Generation IV International Forum – what we do, what we achieved in TRISO fuel development

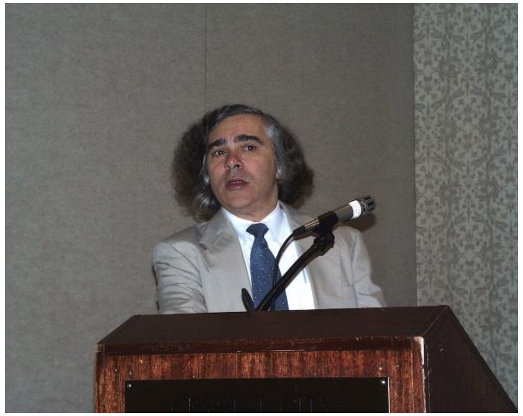
Waclaw Gudowski – NCBJ
with support of
Kamil Tuček - Joint Research Centre (JRC)
Paul Demkowicz, INL and Gen IV Fuel and Fuel Cycle Project materials

Program

- What is GIF
  - Short history
  - Gen IV reactors
  - Mode of operation
- Highlights 2019-2021 for each reactor type
- Very High Temperature Reactor System Fuel & Fuel Cycle Project
  - Sharing results
- Lessons learnt for NCBJ
- Applications of TRISO fuels - summary

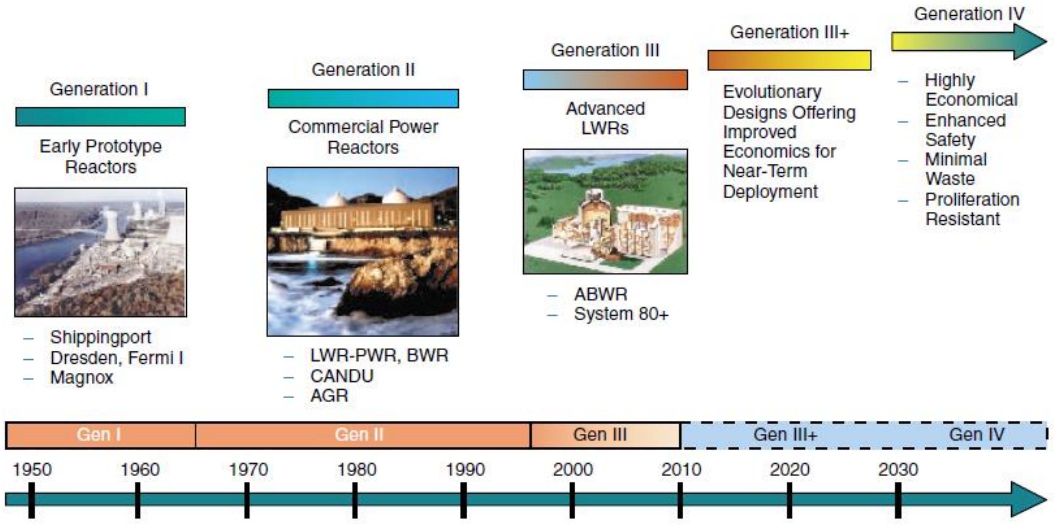
What is GIF – Gen IV International Forum?

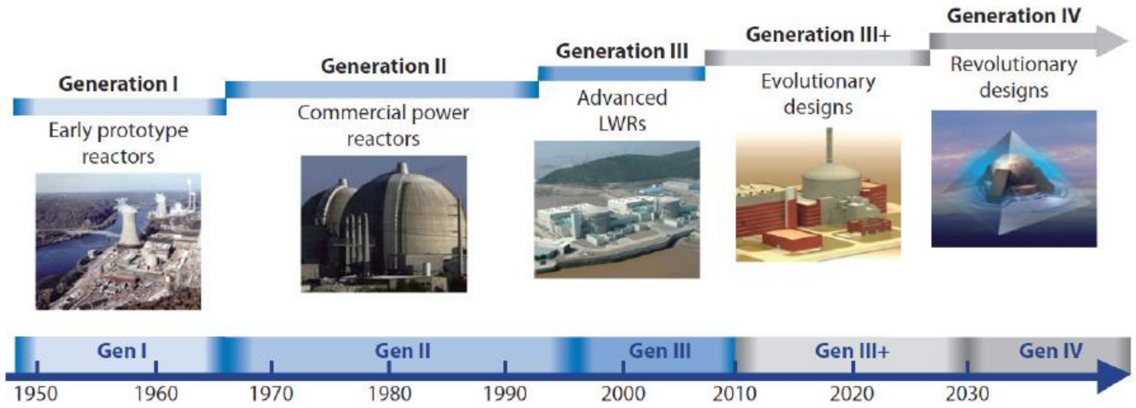
The **Generation IV International Forum** (GIF) is "a co-operative international endeavour which **was set up to carry out the research and development needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems."** It was founded **20 years ago in June 2001**. Currently, active members include: Australia, **Canada,** China, the European Atomic Energy Community (*Euratom*), **France, Japan,** Russia, **South Africa, South Korea,** Switzerland, **the United Kingdom and the United States**. The non-active members are Argentina and Brazil. Switzerland joined in 2002, Euratom in 2003, China and Russia in 2006, and Australia joined the forum in 2016.

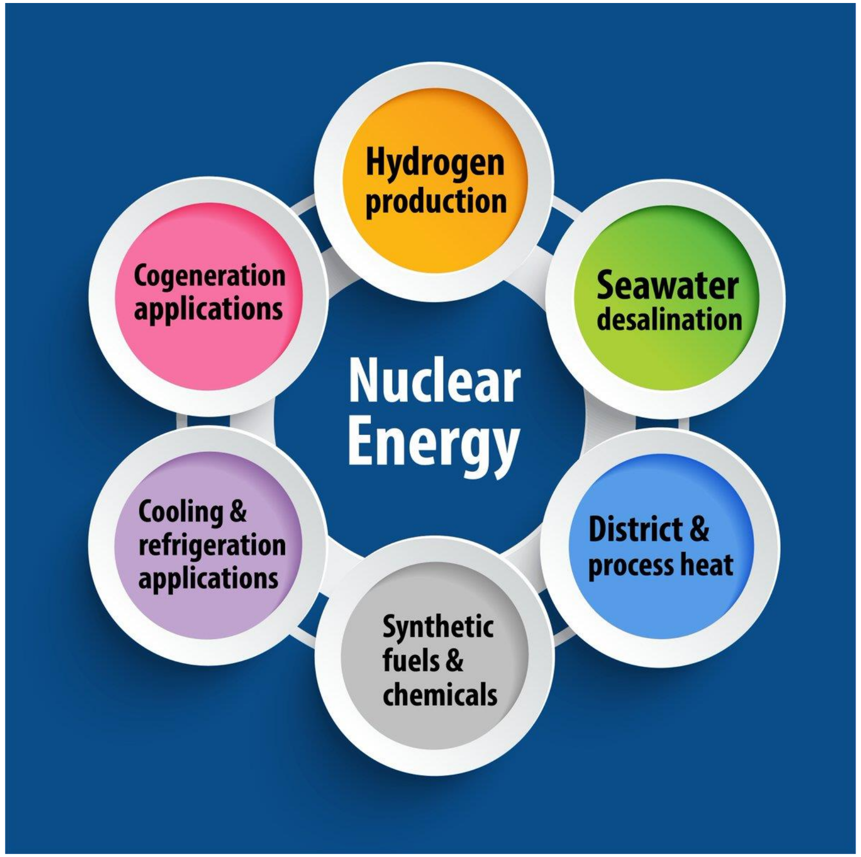




Washington, July 1999

Today's expectations on a key role of nuclear energy

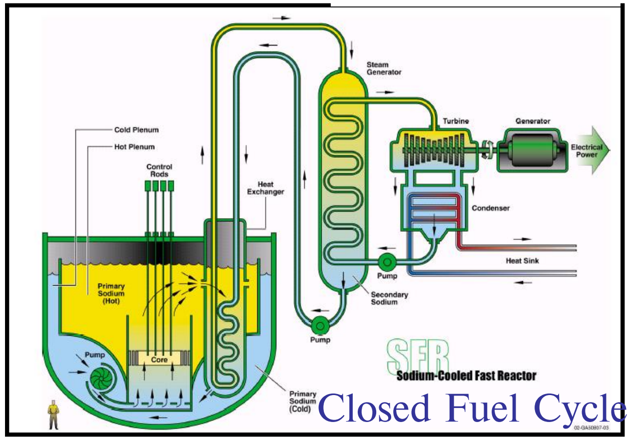




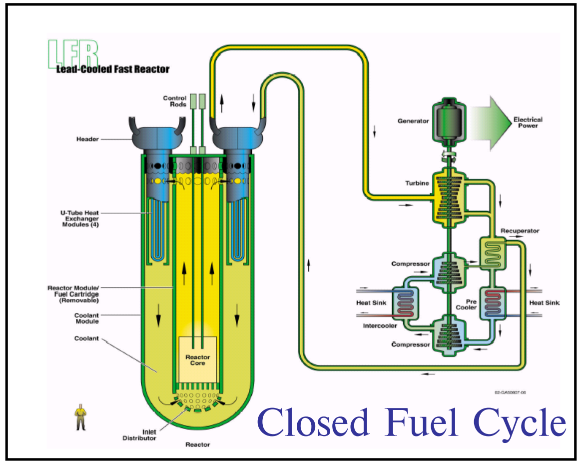


Generation IV : 6 « innovative » systems

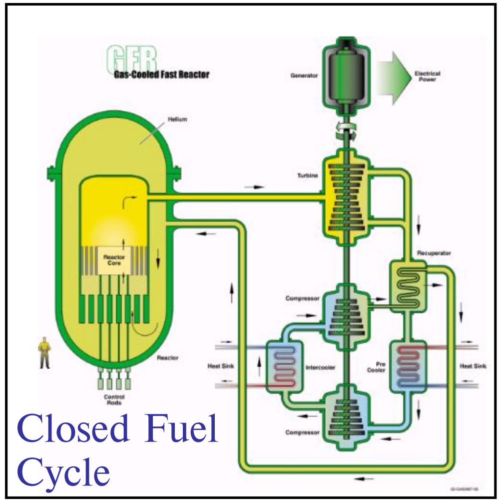
Sodium Fast reactor 500 - 550 ºC



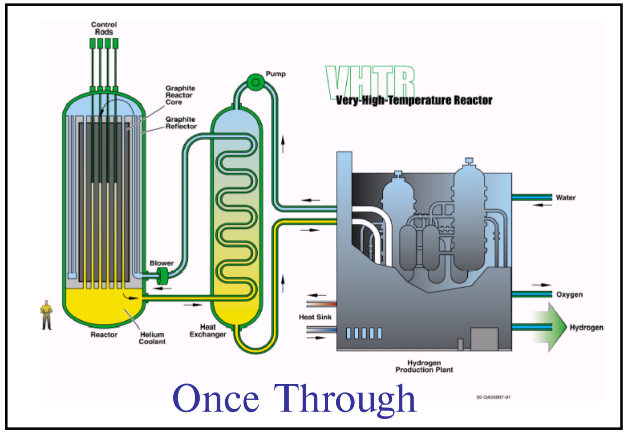
Lead Fast 480 - 800 ºC



Gas Fast Reactor 850 ºC

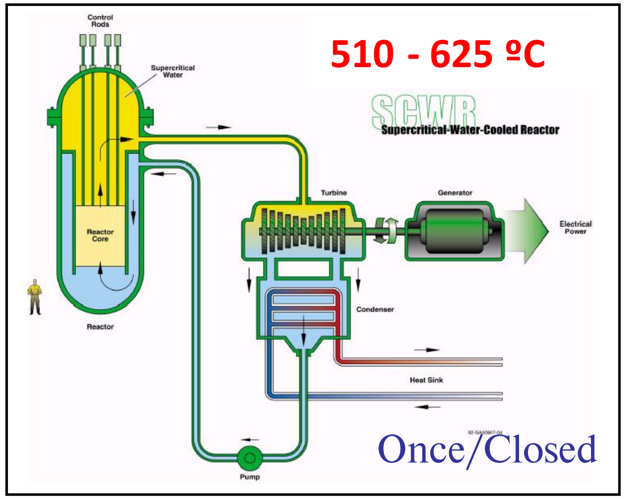


Very High Temperature Reactor

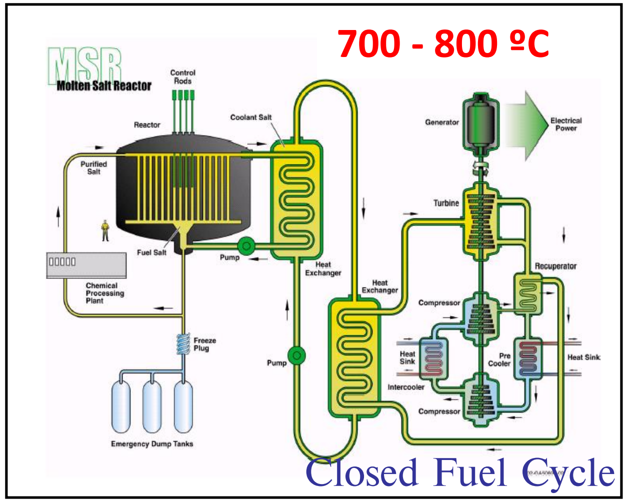


800 - 1000ºC

Supercritical /High Performance Water Reactor



Molten Salt Reactor



Aiming at improvements in:

- Sustainability
- Economics
- Safety and reliability
- Proliferation resistance and physical protection

See: https://youtu.be/J1OPqNgAuSk

GEN IV International Forum[SM]

Expertise | Collaboration | Excellence

System	CA	CN	EU	FR	JP	KR	RU	CH	US	ZA
SFR		✓	✓	✓	✓	✓	✓		✓	
VHTR		✓	✓	✓	✓	✓		✓	✓	
SCWR	✓		✓		✓		✓			
GFR			✓	✓	✓			✓		
LFR			P		P		P			
MSR			P	P			P			

✓= Signatory to the System Arrangement; P = signatory to the Memorandum of Understanding; Argentina, Brazil, and the United Kingdom are inactive.

GIF Governance

Policy Group

Expert Group

Senior Industry Advisory Panel (SIAP)

Vertical, cross-cutting structure

Methodology Working Groups (WGs)

- Economics Modelling (**EMWG**)
- Proliferation Resistance and Physical Protection (**PRPPWG**)
- Risk and Safety (**RSWG**)
- Education & Training (**ETWG**)

Task Forces (TFs)

- Safety Design Criteria (**SDC-TF**)
- R&D Infrastructure (**RD-TF**)
- Advanced Manufacturing & Material Engineering (**AMME-TF**)

System Steering Committees for six Generation IV Reactor systems (GFR, LFR, MSR, SFR, SCWR, VHTR)

Horizontal structure

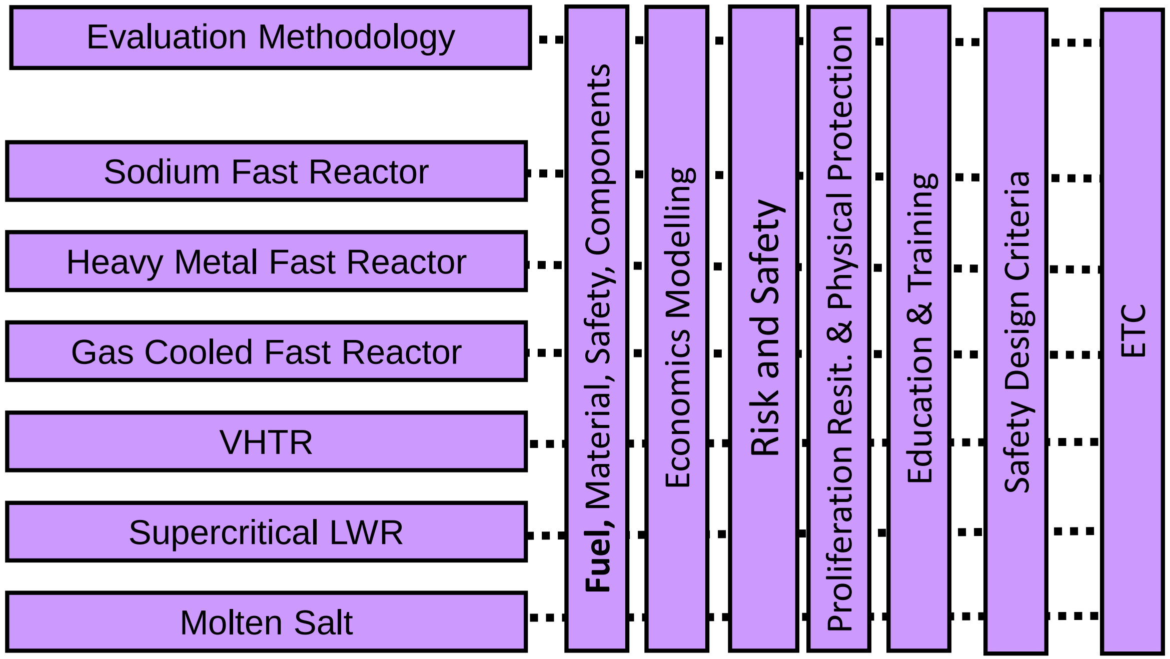
Projects

Fuel, Material, Safety, Components etc.

Vertical, cross-cutting structure

Working groups,
projects,tasks

System Steering Committees for six Generation IV Reactor systems



GIF Board 2020-2021

GIF Chairman

Hideki Kamide, Japan

Vice-Chairs

Alice Caponiti, USA, Vice Chair, (Regulatory issues)
Sylvestre Pivet, France, Vice Chair, (Market issues)
Jong Hyuk Baek, Korea, Vice Chair, (R&D collaboration)

Policy Secretariat

Policy Director

Nobuchika Kawasaki
Japan

Technical Director

Gilles Rodriguez
France

GIF Secretariat
Chief of Staff

Nobuchika Kawasaki
Masahiro Nishimura
Japan

Technical Secretariat

Sama Bilbao Y Leon (until Aug. 2020)
Philippe Guiberteau (since Sept. 2020)
NEA

GIF Secretariat
Support Team

Kyoko Mukaida, Japan
Katsunori Ishii, Japan
Hiroshi Taninaka, Japan
Kazunori Hirao, Japan

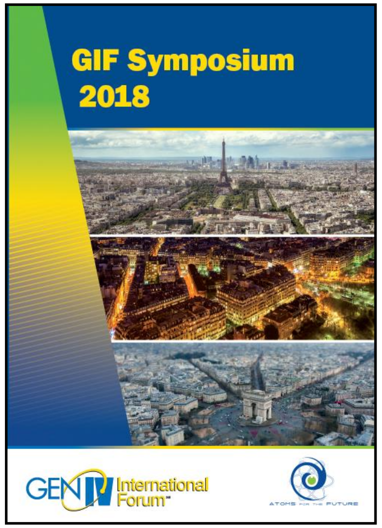
Main missions of GIF (2019-2021)

- **Market Opportunities and Challenges for Deployment**
  - Enhanced interaction with industry, incl. with **SMR vendors**
  - Investigation of increased **flexibility and coupling with non-electrical applications of nuclear heat**
- **Safety and Regulation**
  - **Increased interaction with the regulators**, e.g. in the frame of the NEA Working Group on Safety of Advanced Reactors (**WGSAR**)
  - Development of system-specific Safety Design Criteria (SDC) and Guidelines
- **Enhancement of R&D cooperation**
  - Use of R&D infrastructures to improve international collaboration - R&D Infrastructure TF
  - Advanced manufacturing - Advanced Manufacturing & Materials Engineering TF
- **Improved communication of GIF Results to Citizens, Policy makers, Regulators, Industry**
  - New GIF newsletters and GIF visual branding
- **Enhanced Education & Training as well as Knowledge Management/Development**

Position better the Gen-IV systems in the global decarbonised energy mix to facilitate deployment

https://www.gen-4.org/gif/jcms/c_122378/newsletters-archive

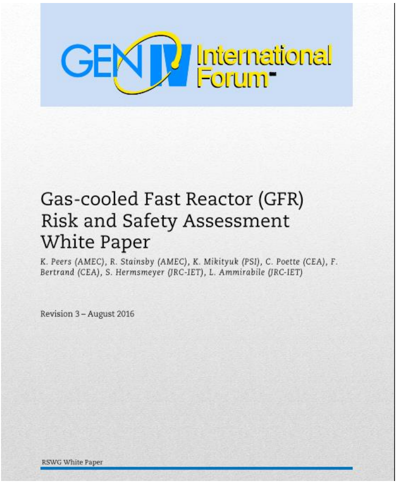
Current Highlights of the GIF activities



https://www.gen-4.org/gif/jcms/c_117864/2018-gif-symposium-proceedings
https://www.gen-4.org/gif/jcms/c_119034/gif-2019-annual-report

Highlights related to GFR

- GFR System Arrangement signed by Euratom, France, and Japan
  - Existing **Project Arrangement** on Conceptual Design and Safety
  - Provisional project on Fuel and core materials
  - Proposed project on GFR Technology
- Development of **GFR reference documents**
  - GFR Risk and Safety Assessment White Paper (completed in 2016)
  - GFR System Safety Assessment (draft)
  - GFR Safety Design Criteria (draft)
- **Europe**: The main project **ALLEGRO** - preparatory phase is carried out by the V4G4 Centre of Excellence. The work is being supported by the Euratom collaborative project **SafeG**, among others aiming at:
  - strengthening of inherent safety
  - resolving **remaining open questions** in residual heat removal in accident conditions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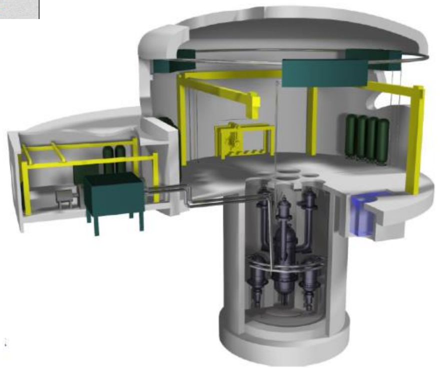
Gas-cooled Fast Reactor (GFR)
Risk and Safety Assessment
White Paper

K. Peers (AMEC), R. Stainsby (AMEC), K. Mikityuk (PSI), C. Poette (CEA), F. Bertrand (CEA), S. Hermsmeyer (JRC-IET), L. Ammirabile (JRC-IET)

Revision 3 – August 2016

RSWG White Paper

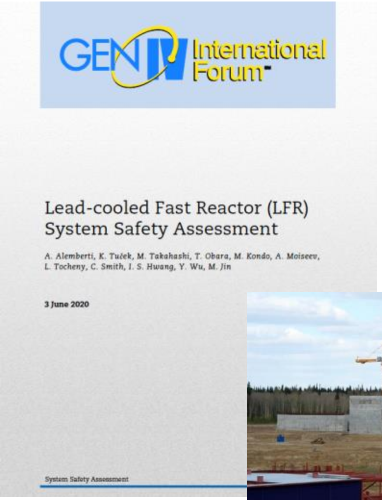
ALLEGRO concept



https://www.gen-4.org/gif/upload/docs/application/pdf/2016-10/rswg_gfr_white_paper_final_2016.pdf
https://cordis.europa.eu/project/id/945041

Highlights related to LFR and HLM technology

- Withing GIF, LFR members work under the framework of MoU
- Activities concentrate on the development of top-level reports
  - **LFR System Safety Assessment (SSA)** was published in June 2020
  - **White Paper on the LFR PRPP (Proliferation Resistance and Physical Protection) aspects** has been finalised in cooperation with GIF PRPPWG and transmitted to EG
  - **LFR Safety Design Criteria (SDC)** document is being prepared in collaboration with GIF RSWG, and is expected to be finalised and transmitted to GIF Expert Group in early 2021
- **World**: Construction license for BREST-OD-300 LFR research demonstrator issued by Rostechnadzor on 10 Feb 2021; construction started in Tomsk, Russian Federation
- **Europe**: Two main projects: (i) **MYRRHA** R&D infrastructure (ADS demonstrator) under construction in Belgium; and (ii) LFR demonstrator **ALFRED** in Romania. Euratom collaborative projects supporting LFR- and heavy liquid metal (HLM)- R&D activities: **GEMMA, PATRICIA** and **PASCAL**


GEN IV International Forum

Lead-cooled Fast Reactor (LFR) System Safety Assessment

A. Alemberti, K. Tuček, M. Takahashi, T. Obara, M. Kondo, A. Moiseev, L. Tocheny, C. Smith, I. S. Hwang, Y. Wu, M. Jin

3 June 2020

System Safety Assessment


Site preparations for the BREST-OD-300 construction

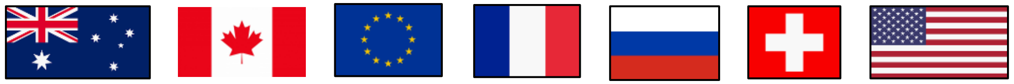
GEMMA

PATRICIA

PASCAL

https://www.gen-4.org/gif/upload/docs/application/pdf/2020-06/gif_lfr_ssa_june_2020_2020-06-09_17-26-41_202.pdf
https://www.riatomsk.ru/article/20201109/seversk-brest-300-sroki/
http://www.eera-jpnm.eu/gemma/
https://patricia-h2020.eu/
https://cordis.europa.eu/project/id/847715
PASCAL   https://cordis.europa.eu/project/id/945341

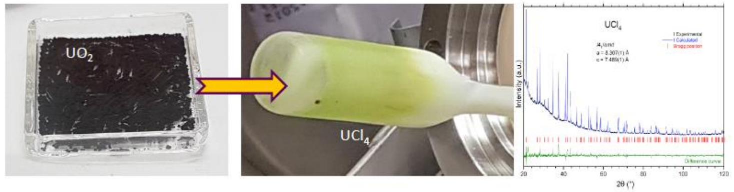
Highlights related to MSR



- A large interest around the MSR technology, with more than 40 concepts of a large variety being developed worldwide
- Within GIF, the MSR system is currently ongoing transition from Memorandum of Understanding (MoU) to **System Arrangement** (SA)
- Three (3) **Project Arrangements** are under development:
  - *Fuel and coolant salt properties*
  - *Materials and components*
  - *System integration and cross-cutting issues*
- Safety aspects have been identified as a key driver for the R&D Roadmap → ongoing interactions with GIF RSWG (Risk and Safety WG) to create Task Force on the **MSR safety approach**
- **World**: Prototype MSR - TMSR-LF1 - is under construction in China
- **Europe**: Euratom collaborative project **SAMOSAFER** focuses on development of DiD approaches, development of theoretical models for safety-relevant phenomena, as well as related experimental setups

TMSR-LF1

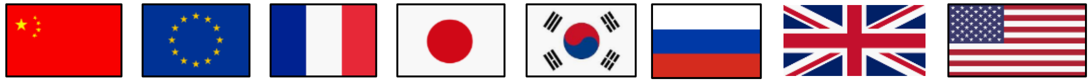
SAMOSAFER



Successful synthesis of UCl_4 at JRC Karlsruhe

https://samosafer.eu/

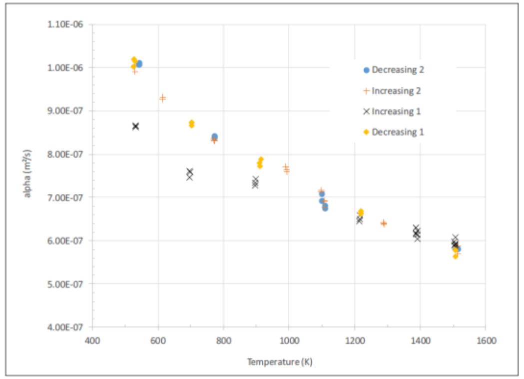
Highlights related to SFR



- **Most active GIF system (together with VHTR) with four R&D Projects running:**
  - System Integration and Assessment (SIA)
  - Safety and Operations (S&O)
  - Advanced Fuel (AF)
  - Component Design and Balance of Plant (CD&BOP)
- **Five SFR Design Concepts:**
  - Loop Option (JSFR Design Track)
  - Pool Option (KALIMER-600, ESFR, and BN1200 Design Tracks)
  - Small Modular Option (SMFR Design Track)
- Revision of **SFR System Research Plan** was completed and approved by System Steering Committee in October 2019
- **White Paper on the SFR PRPP aspects** has been finalised and transmitted to EG
- **World**: Construction of two pilot SFR units (CFR-600) is ongoing in China
- **Europe**: Euratom collaborative project **ESFR-SMART** focuses on enhancing the safety of Generation-IV SFRs

Construction site of CFR-600

ESFR-SMART
sodium fast reactor safety

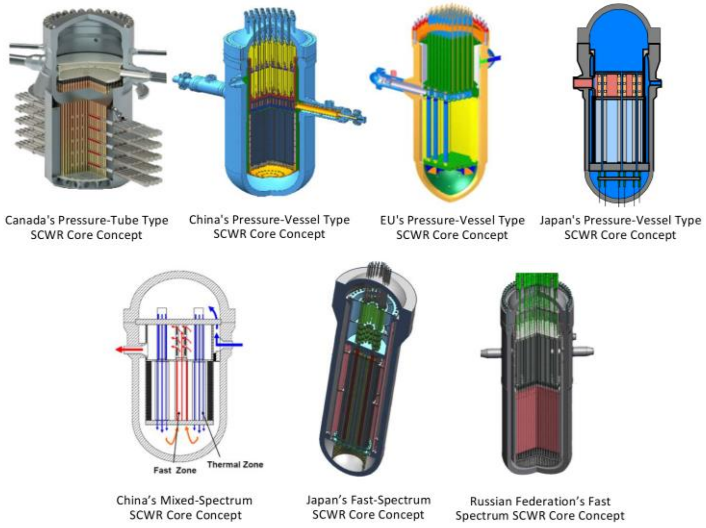


Thermal diffusivity measurements of $(U,Am)O_{2-x}$ at JRC Karlsruhe

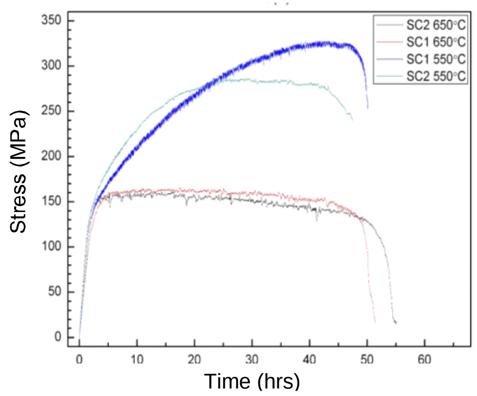
https://www.gen-4.org/gif/jcms/c_95916/gif-sfr-safetyassessment-20170427-final
https://world-nuclear-news.org/Articles/China-starts-building-second-CFR-600-fast-reactor
http://esfr-smart.eu/

Highlights related to SCWR

- **Two R&D Project arrangements established (currently being extended):**
  - Materials and Chemistry (2010)
  - Thermal-Hydraulics and Safety (2009)
- Provisional project on System Integration and Assessment
- Within GIF, four SCWR core concepts with **thermal spectrum** and three other core concepts with **mixed or fast spectrum** have been proposed
- **Europe**: Joint Euratom-China-Canada project **ECC-SMART** has just started. It aims at the assessment of the feasibility and identification of safety features of an intrinsically and passively safe SMR cooled by supercritical water



ECC smart



Measurement of stress corrosion cracking in the SCW conditions at JRC Petten

https://www.gen-4.org/gif/jcms/c_103619/gif-scwr-safetyassessment-finaldec2018
https://cordis.europa.eu/project/id/945234

Highlights related to VHTR

- **Four active VHTR "pre-competitive" Projects**
  - **Materials:** Graphite, metals, ceramics - corrosion, joining, irradiations
  - **Fuel:** Fabrication, characterisation, qualification, waste management
  - **Hydrogen Production:** Iodine-Sulphur (850°C), Copper-Chlorine (530°C), High temperature electrolysis (650°C)
  - **Computer Tools for Design and Licensing:** Thermal-hydraulic analysis (CFD), Neutronics and nuclear cross-section data, Radioisotope chemistry and transport, Reactor and plant dynamics
- Development of **VHTR Safety Design Criteria** on the basis of IAEA TECDOC and in cooperation with RSWG
- **World:** Construction of HTR-PM HTR demonstration plant is ongoing in China. HTTR in Japan got operational permission
- **Europe**: Euratom collaboration project **GEMINI+** project, research HTGR program in Poland, broaden spectrum of potential stakeholders (industrial partners, both private and state-owned) actively interested in nuclear heat and electricity

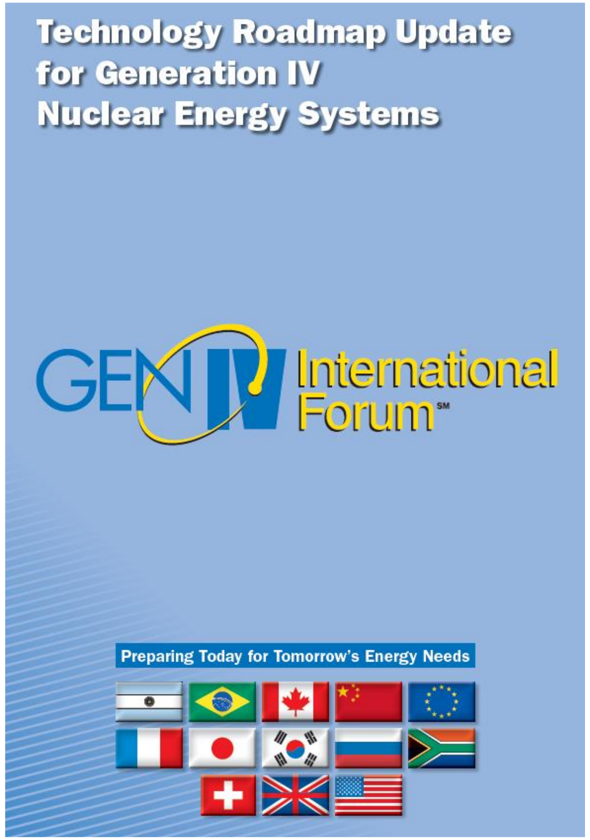
Construction site of HTR-PM

GEMINI+

https://www.gen-4.org/gif/jcms/c_103659/gifvhtr-safety-assessment-finaldec2018
https://www.world-nuclear-news.org/Articles/Cold-testing-of-HTR-PM-reactors-completed
https://htr2020.org
http://www.gemini-initiative.com/geminiplus/

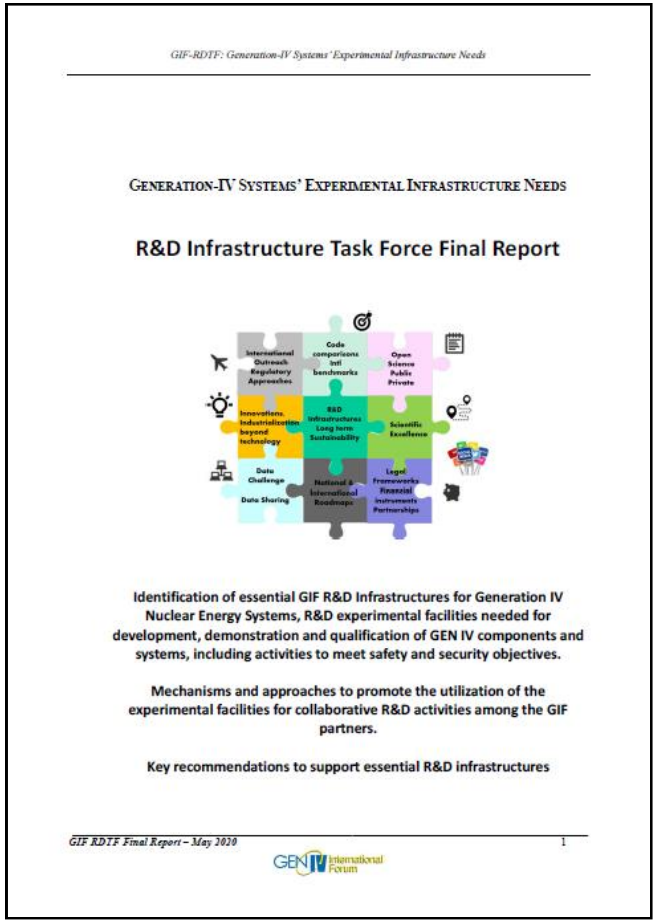
Technology roadmap (2014) and Annual Reports

https://www.gen-4.org/gif/jcms/c_178290/gif-2020-annual-report



Task Force on R&D Infrastructure

- **Final report issued in May 2020**
  - **Identifies essential large (and key) experimental infrastructures needed in support of Gen-IV systems** R&D activities in terms of feasibility / performance as well as demonstration / deployment
  - Facilitates R&D collaboration across Gen-IV systems
  - **Promotes utilization of experimental facilities for collaborative R&D activities among GIF partners**
  - Facilitates GIF partners' access to the various R&D facilities in the GIF member countries
- The document is freely downloadable on the GIF.


GIF-RDTF: Generation-IV Systems' Experimental Infrastructure Needs

GENERATION-IV SYSTEMS' EXPERIMENTAL INFRASTRUCTURE NEEDS

R&D Infrastructure Task Force Final Report

Identification of essential GIF R&D Infrastructures for Generation IV Nuclear Energy Systems, R&D experimental facilities needed for development, demonstration and qualification of GEN IV components and systems, including activities to meet safety and security objectives.

Mechanisms and approaches to promote the utilization of the experimental facilities for collaborative R&D activities among the GIF partners.

Key recommendations to support essential R&D infrastructures

GIF RDTF Final Report – May 2020 1

GEN IV International Forum

(Very) High Temperature Reactor system
Fuel & Fuel Cycle Project.
6 Workpackages

- WP1: Irradiations and PIE
- WP2: Fuel Attributes and Material Properties
- WP3: Safety
- WP4: Enhanced and Advanced Fuel
- WP5: Waste Management
- WP6: Other Fuel Cycle Options

Tasks of the Project

Task	Description
WP 1	IRRADIATION AND PIE
Task 1.01	Irradiation devices and procedures
Task 1.02	Shared irradiation tests
Task 1.03	PIE protocol and procedures
Task 1.04	Irradiation and post irradiation examination results
WP 2	FUEL ATTRIBUTES AND MATERIAL PROPERTIES
Task 2.01	Identification and measurement of critical material properties
Task 2.01.01	Irradiation and material sample supply
Task 2.01.02	Materials properties
Task 2.02	Establishment of fuel material property database
Task 2.03	Characterization techniques of fuel attributes
Task 2.04	Fuel performance modeling
WP 3	SAFETY
Task 3.01	Pulse irradiation testing
Task 3.02	Establishment of heating test capability
Task 3.03	Heating test
Task 3.04	Source term experiments
WP 4	ENHANCED AND ADVANCED FUEL FABRICATION (e.g. UCO, ZrC)
Task 4.01	Process development
WP 5	WASTE MANAGEMENT
Task 5.01	Head-end processes
Task 5.02	Graphite management
Task 5.03	Disposal behavior and waste package
WP 6	OTHER FUEL CYCLE OPTIONS
Task 6.01	Plutonium burning and transmutation
Task 6.02	Thorium cycle

Main achievements of the **Fuel and Fuel Cycle Project of GIF VHTR**

- Task 1.2 share irradiation tests: Irradiation tests that contain fuels from VHTR/F&FC signatories.
- Task 1.3 Post-irradiation Examination Protocol and Procedures: Comparison of protocol and procedures for PIE to develop a common understanding of these “tools” that are critical to successful PIE.
- Task 2.1, Identification and Measurement of Critical Material Properties: Definition of experimental protocol and perform measurements of critical properties on irradiated fuel materials.
- Task 2.2 Establishment of Fuel Material Property Database
- Task 2.4 Fuel performance modeling: Models and evaluation methods for source terms under normal and accident conditions for the VHTR
- Task 3.1: Pulse irradiation testing-issues specifications for joint safety testing
- Task 5.3 disposal behavior and waste package, separate effect tests with unirradiated and irradiated material representing the different barrier
- Task 6.1 plutonium burning and transmutation, analyse present Pu coated particle designs and explore the feasibility for MA fuel

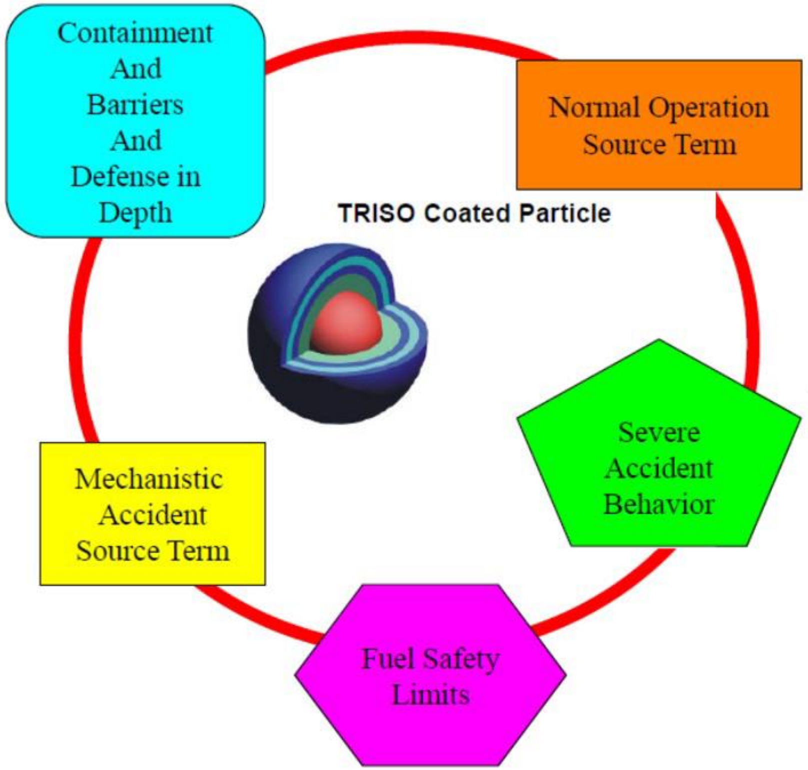
Lessons for NCBJ

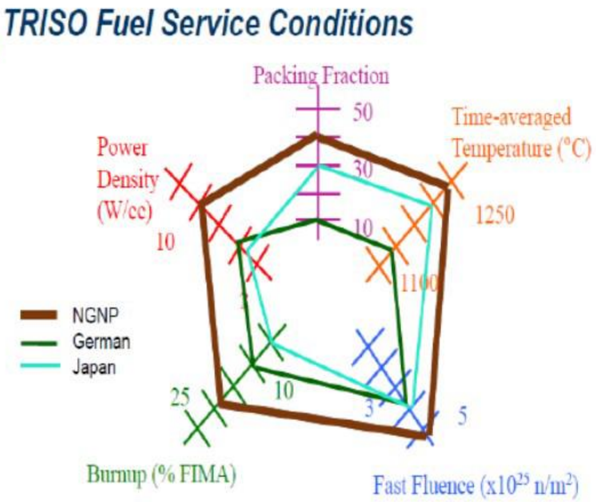
TRISO Particle Fuel Performance Improvement

Excellent TRISO fuel fabrication and performance is needed for high temperature gas-cooled reactor (HTGR) deployment

- *Understand the interplay between fuel fabrication specifications, production methods, and irradiation performance results*
- Learn from past U.S. and German TRISO, Japanese and now Chinese experiences
- Use UCO vs. UO_2 kernels to provide superior fuel performance at high burnup
- **Innovation based on solid science, not by using a “recipe” trial method**

TRISO Particles act as individual fission product "Containments" for Gas-Cooled Reactors





TRISO coated particle fuel performance and fission product retention is the KEY FACTOR for making the HTGR/VHTR/NGNP Safety Case

Advanced Gas Reactor TRISO Fuel Qualification Program

AGR-1: Shakedown capsule, ORNL lab-scale fuel, to show new process parameters could fix historical fuel fabrication problems
AGR-2: Demonstrate engineering scale UCO and UO2 TRISO particle performance, with lab-scale compacting, that fuel works at very high temperature gas cooled reactor (VHTR) service conditions.
AGR-3/4: Designed-to Fail particles (20) in center of compact with driver fuel in ORNL compacts.
AGR-5/6/7: Fuel produced in fuel vendor's pilot fuel fabrication line, is qualified for reactor operating envelope and safety margin conditions with 95%/95 confidence statistical quantities of fuel

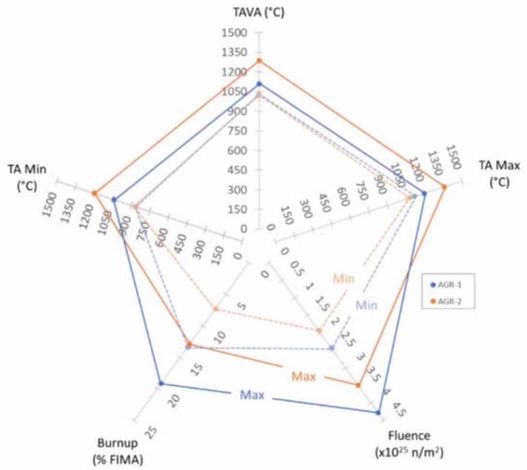
AGR Fuel Fabrication and Experiments

Experiment	Purpose	Kernel Fabrication	TRISO Coating	Overcoating Compacting
AGR-1	Shakedown/ early fuel experiment	Engineering	Laboratory	Laboratory
AGR-2	Performance test fuel experiment	Engineering	Engineering	Laboratory
AGR-3/4	Fission product transport experiments	Engineering	Laboratory	Laboratory
AGR-5/6/7	Fuel qualification and fuel performance margin testing experiments	Engineering	Engineering	Engineering

US sharing results of ”Advanced Gas Reactor TRISO Fuel Qualification Program” for UCO/UO_2 TRISO fuel

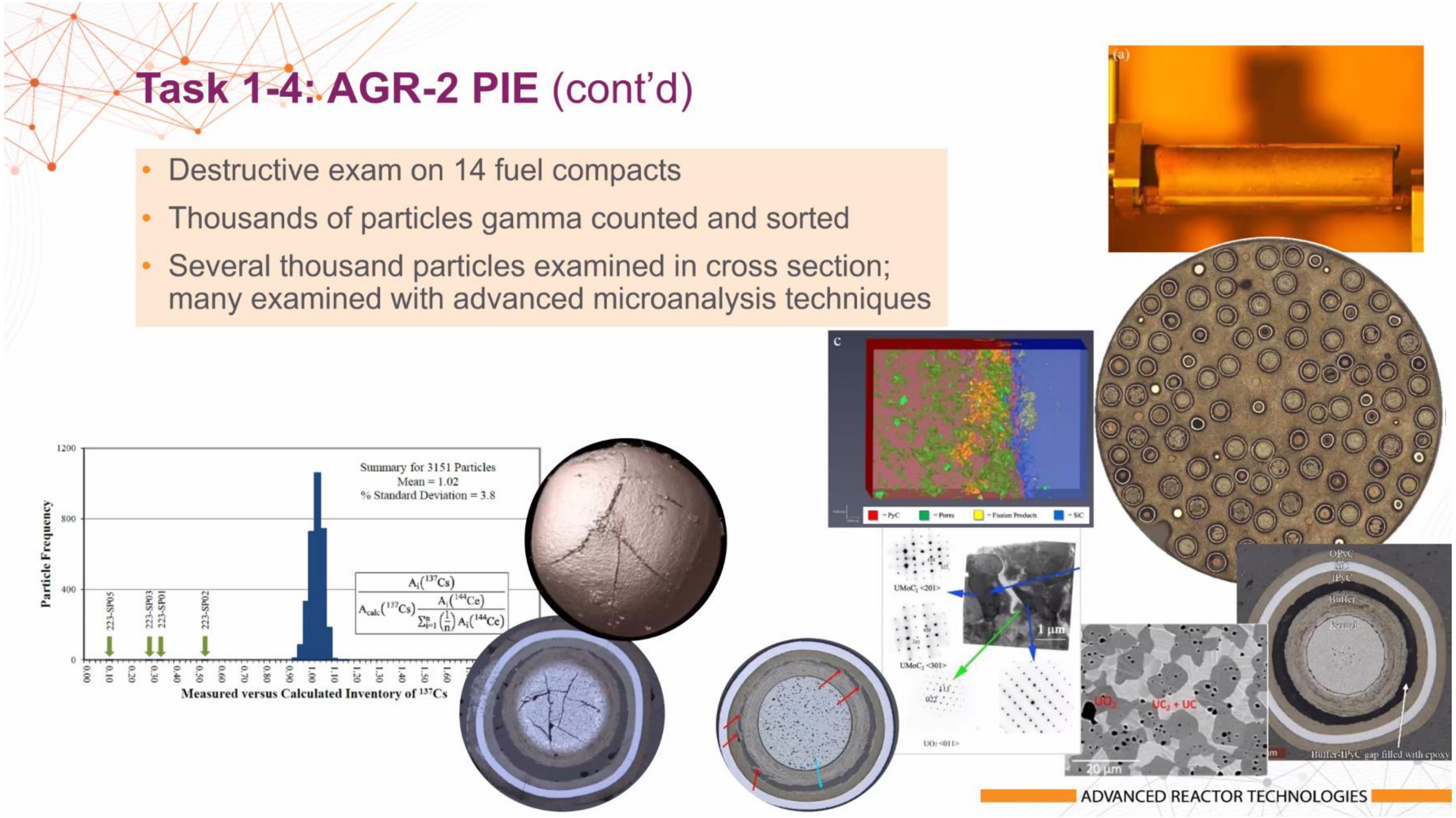
Task 1-4: AGR-2 PIE

- Major components of the AGR-2 PIE have been completed
- Final PIE report issued on Sep 9, 2021
- Includes major conclusions about in-pile behavior of UCO and UO_2 TRISO fuel under a range of irradiation conditions



ADVANCED REACTOR TECHNOLOGIES

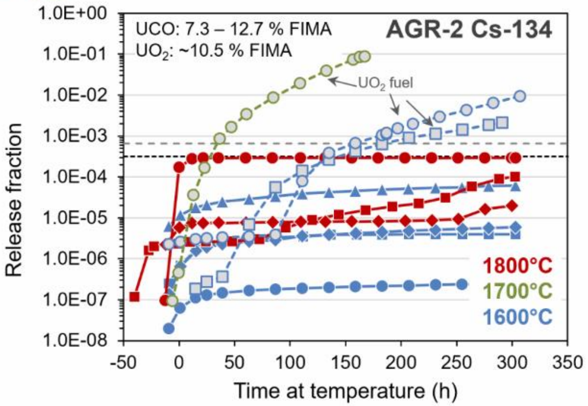
US sharing results of ”Advanced Gas Reactor TRISO Fuel Qualification Program” for UCO/UO_2 TRISO fuel

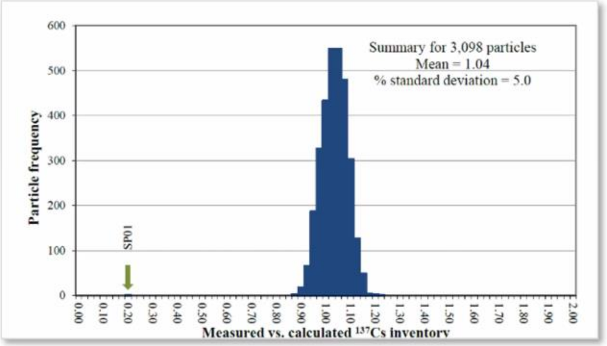


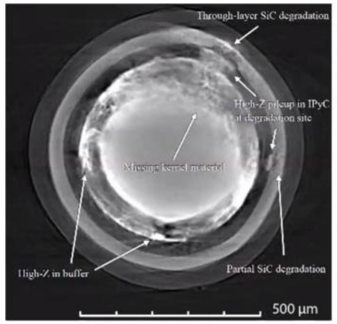
US sharing results of ”Advanced Gas Reactor TRISO Fuel Qualification Program” for UCO/UO_2 TRISO fuel

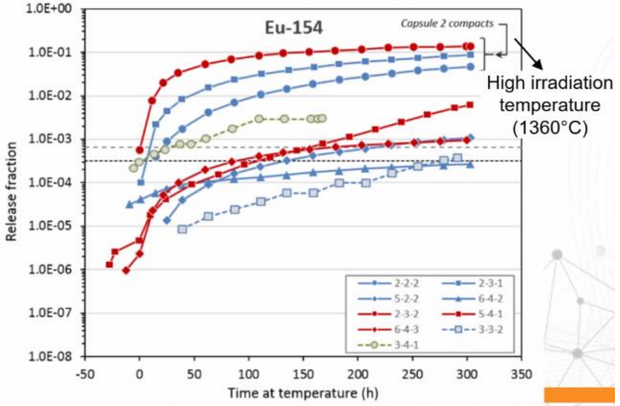
Task 3-3: AGR-2 Accident Safety Testing

- 16 high-temperature safety tests on 18 fuel compacts
- Temperatures 1500 – 1800°C
- Extensive post-test analysis to identify and study compromised particles and determine cause of layer failure







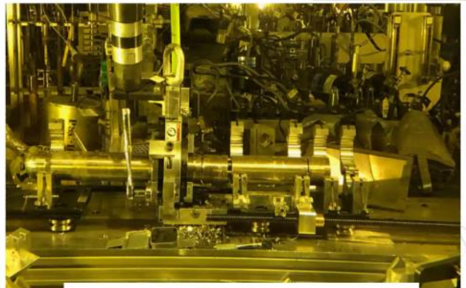


US sharing results of "Advanced Gas Reactor TRISO Fuel Qualification Program" for UCO/UO_2 TRISO fuel

Task 1-4: AGR-5/6/7 Irradiation

- Final fuel qualification irradiation and performance margin test
- 194 UCO fuel compacts (~570,000 particles)
- Large increases in fission gas release from Capsule 1 in Oct 2019 indicate significant number of particle failures
- Cause remains unknown, but nature of the release suggests it is induced by the experiment (i.e., this is most likely not intrinsic fuel failure); PIE needed to fully understand this behavior
- Experiment terminated early in July 2020 after approximately 360 EFPD and peak burnup ~15% FIMA
- PIE began in spring 2021
  - Non-destructive exam of all five capsule (neutron radiography and gamma scanning)
  - Disassembly of Capsule 2 is in progress

Neutron radiograph of Capsule 1



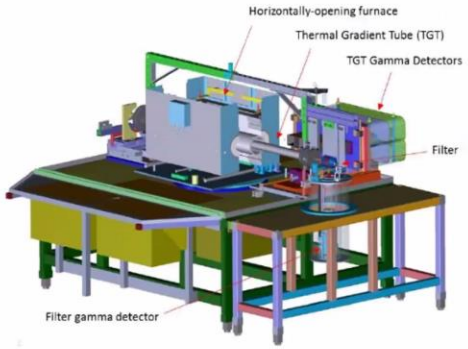
Disassembly of Capsule 2

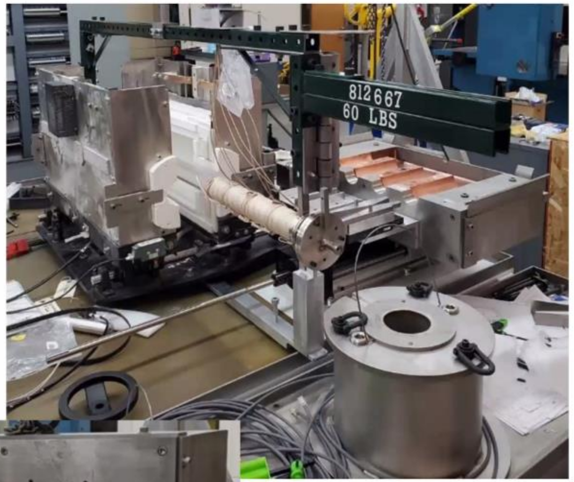
ADVANCED REACTOR TECHNOLOGIES

US sharing results of ”Advanced Gas Reactor TRISO Fuel Qualification Program” for UCO/UO_2 TRISO fuel

Task 3-2: Develop furnace system for air/steam tests on irradiated fuel

- Development of the Air Moisture Ingress Experiment (AMIX) furnace system continues at INL.
- System will be used to perform post-irradiation heating tests on fuel and materials specimens in oxidizing atmospheres while measuring the release of fission products
- System is expected to be operation in 2023



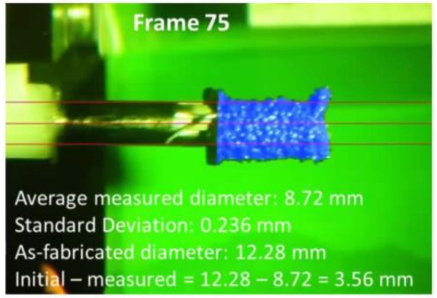


ADVANCED REACTOR TECHNOLOGIES

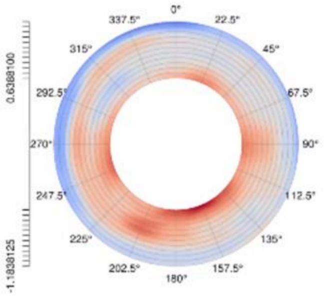
US sharing results of ”Advanced Gas Reactor TRISO Fuel Qualification Program” for UCO/UO_2 TRISO fuel

Task 3-4: AGR-3/4 PIE

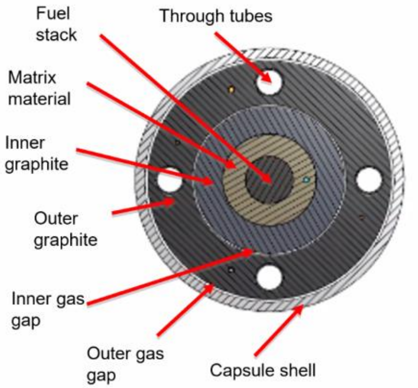
- AGR-3/4 PIE activities are mostly completed
- Primary remaining activity is destructive examination of fuel compacts by “radial deconsolidation-leach-burn-leach”.
- 12 compacts have been analyzed
- 9 compacts still to be analyzed



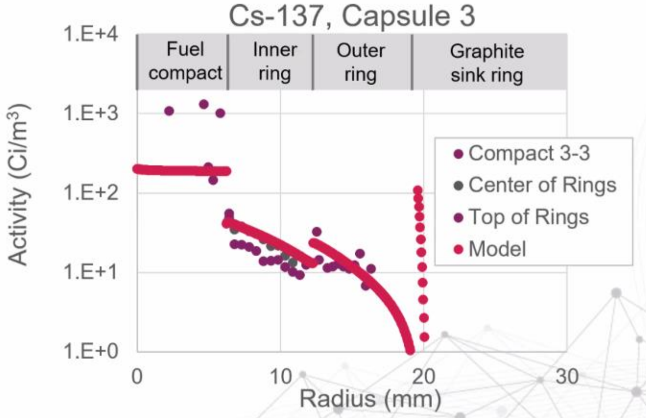
Compact after several deconsolidation steps, leaving only the core



IR-07 Cs-134 activity distribution



AGR-3/4 Capsule Cross Section

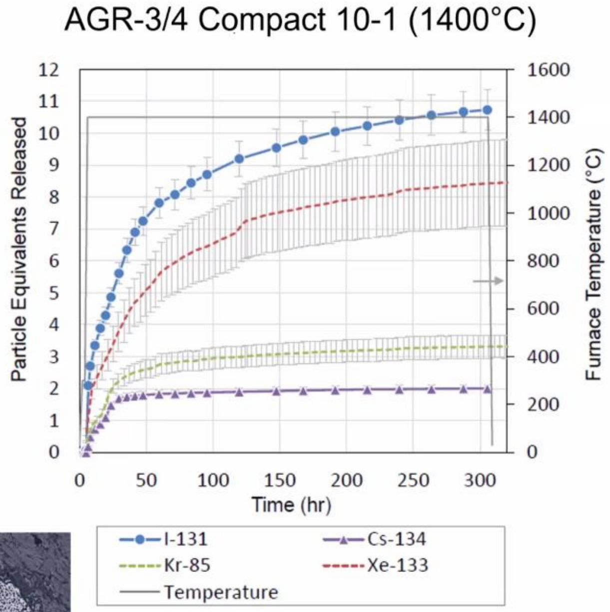


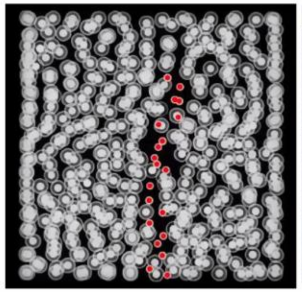
ADVANCED REACTOR TECHNOLOGIES

US sharing results of "Advanced Gas Reactor TRISO Fuel Qualification Program" for UCO TRISO fuel

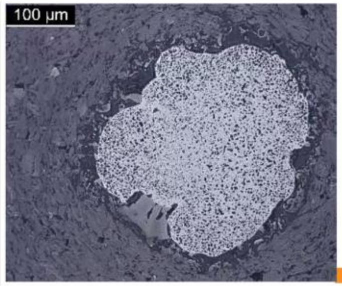
Task 3-4: AGR-3/4 heating tests

- Post-irradiation heating of AGR-3/4 compacts at 1200 – 1700°C while measuring fission product release in FACS furnace
- Some compacts are re-irradiated in the NRAD TRIGA reactor prior to heating tests (Task 1-1)
- Explore fission product release from "designed-to-fail" particles (exposed kernels) to help understand transport behavior
- Tests completed:
  - 4 "as-irradiated" compacts
  - 5 "re-irradiated" compacts
  - 2 tests remain for 2022
- Radial deconsolidation of heated compacts:
  - 4 complete
  - 5 remaining





X-radiograph of unirradiated AGR-3/4 compact; DTF highlighted by red dots



Irradiated DTF particle cross section

ADVANCED REACTOR TECHNOLOGIES

Korea sharing results on TRISO manufacturing technologies

Current Status of TRISO Fuel R&D in Korea

- Development of coated particle fuel technology (2006.03~2017.02)
  - External sol-gel process for UO_2 kernel fabrication
  - FB-CVD process for ZrC-SiC coating
  - Fuel compaction processes
  - Performance analysis code COPA
  - 1st neutron irradiation and PIE tests
- Development of fundamental technologies for improvement of TRISO fuel burn-up performance (2018.09~2020.12)
  - Modified external sol-gel method for large-sized UO_2 kernel
  - FB-CVD process for large UO_2 kernels
- Materials Performance Verification for Very High Temperature System (2021.01~2022.12)
  - Phase stability of ZrC-SiC interface under irradiation condition
  - Corrosion resistance of ZrC coating layer by fission product

FB-CVD - Fluidized Bed - Chemical Vapor Deposition

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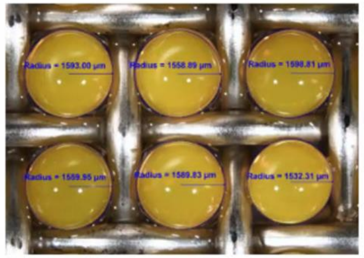
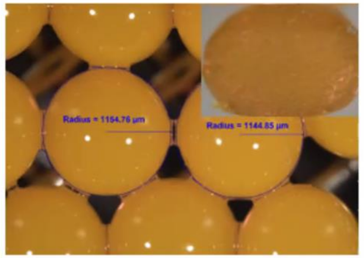
Large UO_2 Kernel Fabrication

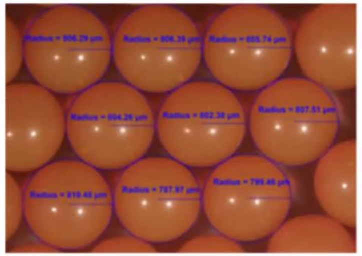
- Enhancing NH_4 gas contact and applying NH_4OH solution spraying system
- Addition of HMTA to uranium broth solution **HMTA - hexamethylenetetramine**
- Optimization of aging, washing and drying parameters
- High sphericity (0.949) and high density (10.78g/cm$_3$) of large UO_2 kernel (mean dia. : 804μm)



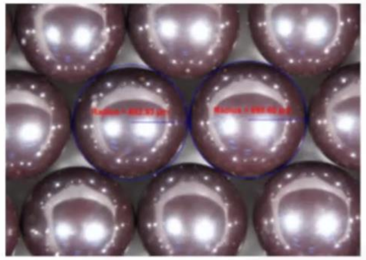
Casting



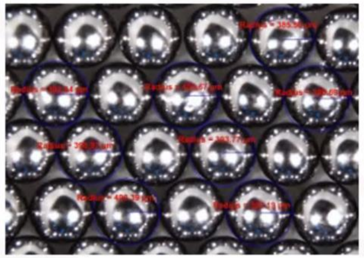
Aging



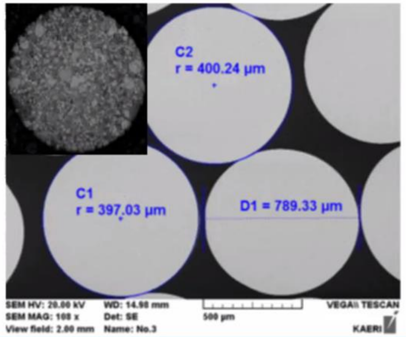
Drying

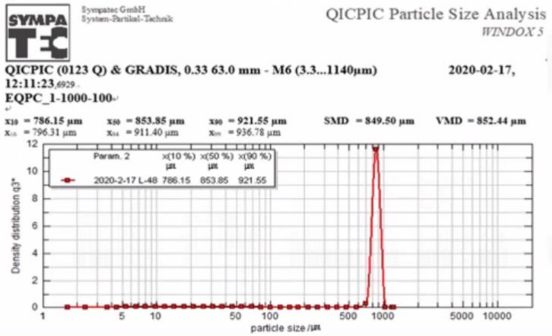


Calcination



Sintring





EQPC	799.926 μm
FERET_MAX	814.177 μm
FERET_MIN	798.560 μm
FERET_MEAN	804.533 μm
Sphericity	0.949
Aspect ratio	0.981
Image number	11868

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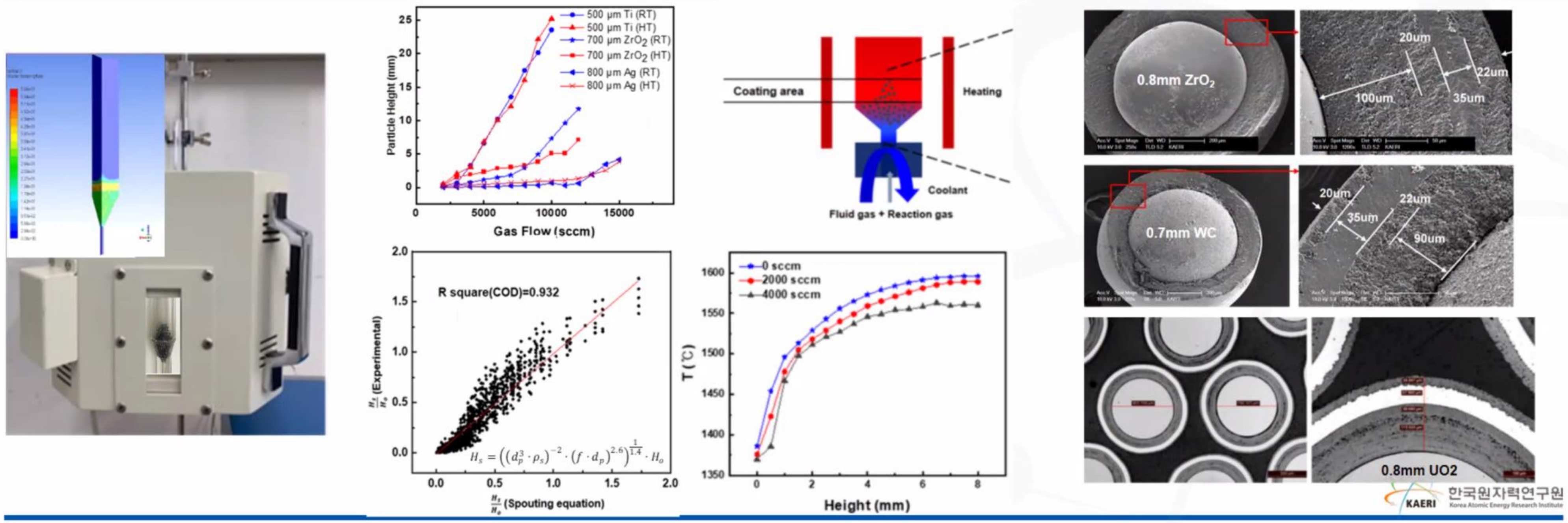
Fluidized Bed-Chemical Vapor Deposition Coating Process of Large UO_2 Kernels

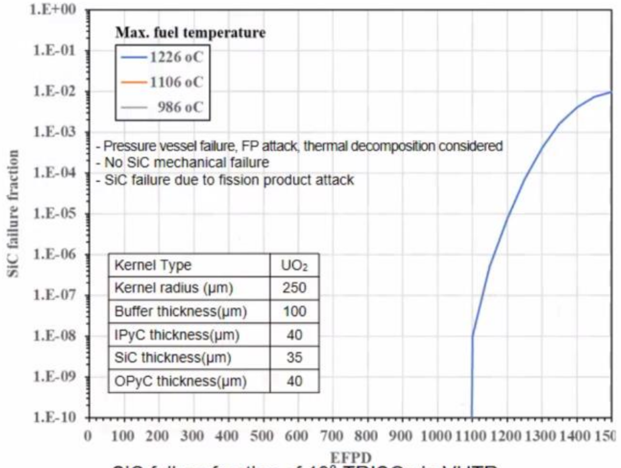
- Estimation of gas flow rate range for spouting of large UO_2 kernel using visualization apparatus and CFD analysis
- Derivation of relationship gas flow rate and spouting height through extensive tests
- Validation of the effectiveness of the empirical equation by coating surrogate kernels (0.8mm ZrO_2, 0.7mm WC)
- Optimization of coating conditions considering the change in hot zone location



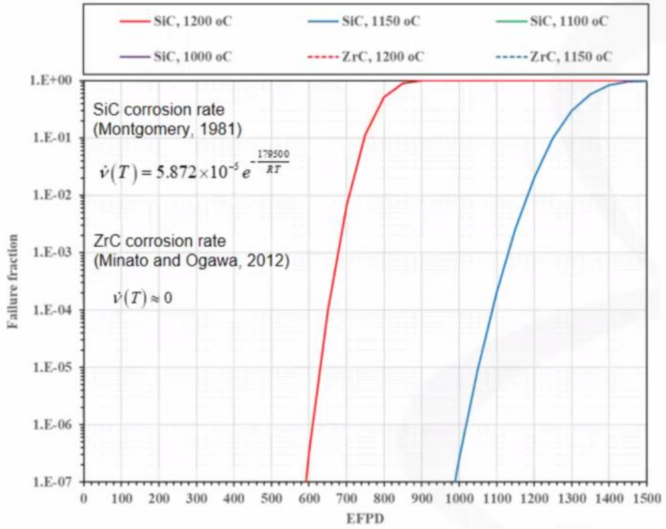
5

Design of an Advanced TRISO Fuel with ZrC Coating

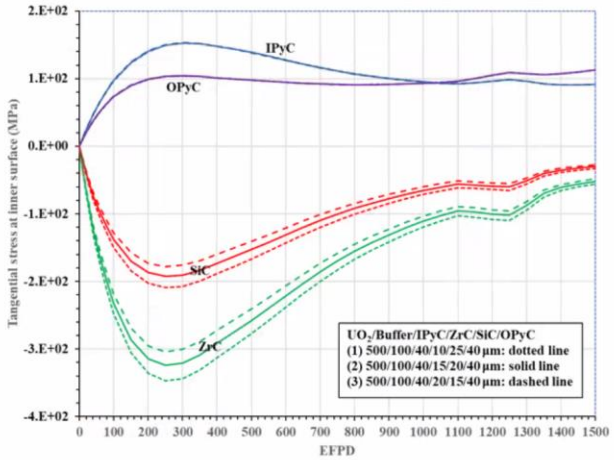
- Need to improve the safety of UO_2 TRISO-coated particle fuel for high burnup and high temperature operation of a VHTR (950C, 1500EPFD)
- Development of ZrC-SiC double layer concept and coating process
- Evaluation of FP corrosion resistance and design of ZrC-SiC double layers



SiC failure fraction of 10^8 TRISOs in VHTR



Failure fraction of TRISOs in VHTR by fission product attack only



Designs of ZrC-SiC double layers in a coated fuel particle

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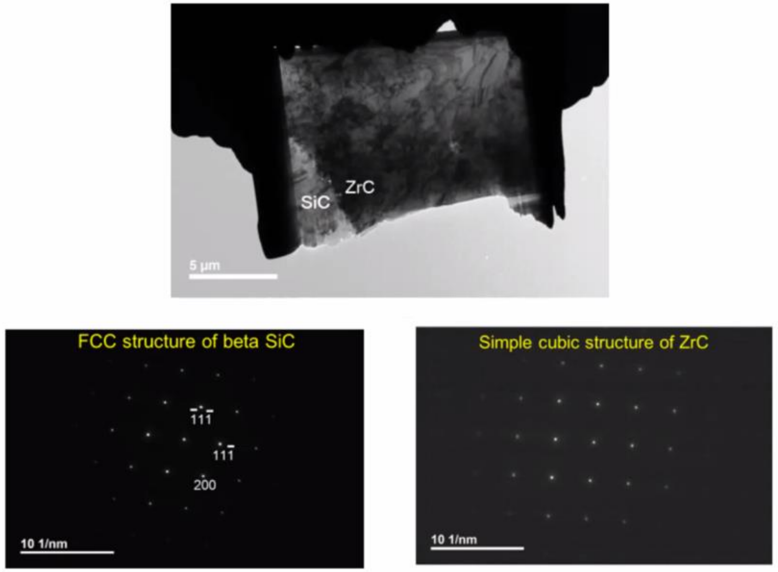
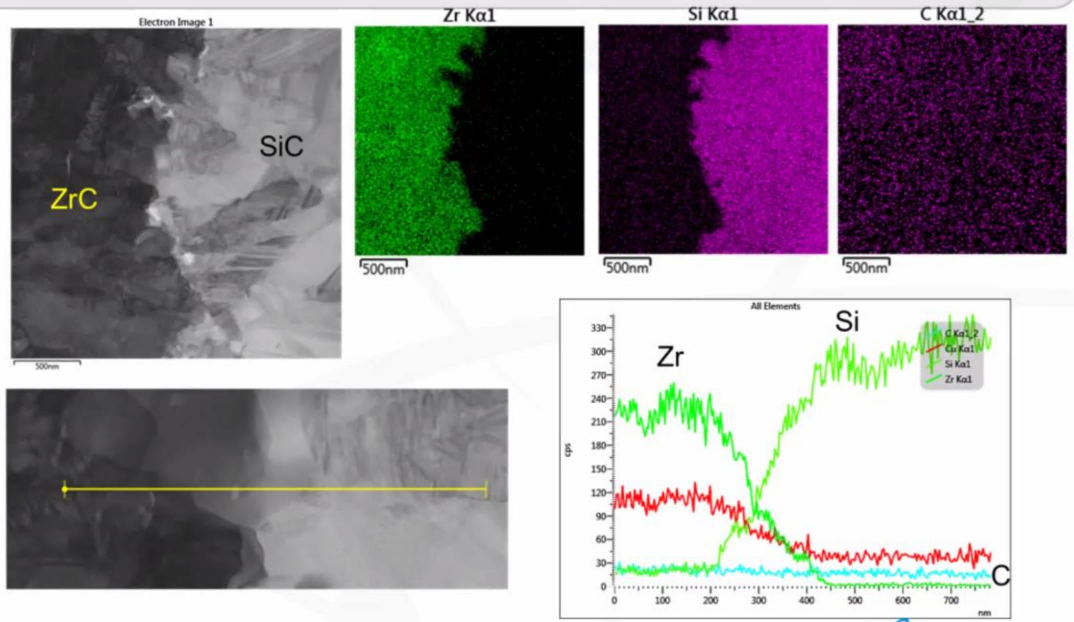
6

Simulated Irradiation Tests for ZrC-SiC Coatings

- Compatibility between ZrC and SiC layers under irradiation environment
- 5MeV proton irradiation to a dose of 1.2×10^{14} p/cm^2
- TEM and EDS analysis for ZrC-SiC interface
- Additional ion irradiation tests with heavy ion (Ar) are planned



Microstructures of ZrC and SiC coating layers



EDS analysis for ZrC and SiC elemental confirmations

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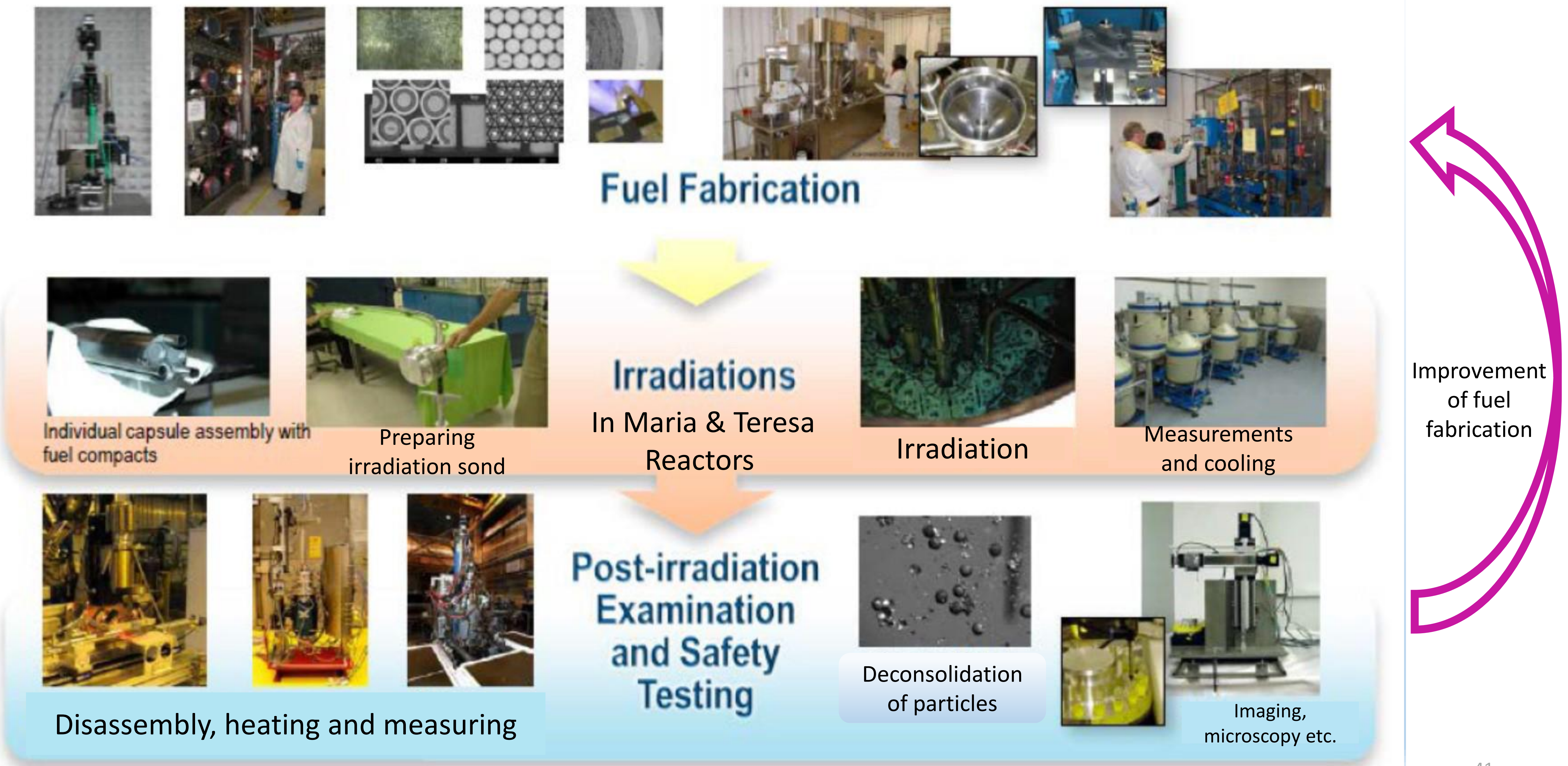
7

Summary

A vision for NCBJ-IChTJ-Industry TRISO fuel development and qualification program



Can TRISO fuel be used in other reactor designs?

- Molten Salt-cooled (e.g., FLiBe, FLiNaK,) reactor concepts use graphite matrix TRISO fuel directly, e.g. Kairos Power based on University of California – Berkeley pebble bed design

- Fast Gas Reactors, using SiC or other non-graphitic matrix compacts
  - French helium fast gas design ZrO_2 coating
  - UC fuel kernels in metallic cladding
  - GA's EM^2 alternate design

- Encapsulated fuel for LWR Accident Tolerant Fuel
  - TRISO in SiC matrix with SiC tubes or Zircalloy cladding (ORNL)

- Fast sodium/metal cooled reactors
  - Dispersion fuels, TRISO-like fuel in metallic matrix, metallic clad
  - TRISO in SiC Mixed Oxide fuel pellets (FFTF or MOX cores)

- Extreme high temperature reactors using refractory metals, UC or UN fuels
  - Space reactors, or niobium (Nb), tantalum (Ta), molybdenum (Mo), rhenium (Re), vanadium (V) and tungsten (W) alloys.

Reactor Design Concepts and Advanced Fuel Designs Using TRISO Fuel

Company or research group	TRISO Fuel Form, Reactor Type, Design Concept
UltraSafe Nuclear	Various TRISO fuel forms: FCM TRISO in SiC matrix pellets in SiC tubes **MMR prismatic HTGR reactor,** TRISO with refractory coatings for Space Applications (NASA contract) Canadian licensing underway, UIUC contracted an MMR for its campus
X-Energy	TRISO pebble-bed HTGR Xe-100 Reactor, TRISO-X fabrication facility. Awarded $80 Million for the Department of Energy's Advanced Reactor Demonstration Program (ARDP)
Dept. of Defense	TRISO fueled mobile micro-reactors for strategic combat locations. **BWX** Technologies and X-Energy were contracted
BWX Technologies	TRISO fuel fabrication for DOD microreactors, contracted for a battlefield microreactor
Kairos Power	TRISO pebble bed, fluoride salt (Li_2BeF_4) cooled, KP-FHR (**K**airos **P**ower **F**luoride Salt-Cooled, **H**igh Temperature **R**eactor
Urenco, Amec Foster-Wheeler+ more (UK)	TRISO compacts, prismatic HTGR, UCO or Th/U/0 TRISO kernels U-Battery 10 MW and 20 MW. UK's –HTGR choice within Advanced Modular Reactor program
StarCore Power (USA)	TRISO in graphite matrix pebbles, helium-cooled HTGR, 20 or 80 MW, STARCORE 20, STARCORE 80, StarCore Nuclear (Canada). Canadian review underway.
General Atomics	UC bare kernels in SiC tubes. May use TRISO-like coating(s) as an optional desiqn for fast-gas reactor Energy Multiplier Module EM^2
ORNL Accident Tolerant Fuel	FCM TRISO particles in SiC matrix pellets inside Zr, SiC or Stainless Steel cladding, as future LWR ATF replacement fuel
MIT (Charles Forsberg concept)	TRISO compacts, prismatic HTGR Fluoride salt (Li_2BeF_4) cooled FHR. Still pretty "academic" reactor
NASA	TRISO fueled compact reactor for future long-range missions for Mars for Space Nuclear Thermal Propulsion (UC or UN) : USNC, X-energy, BWXT

Thank You for your attention!