

Cesium-strontium fraction, which determines more than 95% of the activity and heat release of radioactive waste from SNF reprocessing in the first centuries. Cesium (Cs-137) and strontium (Sr-90) are used as raw material for the production of radioactive sources for further use, or placed in a stable inert matrix for final isolation in intermediate depth or near-surface disposal facilities.

Radioactive waste for compacting and disposal

PLUTONIUM - 1.2%

Used for production of nuclear fuel for light-water (LWR) and fast neutron reactors (FR)

Raw material for FR start-up, uranium savings for LWR.

MINOR ACTINIDES - Am 0.035%, Np 0.05%, Cm 0.006%

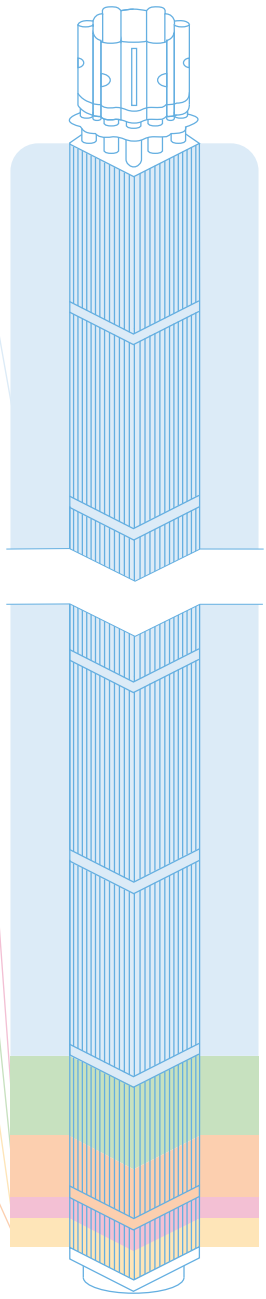
Transplutonium elements americium (Am), neptunium (Np) and curium (Cm).
Am and Np are to be burned in FRs as part of U-Pu fuel.
Cm has a significantly shorter half-life and is transmuted into plutonium during storage, which makes it possible to store it with subsequent use.

Am, Np — burnup in FR,
Cm — storage for 70 years before decay into Pu-238 (source for compact fuel cells)

Other fission products - (Zr, Al, Cr, Ni, Fe, Pb, ...) 0.15%

Other uranium and plutonium fission products belong to intermediate level RW are conditioned and sent for safe disposal, to be separated to ensure the most efficient packaging and storage/disposal of individual fractions.

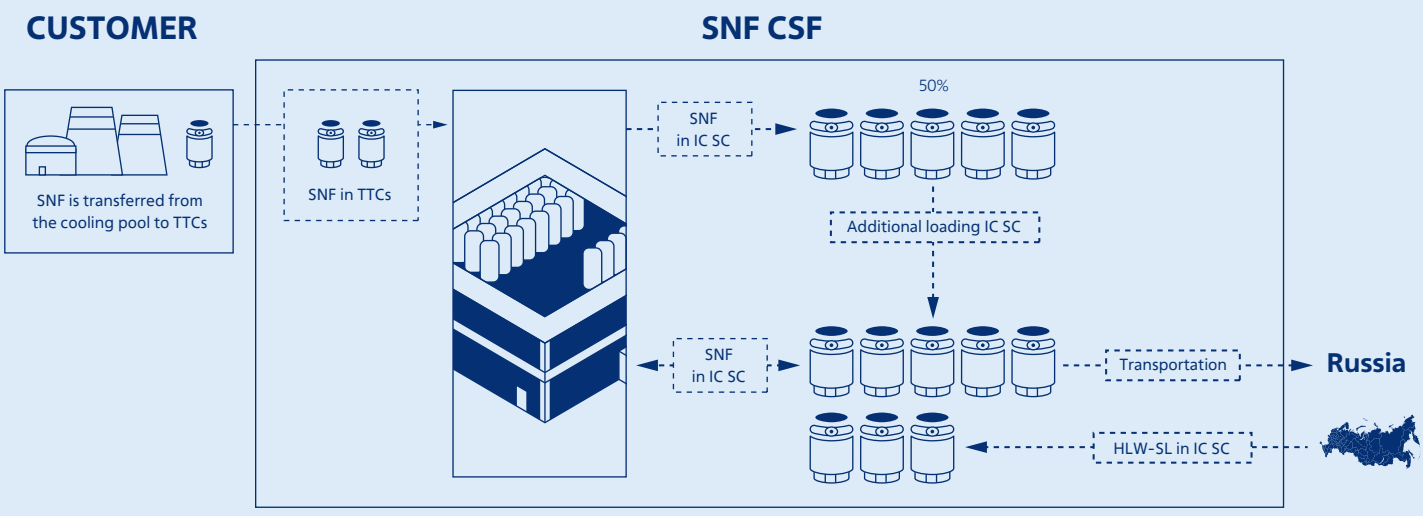
Intermediate level waste— compaction and disposal



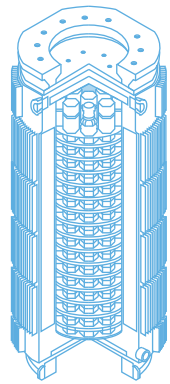
Long-term storage systems for SNF and HLW

Solutions of ROSATOM for transportation and long-term storage of SNF and HLW:

- prepare SNF for short-term storage and transportation to a reprocessing facility;
- provide long-term storage of SNF in the customer's country;
- do not require changes in case of switch to SNF reprocessing - the infrastructure being created on the territory of the customer allows handling of HLW-SL from SNF reprocessing;
- unified: the same cask can be used for SNF long-term storage in the customer's country, SNF transportation to the Russian Federation, return, storage and/or final isolation of the HLW-SL in the customer's country.



Transport & Transfer SNF Cask based on the TUK-137T family (TTC)



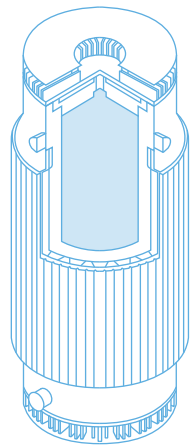
Application

- SNF unloading from NPP cooling pool and temporary storage until reloading to IC SC
- Multiple shipments of SNF for reprocessing

Characteristics

- 18 SFAs VVER-1000/1200/1300
- Multilayer cask body design in a stainless steel shell
- Maximum cask size (⌀2540 mm)
- Weight of loaded cask: 117 t

Increased Capacity Storage Cask for SNF and HLW (IC SC)



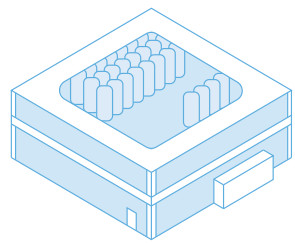
Application

- Long-term SNF storage (up to 60 years) in CSFs
- Single SNF transportation for reprocessing
- HLW-SL return to the customer and its long-term storage in the CSFs

Characteristics

- 30-32 VVER-1000/1200/1300 SFAs or 5.4-6.3 m3 of HLW
- Cask diameter is limited by the limits of rail transport
- Structural transformation (removable elements)
- Weight of loaded IC SC: less than 160 t
- Increased cask capacity and reduced storage costs

Cask Storage Facility (CSF)



Application

- Heat dissipation and protection of casks from climatic and external influences

Characteristics

- One unit - 16 TUK-137T.E (TUK-137T.R) and 38 IC SCs
- Possibility to attach additional units with 112-120 IC SCs

Casks for SNF and HLW storage and transportation fully comply with all IAEA safety requirements

U-Pu fuel

Uranium and plutonium are nuclear materials recovered from SNF that have significant energy potential. Its effective use is an important task in terms of responsible consumption and environmental safety.

ROSATOM offers a wide range of solutions for handling these materials:

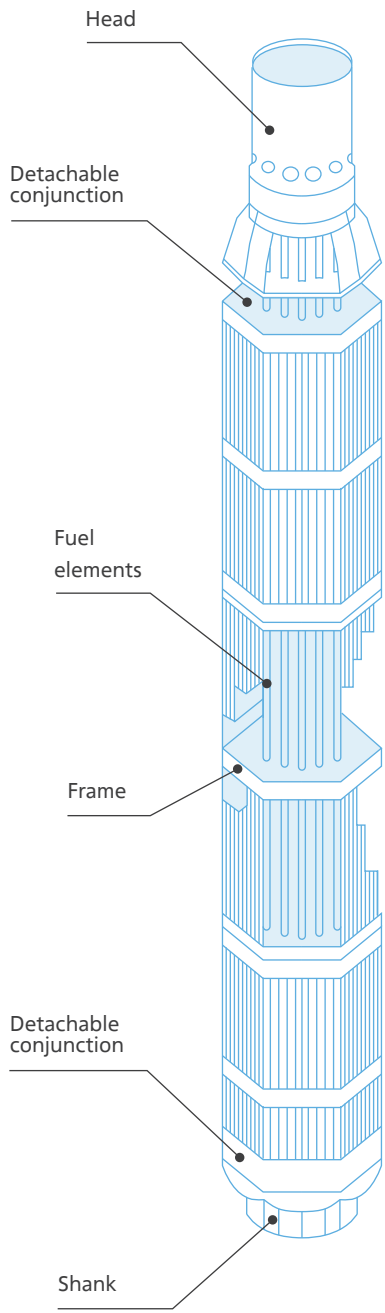
- purification and enrichment of reprocessed uranium with its subsequent use for the production of standard uranium fuel for light-water reactors (VVER, PWR, BWR)
- use of reprocessed uranium and plutonium as part of REMIX fuel for light-water reactors
- use of plutonium extracted from SNF in MOX fuel and mixed nitride uranium-plutonium fuel in FR
- assistance in licensing light-water reactors to operate with reprocessed uranium fuel and plutonium-containing fuel
- joint development of new fuel cycles with customers depending on the selected raw material

Uranium-plutonium fuel for LWRs is the most modern and advanced technology in the world. Russian uranium-plutonium fuel – REMIX, assumes 100% core loading and multiple recycle of nuclear materials. The efficiency of using natural resources proceedes to a new, previously inaccessible level.

ROSATOM is a high-tech company that owns breakthrough solutions and provides flexible conditions for the use of SNF reprocessing products - either they are loaded into the customer's NPPs or used in the fuel cycle of Russian NPPs.

Advantages of 5th generation fuel assemblies (FA-5) design for U-Pu fuel

- Remote assembly of a fuel rod bundle without the use of varnish, exclusion of liquid RW during fabrication
- Repair of a leaky fuel assembly after irradiation in reactor (removal of a failed fuel rod)
- Opportunity of disassembling FA after irradiation in the reactor (removable head, fuel elements/ fuel elements with gadolinium without attachment in the lower grid, removable shank)



UP TO 97%

of the SNF mass is made up of nuclear fissile materials that can be recycled

UP TO 1.5%

the amount of plutonium in REMIX fuel while maintaining the opportunity of multi-recycling

100%

of the core of a light-water reactor can be loaded with REMIX fuel

UP TO 32%

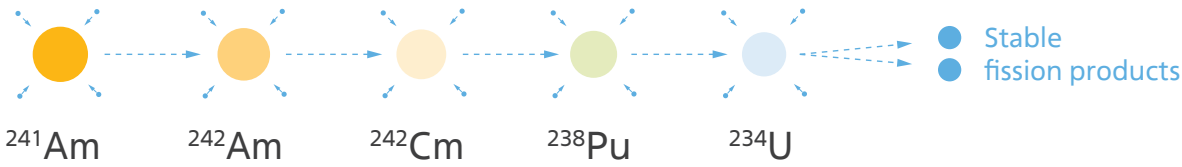
saving natural uranium when closing the NFC with REMIX fuel

Minor actinides burning in FRs

Minor actinides - americium (Am), neptunium (Np), curium (Cm) - are transmutation products of uranium and plutonium. Their total content in SNF is less than 1%.

ROSATOM proposes to utilize minor actinides by irradiating them in FRs. The reactors operated, constructed and designed by ROSATOM allow performing minor actinides industrial scale burning (transmutation).

This element of the complex proposal of ROSATOM makes the customers' NFC truly responsible and consistent with the UN sustainable development goals.



0.2 kg

Am is contained in 1 ton of SNF after 10 years of storage (after unloading from the reactor)

UP TO 24 kg

Am per year may be burned up in the BN-800 fast reactor

10 times

decrease in the amount of RW sent for disposal after partitioning of HLW and futher transmutation of minor actinides

Sustainable development

One of the most important conditions for the work of ROSATOM is to promote the implementation of the 17 UN Sustainable Development Goals. ROSATOM is a member of the UN Global Compact network, which brings together sustainable businesses around the world.

Nuclear energy is a clean and reliable source of energy with zero direct greenhouse gas emissions during generation and minimal emissions throughout the entire life cycle. The fundamental solution to the NFC back-end provides an additional contribution to the long-term demand for nuclear power.

The Sustainable NFC concept assumes that the most advanced technologies and innovative materials are used throughout the entire cycle of SNF, HLW and regenerated materials handling.
(Examples of such solutions are given on page 14).

The solution to the global problem of SNF accumulation is based on innovative recycling technologies. The reprocessing of SNF allows, inter alia, recycling valuable nuclear materials, thus providing a rational model of production and consumption.

Sustainable NFC provides international cooperation with customers and stakeholders at all the stages of product development.

ROSATOM and its institutions comply with all applicable international safety standards and requirements throughout the entire product life cycle. Suppliers are monitored for compliance with relevant requirements, including through audits.

According to the results of a study by the United Nations Economic Commission for Europe (UNECE), emissions from the life cycle of nuclear energy are the lowest in comparison with other types of generation (the average value is 5.5 g CO2 eq/kW*h).
Source: https://unece.org/sites/default/files/2021-10/LCA-2.pclf.

Innovative solutions

The Sustainable NFC is based on modern innovative technologies

Russia uses “third-generation” technologies in SNF reprocessing, which are characterized by the complete absence of liquid RW discharge into the hydraulic circuit - all process fluids used in SNF reprocessing are regenerated and reused without leaving the process scheme.

To separate individual liquid radioactive waste from the composition of high-level liquid RW, unique extraction agents and sorbents are used. Selecting these substances from a variety of chemical compounds and choosing the optimal operating modes of the equipment is the most difficult task that can be solved using computer modeling. Existing technologies make it possible to isolate minor actinides with a purity of 99.99% and even higher.

To minimize the radiation load on personnel during fabrication of plutonium-containing fuel, a fuel assembly and technology process have been developed that allow assembling a bundle of fuel elements remotely and without the use of varnish to exclude liquid RW formation during fabrication.

Transmutation of minor actinides is the most effective when exposed to FRs. Russia is the only country in the world that operates FRs with a capacity of 600 MW (BN-600) and 880 MW (BN-800) and has begun construction of a generation IV BREST-OD-300 reactor.

TTCs use a unique basket design that provides effective heat removal from high burnup SFAs (>50 GW-day/tU) and ensures nuclear safety using an innovative composite neutron-absorbing material.

IC SCs use a transforming design optimized for long-term storage, innovative materials and manufacturing technologies to ensure structural strength and corrosion resistance even when the IC SCs are disposed.

Basic terms and abbreviations

ABE

Americium-burnup element - a device for placing minor actinides in fast neutron reactors for the purpose of their burning (transmutation)

CSF

Cask Storage Facility

FA

Fuel assembly - nuclear fuel loaded into the reactor core for power generation

FRs

Fast-neutron reactors - reactors in which nuclear fission reaction is caused by neutrons, which have a higher energy than in traditional light-water reactors

HLW

High-level radioactive waste generated during SNF reprocessing and requiring increased safety measures (shielding and heat removal)

HLW-SL

Short-lived fraction - cesium and strontium recovered from HLW - elements from the SNF composition that have the highest heat release and radioactivity during the first 300 years after SNF is unloaded from the reactor

IC SC

Increased Capacity Storage Cask for SNF and HLW

LWR

Light-water reactors - PWR, BWR, VVER

MA

Minor actinides are long-lived radioactive Am, Cm, Np isotopes, formed in nuclear fuel during reactor operation. As a part of HLW they have the greatest heat release and radioactivity after 300 years from the moment of SNF unloading from the reactor

NFC

Nuclear fuel cycle - a set of operations ensuring the fabrication and delivery of fuel for nuclear reactors, and the management after its removal from the reactor

SFA

Spent fuel assembly - fuel assembly unloaded from the reactor, which further use is not foreseen

SNF

Spent nuclear fuel - fuel irradiated in the reactor core

TTC

Transport & Transfer Cask

REMIX FUEL

Uranium-plutonium fuel containing relatively small amount of Pu and RepU

RW

Radioactive waste - waste containing radioactive substances in quantities exceeding the established standards and not subject to further use

TRs

Thermal - neutron reactors – nuclear reactors where uranium and plutonium fission is caused by neutrons with relatevely low energy. All LWR and PHWR reactors belong to TRs type

About ROSATOM companies

On behalf of ROSATOM, TENEX and TVEL are responsible for the implementation of the Sustainable NFC concept as a complex product, as well as its components

TENEX

One of the world's leading suppliers of nuclear fuel cycle products. For about 60 years it has been successfully representing Russian nuclear industry on the world market.

Core businesses of TENEX are the supply of uranium products, full range of logistics services (ensuring the supply of NFC products), as well as goods and services in the field of SNF and RW management. In particular, the company organizes reprocessing of foreign SNF in the Russian Federation and actively developes engineering, allowing adaptation of SNF and RW management solutions to the requirements of a particular customer. Throughout history, customers from 20 countries have used goods and services in the field of SNF management from the Russian suppliers.

tenex.ru

TVEL

TVEL is one of the world's largest producers of nuclear fuel. It is fuel supplier to all Russian NPPs, naval and research reactors, as well as fuel and its components supplier to NPPs and research reactors around the globe. Currently every sixth power reactor in the world operates on fuel manufactured by TVEL.

Currently, TVEL actively develops and presents on the world market some new solutions in the field of nuclear fuel, including fuel made from reprocessed uranium, accident tolerant fuel, various types of plutonium-containing fuel, high density fuel for fast reactors and others. The company also provides related services, including support for fuel licensing in the national regulatory bodies of the customer, operation support, fuel justification, etc.

tvel.ru

The team developing Sustainable NFC also includes PA Mayak, MCC, LC NFC, RFNC-VNIIEF, Afrikantov OKBM, Proryv, VNIINM, SKhK, MSZ, NZHK, Khlopin Radium Institute, SSC RF-IPPE, Concern Rosenergoatom and other companies of the Russian nuclear industry.