Technical Meeting on the Management of Spent Fuel (Pebbles and Compacts) from High Temperature Reactors,
7 – 11 July 2025
IAEA, Vienna

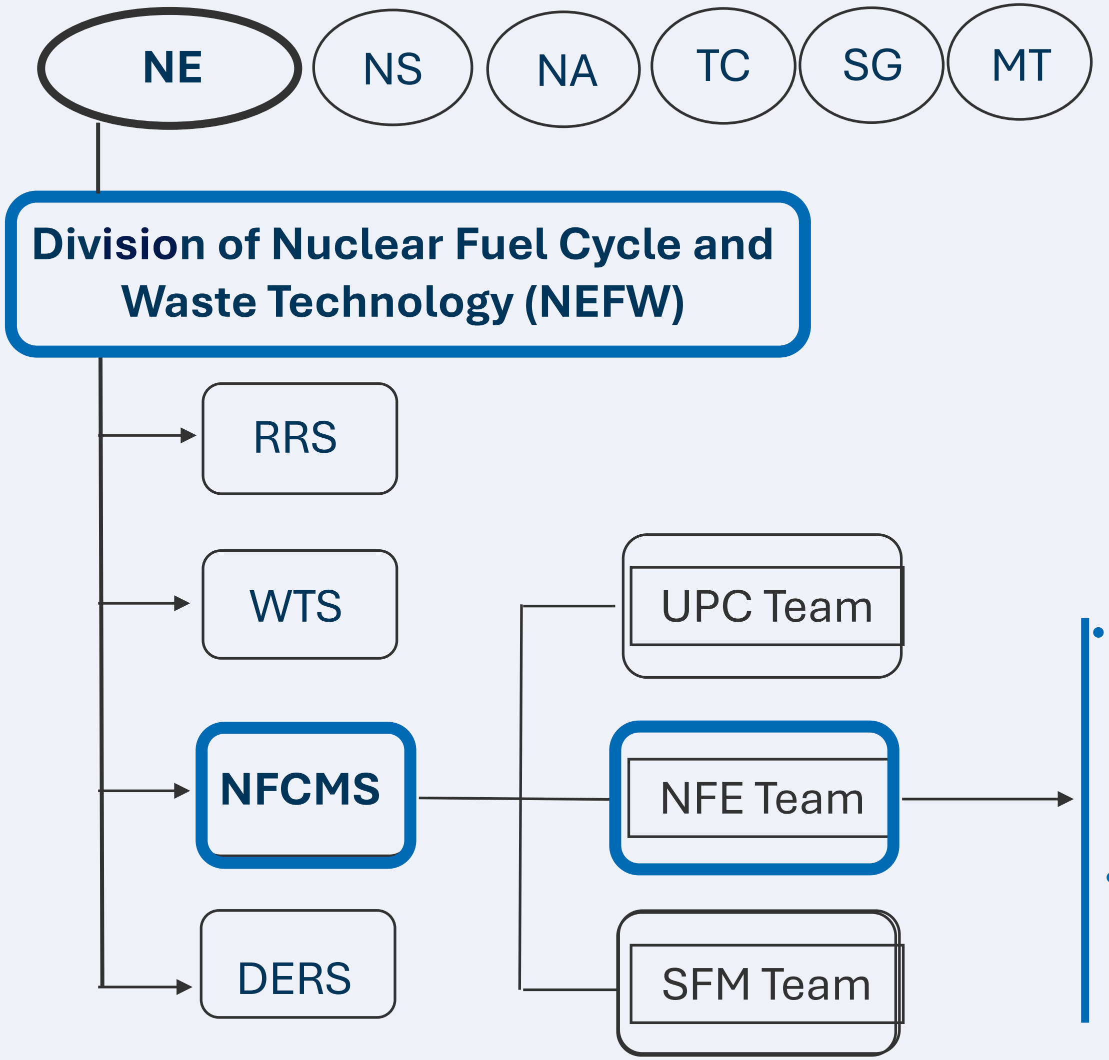
IAEA Activities on HTR Fuels

Anzhelika Khaperskaia,
Technical Lead (Fuel Engineering and Fuel Cycle Facilities)

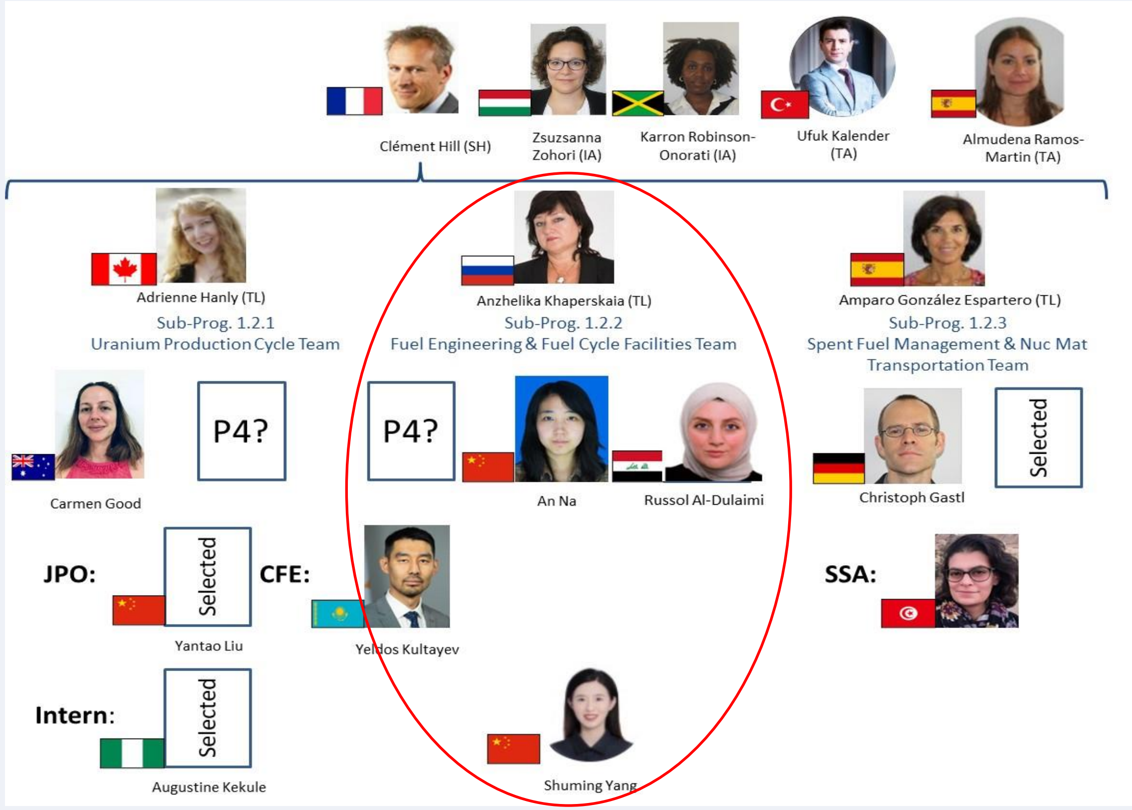
NFCMS /NEFW, IAEA

IAEA's Organization

Department of Nuclear Energy



Nuclear Fuel Cycle and Materials Section (NFCMS)



- **Project 1.2.2.001 Nuclear Power Reactor Fuel Engineering and Operation:** Support Member States (MSs) to understand and address factors affecting the design, fabrication and in-pile behaviour of currently operating and innovative nuclear fuels and materials for power reactors.
- **Project 1.2.2.002 Fuel Cycle Facilities Operation and Life Management :** Support MSs to technically implement IAEA Safety Standards when operating or upgrading existing nuclear fuel cycle facilities, and to understand and address factors affecting the ageing of these facilities

IAEA Sub-Programme 1.2.2: Nuclear Power Reactor Fuel and Fuel Cycle Facilities

Objectives:

- Support Member States (MSs) to understand and address factors affecting the design, fabrication and in-pile behaviour of currently operating and innovative nuclear fuels and materials for power reactors.
- Support MSs to technically implement IAEA Safety Standards when operating or upgrading existing nuclear fuel cycle facilities, and to understand and address factors affecting the ageing of these facilities.

Through:

- Organizing IAEA meetings and developing IAEA publications
- Coordinating research activities (CRPs)
- Maintaining databases (NFCFs, PIE: Integrated Nuclear Fuel Cycle Information System - IAEA INFCIS), IAEA Fuel and material database (The IAEA Fuel and Material Database - IAEA Data Platform) and NFC simulation tools (NFCSS: Nuclear Fuel Cycle Simulation System (NFCSS))
- Developing e-Learning Materials on nuclear fuel: OPEN-LMS: All courses
- Building up Networks among experts (NFE-Net, FCF-Net): Pages - NFE Net, Fuel Cycle Facilities Network - Home
- Supporting the IAEA Technical Cooperation Programme

To foster collaboration and information exchange, provide reference data, preserve knowledge, and capacity building

Advised by Technical Working groups (TWGs comprising of 20 Members + Observers):

- The TWG on Fuel Performance and Technology (TWG FPT) is a group of recognized experts from MSs providing advice to DDG-NE and supporting programme implementation, reflecting a global network of excellence and expertise in nuclear power reactor fuel engineering
- The TWG on Fuel Cycle Facilities (TWG FCF) is a group of recognized experts from MSs providing advice to DDG-NE and DDG-NS and supporting programme implementation, reflecting a global network of excellence and expertise in NFCFs operation areas

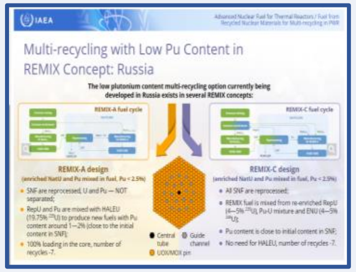
IAEA ongoing activities to support the development of Water-Cooled Reactor fuels

Accident Tolerant Fuels

- **CRP T12032** on “*Testing and Simulation of Advanced Technology and Accident Tolerant Fuels* (ATF-TS)” (2020-2024)
- TM on “*Advanced Technology Fuels: Progress on their Design, Manufacturing, Experimentation, Irradiation, and Case Studies for their Industrialization, Safety Evaluation, and Future Prospects*” (28-31 October 2025)

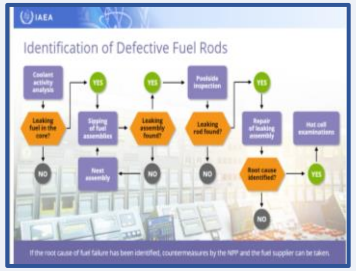
Fuels for recycling/multi-recycling

- TECDOC on “*Mixed Oxide Fuels Design, Operation and Management*” (in preparation to publishing)
- IAEA publications on “*Challenges and Opportunities in Reprocessed Uranium Fuels*” (TECDOC in progress)



Conventional Water-Cooled Reactor fuels

- TECDOC on “*Review of Fuel Failures in Water Cooled Reactors (2016–2020)*” (under internal review)
- TECDOC on “*Advances in Nuclear Fuel Fabrication Technologies for Power Reactors*” (in preparation to publishing)
- TECDOC on “*Structural Behaviour of Fuel Assemblies in Water Cooled Reactors*” (under MSs review)
- TM on “*Advances in Fuel Design, Manufacturing and Examinations for Pressurized Heavy Water Reactors*” (November 2024, Argentina) (TECDOC in progress)

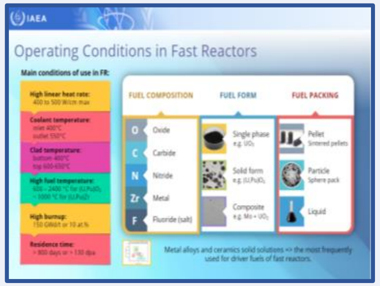


IAEA ongoing activities to support the development of innovative GEN-IV and SMR fuels

Water-cooled SMR fuels

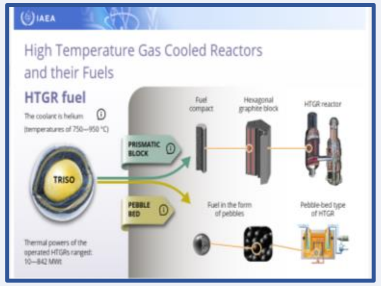
- Workshop on "*Core and Plant Simulation with an Emphasis on* ***Fuel Behaviour in Light Water Reactor Based Small Modular Reactors***" (27-29 February 2024, TECDOC, in progress)

Fast reactor fuels



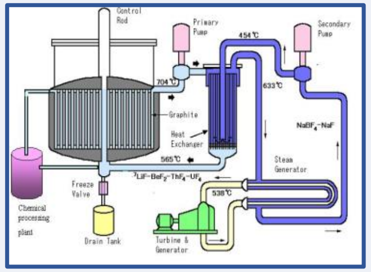
- **CRP T12031** on "*Fuel Materials for Fast Reactors (FMFR)*" (2019-2023: Final report in preparation to publishing)
- NES Technical Report on "*Nuclear Fuel Technologies for Liquid Metal Cooled Fast Reactors (LMFRs)*" (in preparation to publishing)
- Workshop on the "*Behaviour of Liquid Metal Cooled Fast Reactors Fuels*" (30 June – 04 July 2025)

Gas-cooled SMR fuels



- "*Coated Particle Fuels for High Temperature Gas-Cooled, Small Modular Reactors – Progress in Design, Manufacturing, Experimentation, Modelling and Analysis Technologies*" (*just published* **IAEA-TECDOC-2090**)
- **CRP T12034** on "*Fuel Modelling Exercises for Coated Particle Fuel for advanced reactors including SMR*" (open for proposals)

Molten salt SMR fuels

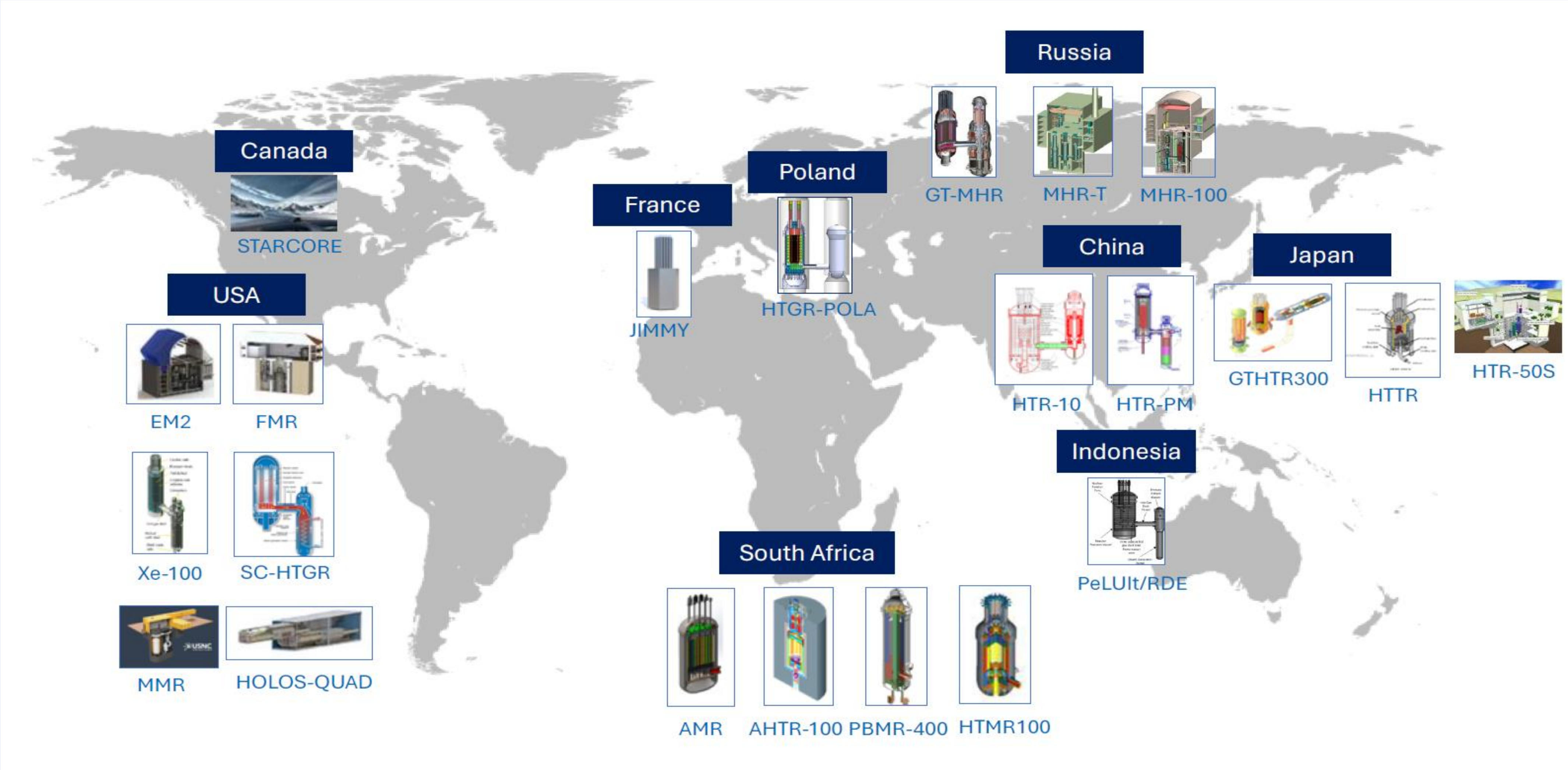


- New Simulation tool module development for MSR with relevant fuel cycle
- Workshop on "*Molten Salt Reactor Fuel: Recent Development and Future Challenges*" (21-25 July 2025)

PIE for SMR fuels

- **CRP T12033** on "*Standardization of Subsized Specimens for Post-Irradiation Examination and Advanced Characterization of Fuel and Structural Materials for Small Modular Reactor and Advanced Reactor Applications* (PIE for SMR)" (open for proposals)

Global Activities on HTR-SMR development



TRISO Particle Fuel Design and Performance

TRISO fuel consists of U/Th/Pu-bearing particles coated with ceramic layers, forming tiny pressure vessels that retain fission products and remain stable under high temperature and radiation.

TRISO-Coated Particle Structure (Tristructural Isotropic)

1.Kernel

1. Primary barrier to FP release
2. Addition of carbon acts as an oxygen "getter"

2.Buffer layer *(low-density pyrolytic carbon)*

1. Accommodates kernel swelling during irradiation

3.IPyC (Inner Pyrolytic Carbon) layer

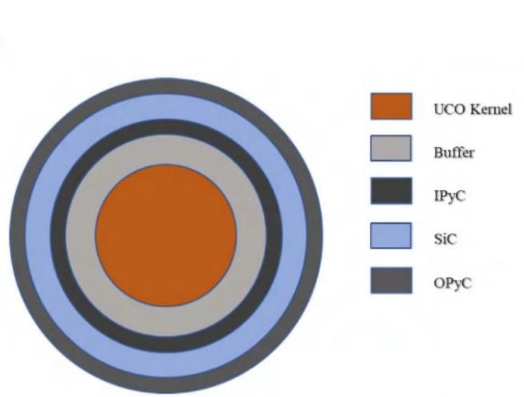
1. Acts as a barrier to prevent CO gas and FPs from reaching the SiC layer

4.SiC (Silicon Carbide) layer

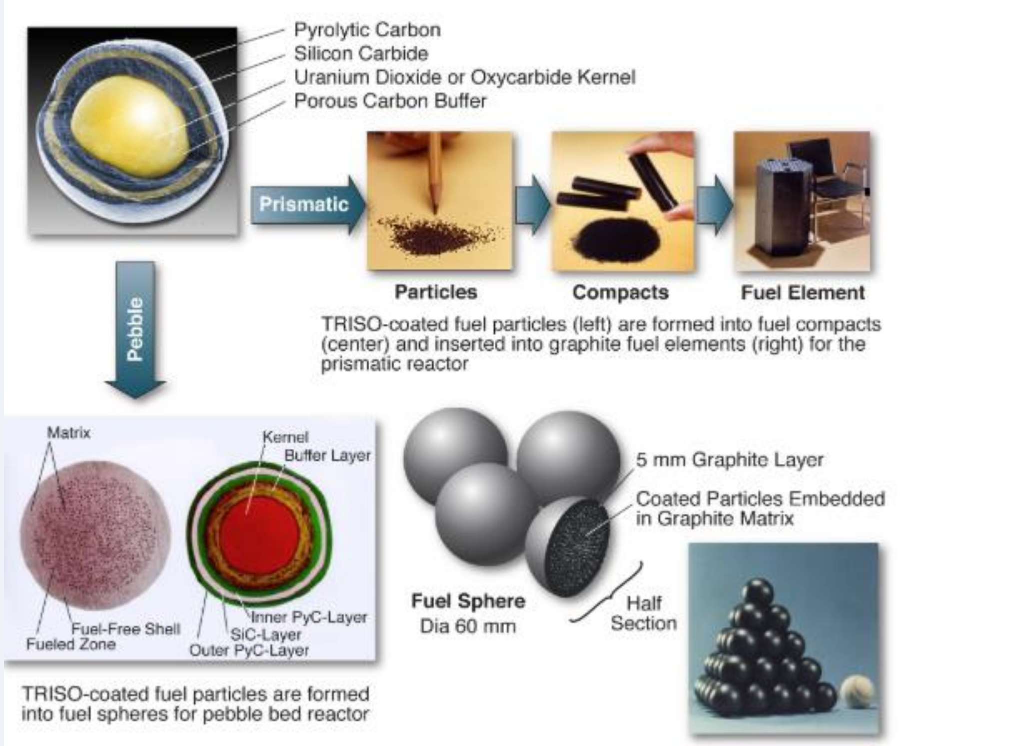
1. Provides structural integrity for the TRISO particle
2. Responsible for retention of most FPs

5.OPyC (Outer Pyrolytic Carbon) layer

1. Protects the SiC layer from physical damage during handling and compacting
2. Provides the final barrier in the particle for fission product retention



Tristuctural Isotropic (TRISO)-coated particle



TRISO particles are imbedded a non-fissile matrix material to form a fuel of some geometry such as a sphere (pebble), circular cylinder (prismatic), or rectangular solid.

HTRs fuel types

Kernels are mechanically decoupled from the outer coating layers, giving great flexibility in kernel types

UC_2, UO_2, UCO, PuO_2

$(Th,U)C_2$, ThC_2, $(Th,U)O_2$, ThO_2

LEU UO_2 is most widely used fuel type:

Used in AVR (Germany), HTTR (Japan), HTR-10 and HTR-PM (China)

Extensive irradiation and heating test database from German HTGR Program

UCO fuel is judged as the better fuel of choice for higher burn-ups and tends to produce minimal CO

UO_2 has the highest retention of metallic fission products

Kernel	*Advantages*	*Disadvantages*
UC_2	*- No CO formation (minimum internal gas pressure)* *- Highest U loading* *- Insignificant kernel migration* *- High burnup potential*	*- Hydrolysis when exposed to H_2O with increased fission product release* *- Fabrication requires very high temperatures* *- Lowest retention of metallic fission products* *- La release enhances SiC corrosion*
UCO	*- Negligible CO formation* *- Good retention of metallic fission products* *- Retention of La reduces SiC corrosion* *- Less susceptible to hydrolysis than UC_2* *- High burnup potential*	*- More difficult to manufacture* *- Control of kernel stoichiometry is required* *- Release of Eu, Ce and Sr fission products*
UO_2	*- Highest retention of metallic fission products* *-Most resistant to hydrolysis* *-Easy fabrication by sol-gel process*	*- CO formation (maximum internal gas pressure)* *- Lowest U loading* *- Highest kernel migration* *- Apparent burnup limit*

Ceramic Core : Fuel Based Safety

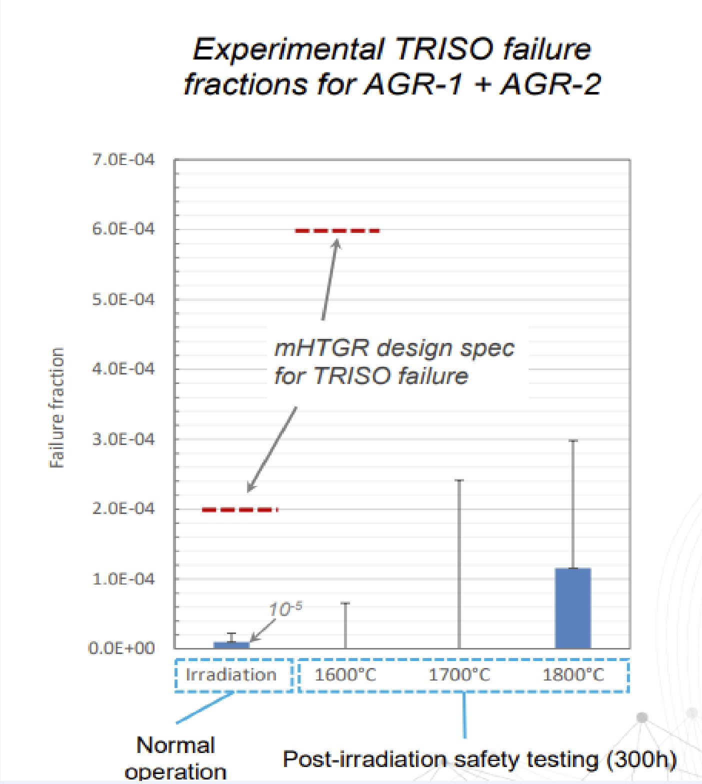
Backed by over 60 years of development, **TRISO fuel particles are considered the most robust nuclear fuel due to their multi-layered coating, which retains fission products under all reactor conditions.**

- Very low in-pile particle failure rates

- Fuel withstands temperatures of 1600°C and beyond for hundreds of hours without significant TRISO failure

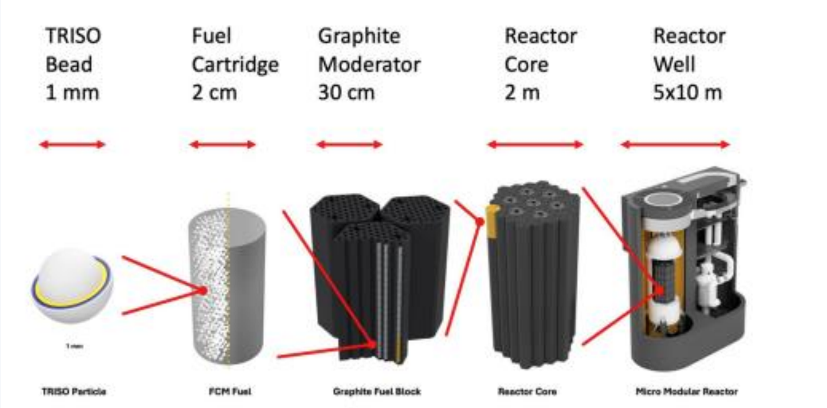
- Release of condensable fission products is dominated due to their accumulation in the matrix and gradual degradation of the SiC layer

- There is significant performance margin in terms of time at temperature



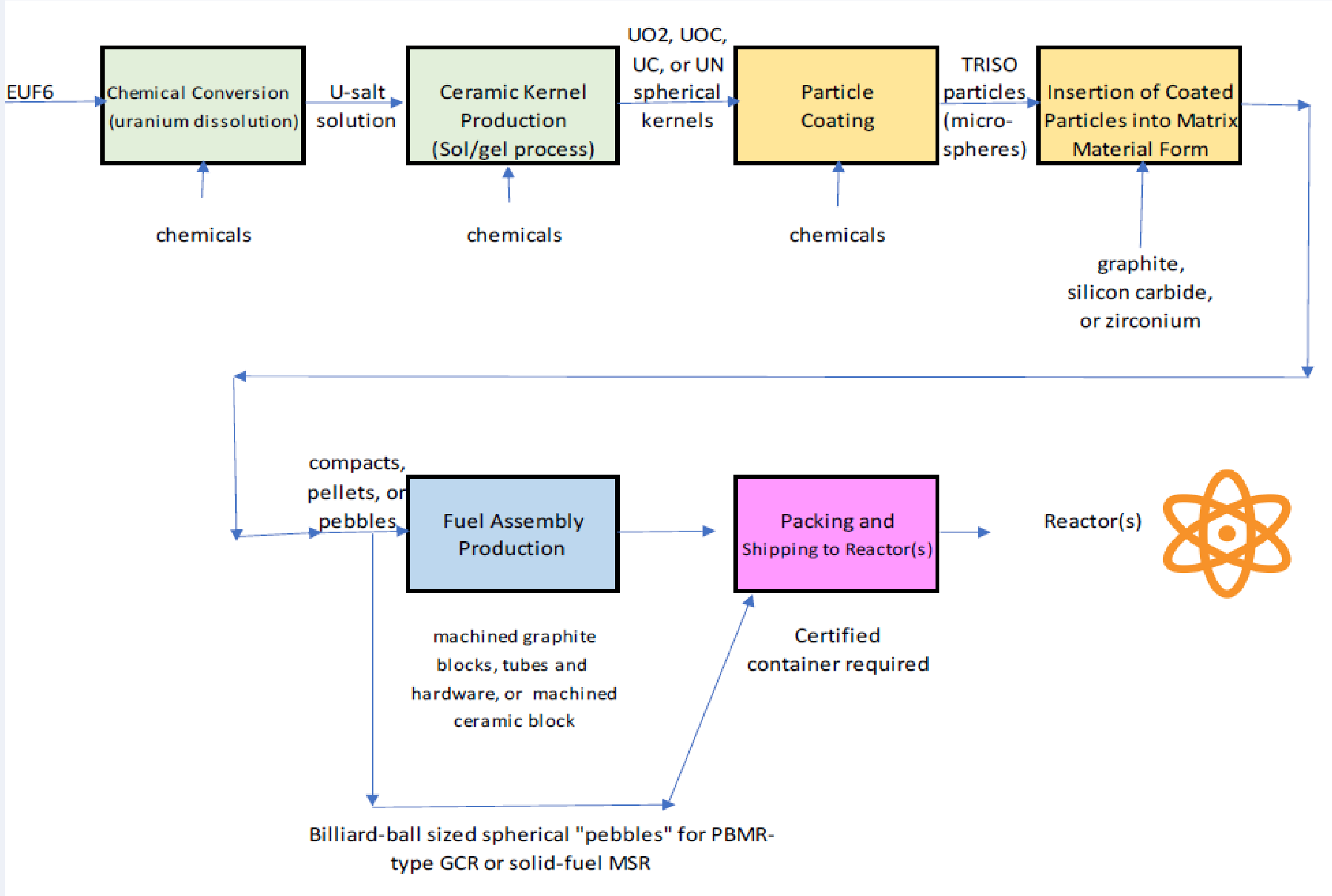
Fully Ceramic Microencapsulated (FCM) fuel enhances safety by embedding TRISO particles into a dense silicon carbide (SiC) matrix.

Additive manufacturing can be used to produce SiC shells (cylindrical or annular), filled with TRISO particles and sealed with additional SiC for strength.

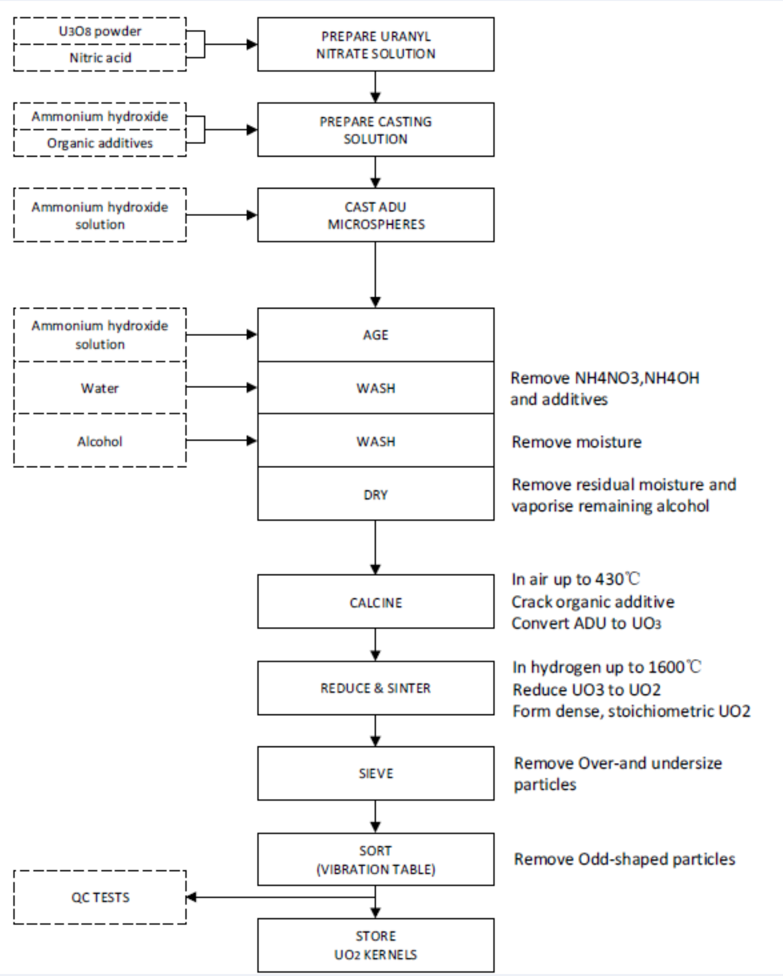


Modular assembly of components to form **Kronos MMR**

TRISO fuel manufacturing



Generic Process Steps for Particle Fuel Fabrication (not specific to a particular reactor technology)

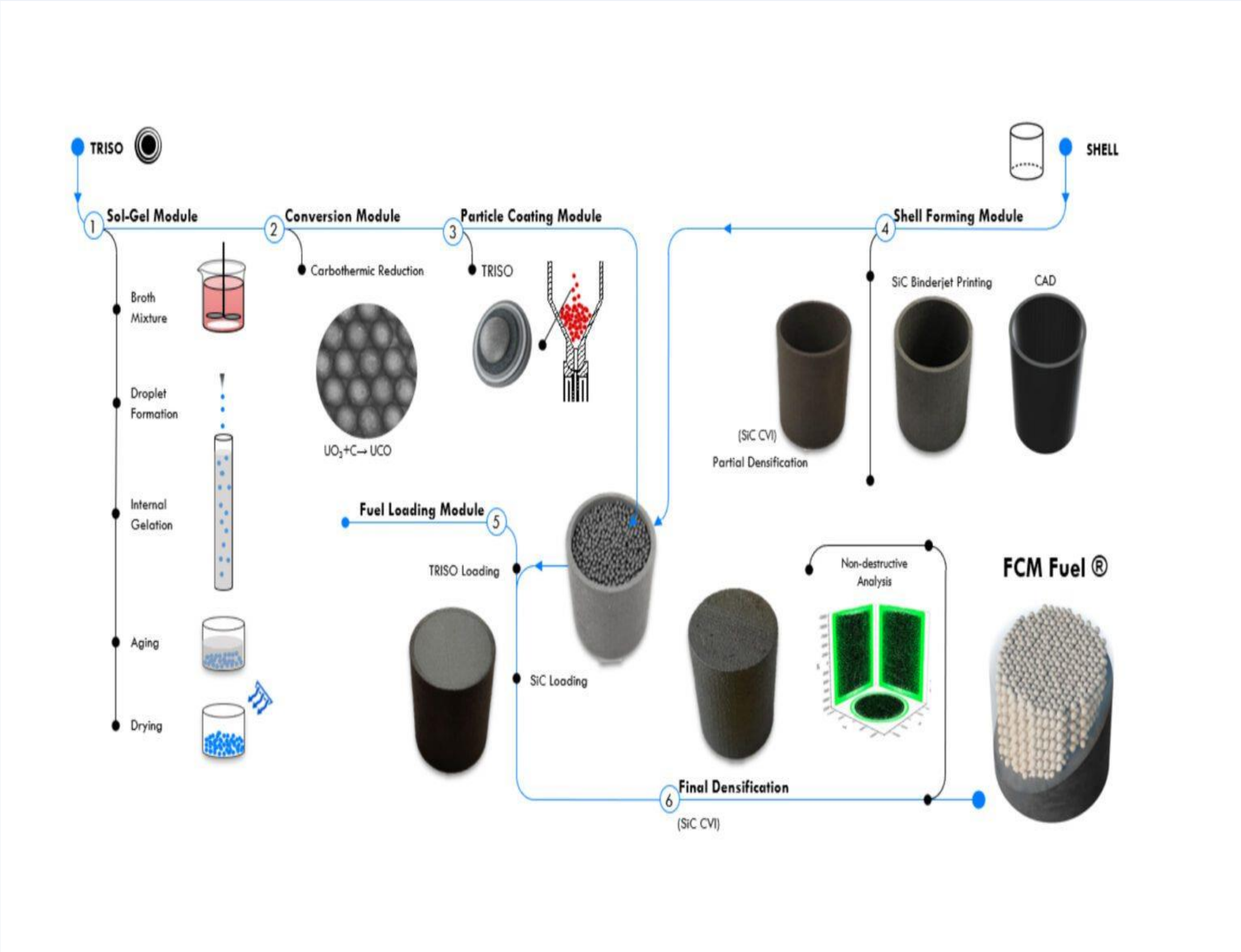


Illustrative flow diagram of the external sol-gel process for kernel fabrication

TRISO fuel fabrication is a process that has matured over the last 50 years

Key technologies: Sol-gel for kernels ; Fluid- bed chemical vapor deposition for coatings, the press technology for both sphere fuel and compact

TRISO Fuel Producers: Key Players



TRISO and FCM manufacturing process. *Courtesy: Ultra Safe Nuclear*

- **Baotou, China:** The world's main HTR fuel fabrication plant, producing 300,000 fuel pebbles per year (~ 3 teU/yr fuel) for the HTR-PM reactor and plans to expand capacity to 3 000 000 FE/annum
- **Nuclear Fuel Industries Ltd (NFI), Japan** has a 400 kgU/yr HTR fuel production capacity at Tokai.
- **X-energy's TRISO-X Fuel Fabrication Facility (USA):** Located in Oak Ridge, Tennessee, facility is set to be operational by 2025 and will initially produce 8 teU/yr, with plans to expand to 16 teU/yr of TRISO fuel by the early 2030s.
- **BWXT's TRISO Production Facility (USA):** BWX Technologies is expanding by 100kgU/yr its qualified "UCO" TRISO fuel production line in Lynchburg, Virginia, with plans for both near-term capacity increases and longer-term upgrades.
- **USNC's (currently -Standard Nuclear) Pilot Fuel Manufacturing (PFM) facility USA :** has demonstrated modular production lines for TRISO particles and Fully Ceramic Micro-encapsulated (FCM) fuel.
- NNL (**UK**) builds expertise through engineering-scale facilities to scale up production
- STL Nuclear (Pty) Ltd (South Africa) HTR fuel design and manufacturing either being in a UO2 or UCO form with either internal or the external gelation processes (kernels, coated particles, effluent treatment, heavy metal recovery, Fuel Compact/Fuel Sphere manufacture)

Key Challenges in HALEU TRISO Fuel Manufacturing

HALEU Availability

Limited global supply; Russia is currently the only major commercial producer

Criticality Safety

Higher U-235 enrichment in HALEU requires stricter safety measures across fabrication, transport, and storage.

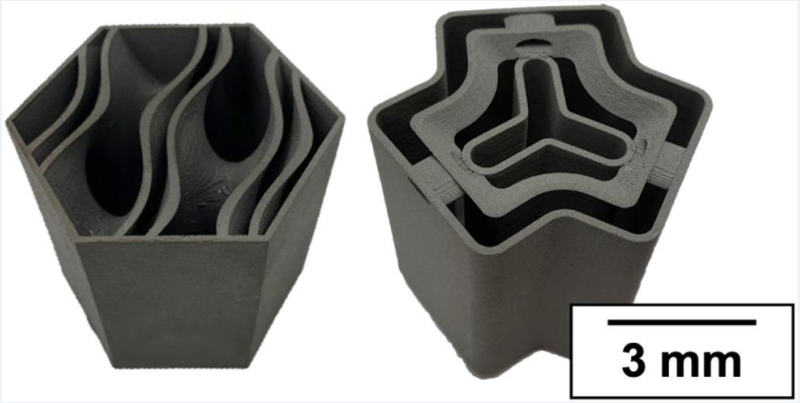
→ Use of **safe geometry equipment** to meet critical mass constraints

Cost Reduction

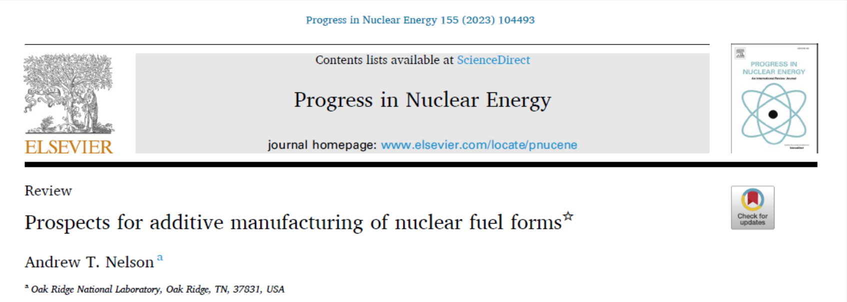
TRISO fuel is more expensive than traditional LWR fuel due to complex manufacturing processes and HALEU-related safety protocols.

→

- **Process Optimization:** Continuous processing and 3D manufacturing
- **Economies of Scale:** scaling up and centralized fuel fabrication facilities serving multiple clients



Examples of fuel compacts fabricated containing coolant flow channels and particle zones using 3D-printed SiC



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Review

Prospects for additive manufacturing of nuclear fuel forms☆

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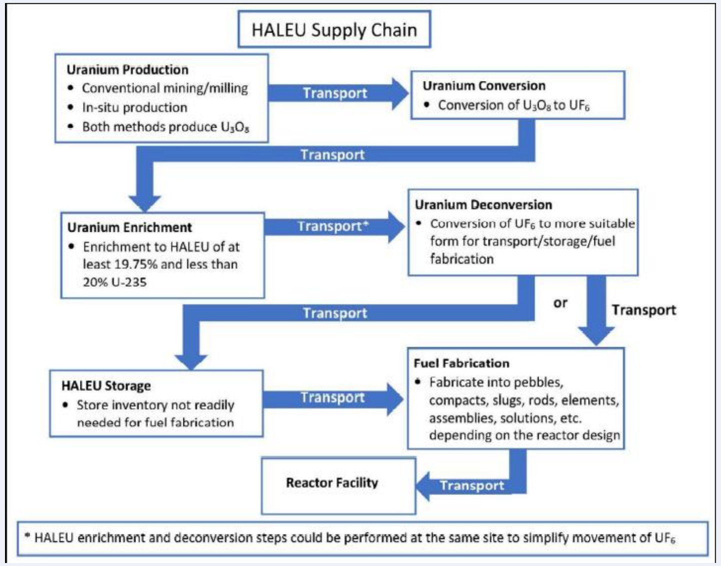
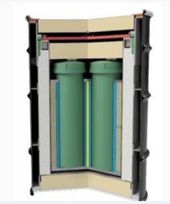
HALEU Supply Chain : status and capabilities

- **Russia** operates full infrastructure for industrial HALEU fuel production

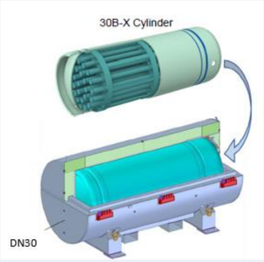
- **USA** is building out its HALEU supply chain. US DOE established HALEU Consortium, and awarded contracts to companies for enrichment and deconversion services, and ensuring access to HALEU for research, development, and commercial use
  - For enrichment services with Louisiana Energy Services, Orano Federal Services, and American Centrifuge Operating. Centrus` demonstration enrichment plant in Piketon started operation in October 2023, in June 2025 reached the first 900 kg of HALEU
  - For reconversion services: Nuclear Fuel Services (BWXT), American Centrifuge Operating (Centrus Energy), Framatome, GE Vernova, Orano, and Westinghouse.



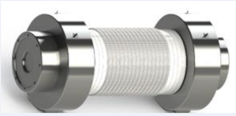
- **ORANO** is prepared to supply enrichment up to LEU+ in 2025 and up to 19.75% thereafter, depending on market demand by 2028, and is working on transport solutions
  - DN30-X -Approved for transporting HALEU UF_6
  - VP-55- Approved for transporting various HALEU uranium products like UO_2, U_3O_8 powder, uranium metal, and TRISO fuel.
  - For HALEU SNF : The TN Eagle transport package



VP-55



The DN30-X



The TN Eagle transport package

- **Urenco** operates enrichment facilities in the UK, USA, Germany, and the Netherlands, and is developing a HALEU facility at its Capenhurst site in the UK (10 tU as UF6, with assays between 10-19.75 % by 2031) and is also involved in expanding its enrichment capacity in the USA.

IAEA activities to support HTR's TRISO fuels development

- **Publications**
  - **IAEA-TECDOC-978** on *"Fuel Performance and Fission Product Behaviour in Gas-Cooled Reactors" (Final report of CRP-2 , 1997)*
  - **IAEA-TECDOC-1645** on *"High Temperature Gas Cooled Reactor Fuels and Materials" (2010)*
  - **IAEA-TECDOC-1674** on *"Advances in High Temperature Gas Cooled Reactor Fuel Technology" (Final report of CRP-6, 2013)*
  - **IAEA-TECDOC-1761** on *"Performance Analysis Review of Thorium TRISO Coated Particles During Manufacture, Irradiation and Accident Condition Heating Tests"* (2015)
  - **IAEA-TECDOC-2090** on *"Coated Particle Fuels for High Temperature Gas-Cooled, Small Modular Reactors – Progress in Design, Manufacturing, Experimentation, Modelling and Analysis Technologies"* (2025)

- **Coordinated Research Projects**
  - **CRP-2 and CRP-6 (completed)**
  - **New CRP T12034** on *"Fuel Modelling Exercises for Coated Particle Fuel for Advanced Reactors Including Small and Modular Reactors"* (2024-2029)

IAEA-TECDOC-2090 on "Coated Particle Fuels for High Temperature Gas-Cooled, Small Modular Reactors – Progress in Design, Manufacturing, Experimentation, Modelling and Analysis Technologies"

State of the art information on coated particle fuel technologies, including design, fabrication, characterization, irradiation performance, performance modelling, covering the period after 2010, as the baseline reference to support fuel technologies of HTR SMRs

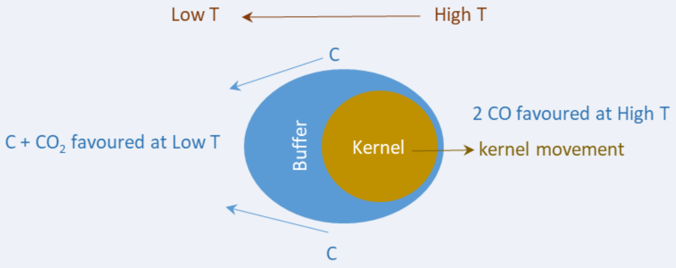
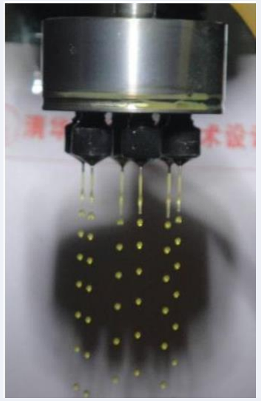
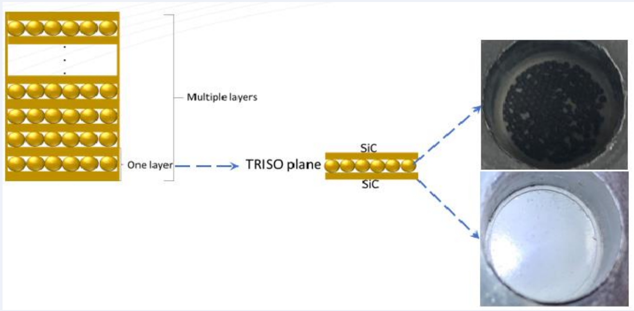


Illustration of the amoeba effect.



Casting equipment of the sol-gel in INET (courtesy of Tsinghua University).



Layered structured of fully ceramic microencapsulated fuel concept and one layer of the layered structure (courtesy of CNL).

- Design description and design requirements (Design bases, Design considerations)
- Updates in Member States
- Coated particle fuel manufacturing (Fuel kernel manufacturing ; Ceramic coatings by fluidized bed chemical vapour deposition, Fabrication of spherical fuel elements; Fabrication of compact fuel elements)
- Quality control for fuel particle characterization (Quality control methods, QA/QC results)
- Irradiation tests, heating tests and PIEs
- Fuel performance assessments (FP, tensile stresses in SiC layer and fuel failures, fuel failure mechanisms, parameters affecting particle performance during NOC, fuel failures during NOC, behaviour of kernel and coating layers and parameters affecting particle behaviour during accident conditions)
- Fuel modelling and code development (Modelling of coated particle fuel performance; Development of fuel analysis codes)

IAEA-TECDOC-2090 main outputs

The design and manufacturing of coated particle fuels for HTGRs are well-established. **Key technologies** like sol-gel for kernels, fluidized bed chemical vapor deposition for coatings, and press technology **have been developed over the past 50 years**, with emerging techniques like additive manufacturing potentially enabling large-scale production.

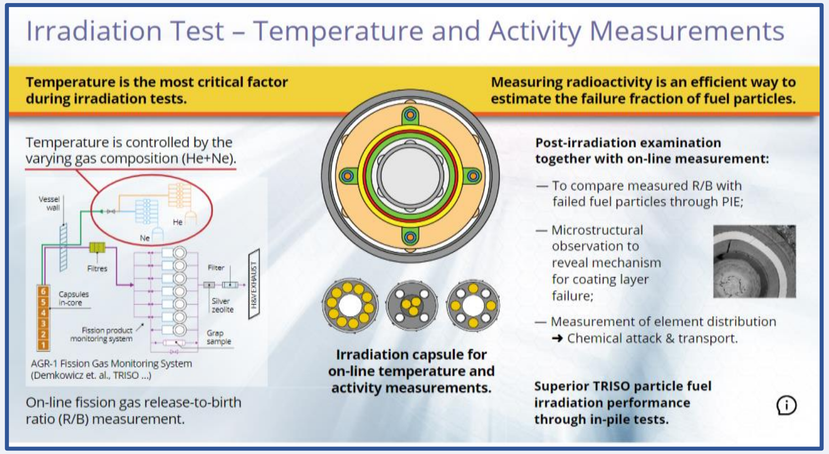
Quality control systems ensure the production of high-quality TRISO-coated fuels for SMRs, supported by irradiation and out-of-pile test data.
However, further testing is needed to better understand fission product behaviour in kernels, the impact of SiC as a matrix material.

Performance analysis codes for HTGR fuels are being developed, with benchmarking exercises revealing discrepancies, particularly in fission gas release predictions.
Future efforts should focus on extending these codes to model UCO kernels more accurately and improving testing for licensing across various reactor types.

CRP T12034 on “Fuel Modelling Exercises for Coated Particle Fuel for Advanced Reactors Including Small Modular Reactors”(2024-2029)

Objectives of the CRP

To support interested IAEA Member States (MSs) in their efforts **to enhance advanced modelling/simulation of TRISO fuel performance, improving** the fundamental understanding of **key TRISO fuel properties** and radiation effects on the TRISO fuel properties in high-radiation environment, to deploy GEN-IV reactors, SMRs and MMRs, that use TRISO-coated particle fuels

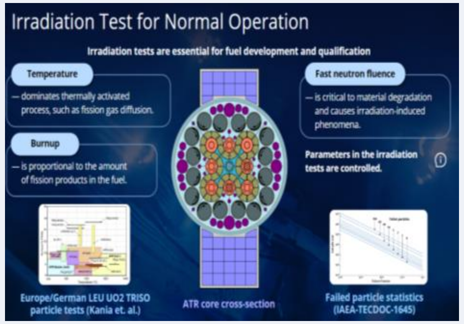


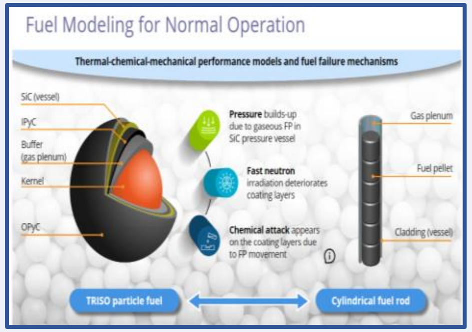
Specific Research Objectives

- To strengthen international collaboration by bringing together experts to better utilize national R&D efforts:
  - To promote the sharing of experimental irradiation data for TRISO fuel, and associated post-irradiation examinations
  - To optimize the use of available experimental data
- To perform simulations of acquired datasets, using various fuel performance codes
  - To compare, analyse and share simulation results among CRP participants, including recommendations on fuel performance codes enhancement

[Fuel Modelling Exercises for Coated Particle Fuel for Advanced Reactors Including Small Modular Reactors | IAEA]

CRP T12034 “TRISO”: Specific Tasks





1) To improve knowledge and **fill the gaps of key TRISO fuel properties** for codes development (e.g., diffusivities, mechanical properties, SiC strength) with new data (e.g., obtained from new experiments and/or generated by multiscale modelling) to provide input to these codes
2) To exchange the information **on operating and transient envelopes for TRISO-fueled reactors** among participating MSs for potential new measurements of fuel properties and new calculations
3) To share **a list of FPs** considered critical for licensing in MSs
4) To develop **a database** based on existing **experimental data** and new dataset collection to validate codes
5) To perform **code benchmark exercises**, including uncertainty propagation

Activity within the CRP TRISO (2024-2029)

Work Task 1.

Data Sets Collection for Fuel Codes Improvement

Coordinators: Dr Kai HE (CNPE, China) **and Dr Taowei WANG** (INET, China)

Work Task 2.

Performing Code Benchmark Exercises and Uncertainty (sensitivity) Analyses

Coordinators: Dr Karl Verfondern (Germany) , Dr **Tian ZHANG** (Harbin Engineering University, China) ,Dr **Marina DU TOIT** (North-West University, South Africa)

Work Task 3.

TRISO Fuel Reactors : Operating and Transient Envelopes, Fission Products for Licensing

RCM-1 was held on 6-9 May 2025

Participants:

China, France, South Africa , Germany, Netherlands, Ghana, Morocco, Indonesia, Bangladesh

Benchmarks:

Fuel Codes: SPFAC (China), COMSOL (Ghana), TRIAC (Indonesia), ATLAS (Framatome), STACY (China, South Africa, Germany), BISON (South Africa)

Potential Cases for benchmark exercises:

HFR-EU1/2 (HTR-10), HTR-PM, AGR-1, AGR-3/4, AGR-5/6/7, HFR-EU1,

UO_2, UCO in different matrix (graphite and SiC (FCM)

New Experimental Data:

Heat-up tests on HTR fuel, new Ag/Cs/Sr/I diffusion coefficients in non-irradiated SiC matrix; ion irradiation of SiC and Ag^+ and Pd^+ diffusion coefficients in irradiated SiC matrix, multiscale modelling simulation data of the FPs diffusion coefficients

International Conference on Fuel Supply Chain for Sustainable Nuclear Power Development, Vienna, from 13 to 15 October 2026

Topic 1. Industry Prospects and Challenges Facing Raising Fuel Supply Demand:

Challenges in supply and front-end services to meet the increasing infrastructure requirements for conversion, enrichment and fuel fabrication

- Market fluctuations impacting supply chains
- Political support: policies and strategies
- Expansion of conversion enrichment and fuel fabrication facilities to meet growing demand
- Technological advancements improving processes' efficiency and sustainability

Topic 2. Supply and demand for raw materials for nuclear fuel supply:

Innovations in the front end of the nuclear fuel cycle, from exploration to mining:

- New uranium exploration and mining projects
- Innovative advancements in uranium exploration and mining
- Uranium and thorium resources, processing and mining and the circular economy

Topic 3. Advanced nuclear fuels for innovative reactor technologies:

Advanced technology fuels and fuels for advanced reactors:

- Design, qualification and operation of ATFs, LEU+ and HALEU fuels, TRISO fuels, fuels for Fast Reactors and multiple recycling in all types of reactors
- Advances in nuclear fuel fabrication processes and quality control (automation, additive manufacturing and use of artificial intelligence)

Topic 4. Industrial and Innovative technologies for recycling nuclear materials:

Industrial operating experience and lessons learned in reprocessing for recycling:

- Experience of uranium (U) and plutonium (Pu) recycling and requirements for multirecycling U and Pu in thermal and Fast Reactors
- Prospects for reprocessing of spent fuels from advanced reactors, including minor actinides management
- Infrastructure development and implementation for reprocessing and managing nuclear materials to be recycled, including nuclear materials transport
- Life cycle of reprocessing and recycling and impacts on the final wastes to be disposed of

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