Status of the SFR technology developments in the Generation-IV International Forum: Reactor Design & Fuel R&D

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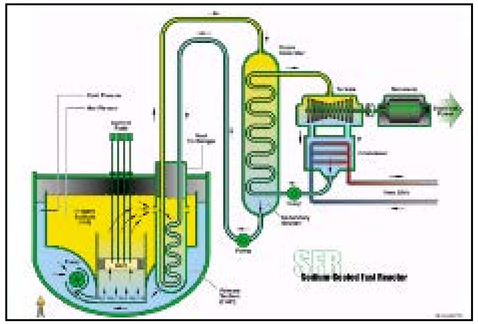
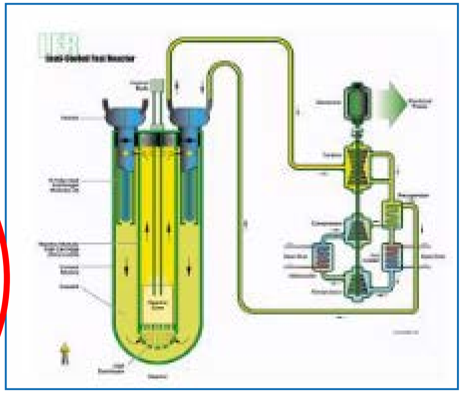
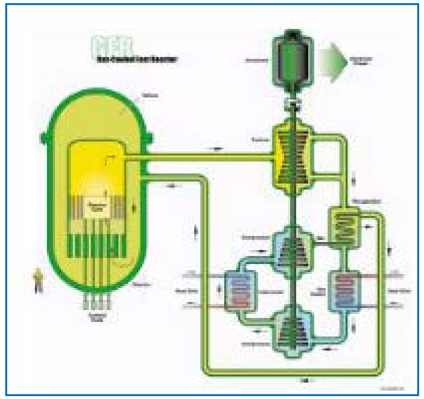
SFR : one of the six Gen-IV Nuclear Reactor Systems



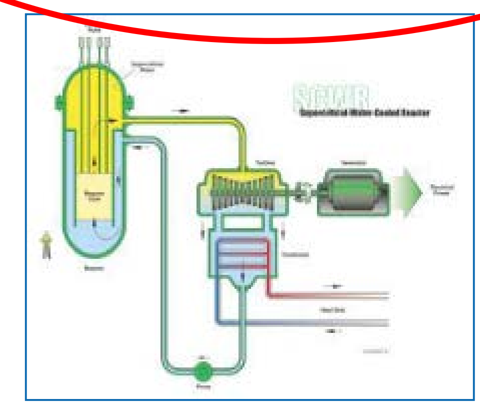
Sodium-cooled Fast Reactor (SFR)



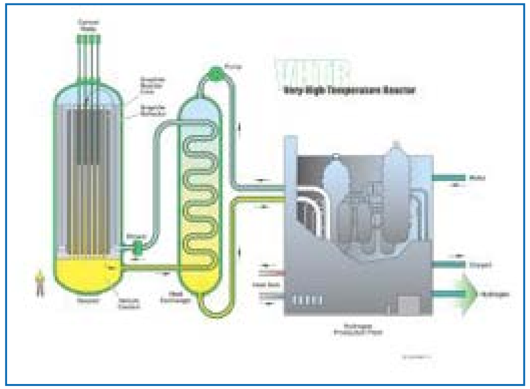
Lead-cooled Fast Reactor (LFR)



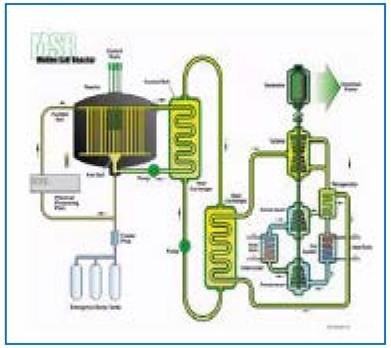
Gas-cooled Fast Reactor (GFR)



Supercritical Water cooled Reactor (SCWR)

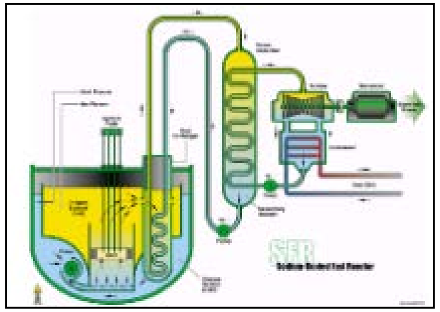


Very High Temperature Reactor (VHTR)



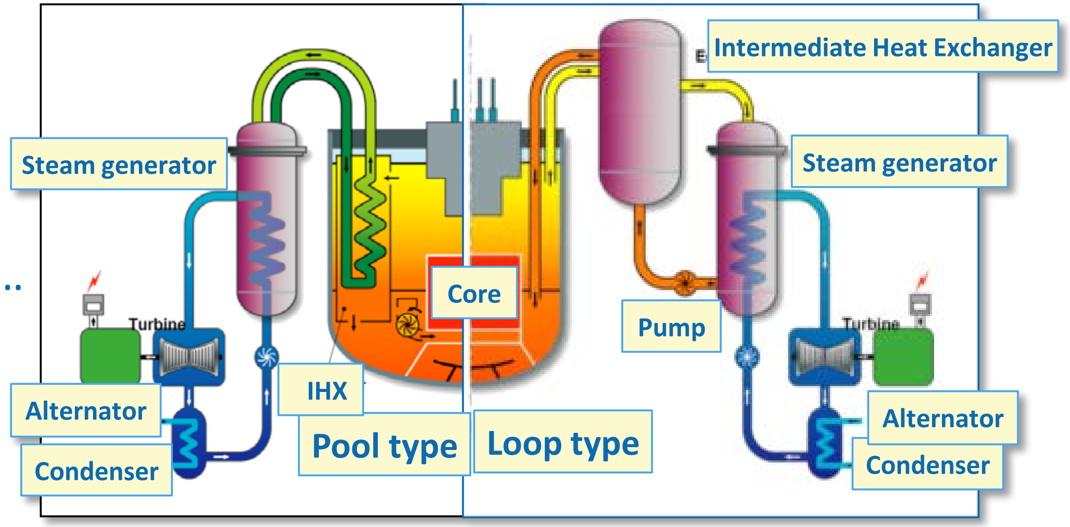
Molten Salt Reactor (MSR)

SFR: a concept with two major design options => Pool or Loop

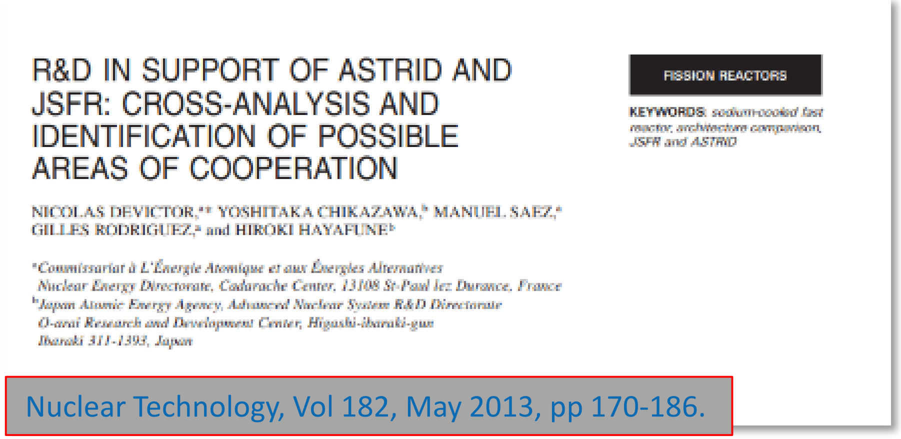


Sodium-cooled Fast Reactor (SFR)

Pool/Loop:
two major options…



… But it is possible to find similarities & joint approach



R&D IN SUPPORT OF ASTRID AND JSFR: CROSS-ANALYSIS AND IDENTIFICATION OF POSSIBLE AREAS OF COOPERATION

FISSION REACTORS

KEYWORDS: sodium-cooled fast reactor, architecture comparison, JSFR and ASTRID

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REGULAR ARTICLE — OPEN ACCESS

France–Japan synthesis concept on sodium-cooled fast reactor review of a joint collaborative work

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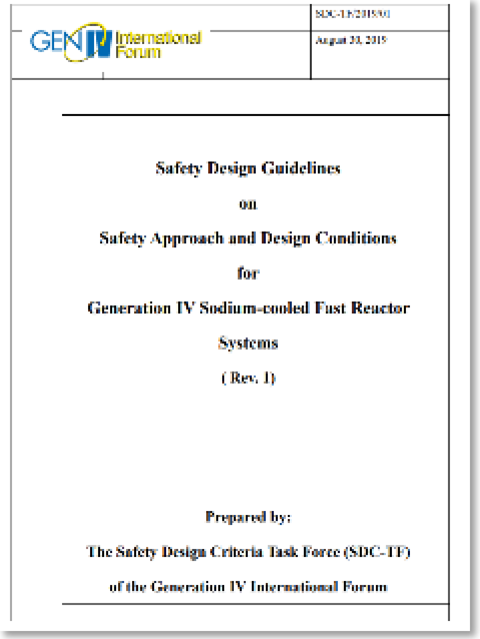


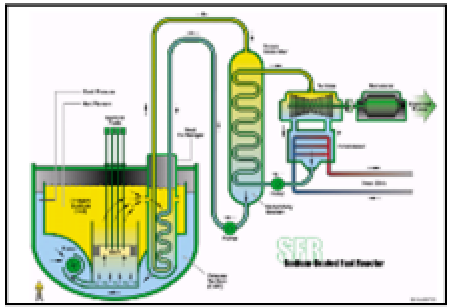
GEN IV International Forum

SDC-TF/2019/01
August 23, 2019

Safety Design Guidelines
on
Safety Approach and Design Conditions
for
Generation IV Sodium-cooled Fast Reactor Systems
(Rev. 1)

Prepared by:
The Safety Design Criteria Task Force (SDC-TF)
of the Generation IV International Forum

SFR: a concept with the highest level of maturity throughout the world



Sodium-cooled Fast Reactor (SFR)

TRL 7-8 is acquired in many countries…

… But R&D is still necessary

Sodium Fast Reactors Operational data (2021)

Reactor (Country)	Thermal Power	First Criticality	Final Shutdown	Operational period (years)
EBR-I (USA)	1,4	1951	1963	12
BR-5/BR-10 (Russia)	8	1958	2002	44
DFR (UK)	60	1959	1977	18
EBR-II (USA)	62,5	1961	1991	30
EFFBR (USA)	200	1963	1972	9
Rapsodie (France)	40	1967	1983	16
BOR-60 (Russia)	55	1968		53
SEFOR (USA)	20	1969	1972	3
BN-350 (Kazakhstan)	750	1972	1999	27
Phenix (France)	563	1973	2009	36
PFR (UK)	650	1974	1994	20
JOYO (Japan)	50-75/100	1977		44
KNK-II (Germany)	58	1977	1991	14
FFTF (USA)	400	1980	1993	13
BN-600 (Russia)	1470	1980		41
SuperPhenix (France)	3000	1985	1997	12
FBTR (India)	40	1985		36
MONJU (Japan)	714	1994	2016	22
BN-800 (Russia)	2000	2014		7
CEFR (China)	65	2010		11
PFBR (India)	1250	Under commissioning		
Total all fast reactors				468

- **R&D prospects are carried out towards:**
  - Enhanced safety demonstration: passive systems + better approach regarding sodium chemical reactivity, severe accident mitigation systems, increase ISI&R* capabilities
  - Investigate better performances in: load factor, reactor lifetime, reactor efficiency and fuel performances**
  - Consumption of transuranics in a closed fuel cycle (reducing the radiotoxicity and heat load), and facilitates waste disposal and geologic isolation. Enhanced utilization of uranium resources through efficient management of fissile materials and multirecycle.
  - Improve the Technico-economy approach: simplification of structures, improve manufacturing conditions for cost reduction and quality increase.
  - + Guaranty the supply chain and preserve the sodium technology knowledge and know-how (liquid metal handling & good practices)

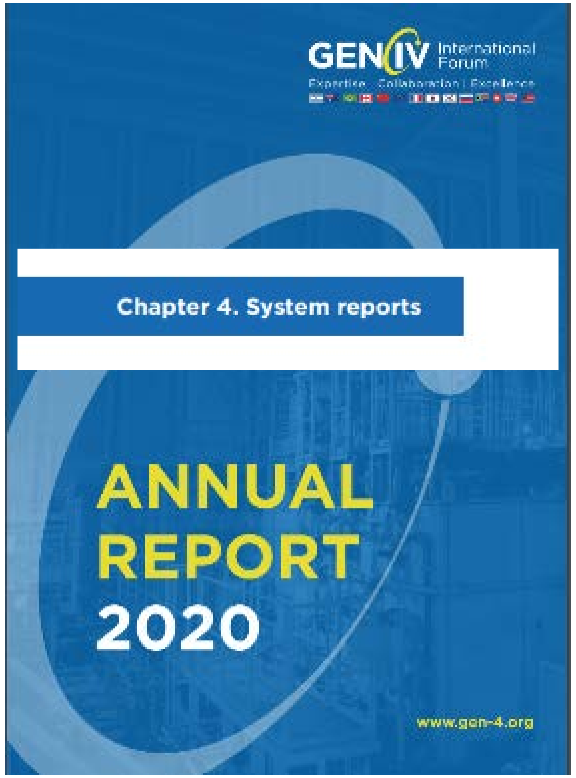
*ISI&R: In-Service Inspection & Repair

**: See focus from F. SERRE

Highlights related to SFR: R&D in GENIV

- **One of the 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)

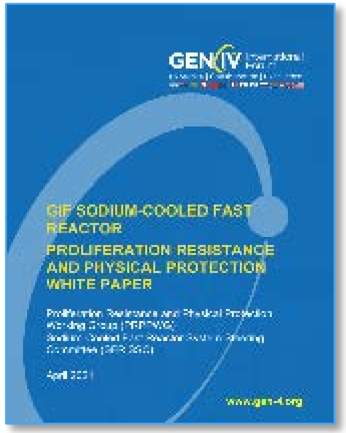
See main R&D progress in the 2020 Annual report / Chap 4
https://www.gen-4.org/gif/jcms/c_178286/gif-2020-annual-report



- **Five SFR Design Concepts:**
  - Loop Option (JSFR Design Track)
  - Pool Option (KALIMER-600, ESFR, and BN1200 Design Tracks)
  - Small Modular Option (SMFR-ANL Design Track)
- Revision of **SFR System Research Plan** was completed and approved by System Steering Committee in October 2019

Significant joint milestones

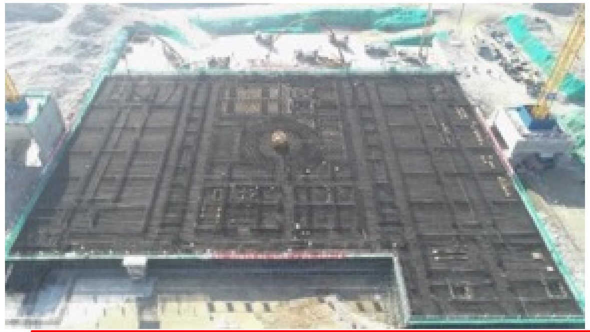
- Joint paper on SFR Safety Design Criteria (SDC) – Safety Design Guidelines (SDG)
- **White Paper on the SFR PRPP aspects** has been finalised and soon published



Some main highlights related to SFR: projects around the World

- **China**: 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 => Continuation foreseen with the New EURATOM Call
- **Russia**: MBIR Project
- **USA**: NATRIUM (TERRAPOWER) & VTR reactors under project

CFR-600
Fuel fabrication site (TVEL) Source TVEL website



Construction site of CFR-600 – source WNN

NATRIUM source: https://www.nrc.gov/docs/ML2119/ML21196A058.pdf

ESFR-SMART
sodium fast reactor safety

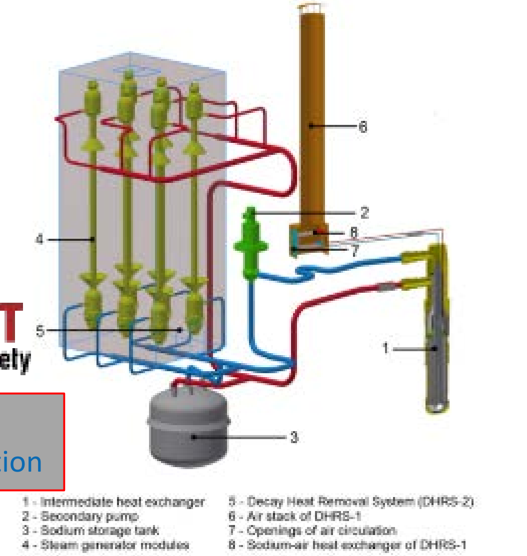


Figure 11. General view of the ESFR-SMART secondary loop with the initial option of flexible pipes between the components.

Figure coming from the GENIV Handbook – 2nd edition

Highlights on Advanced Fuel Project Outcomes

A Long Lasting GIF cooperation on the SFR Advanced Fuel Issues

- **First Advanced Project Arrangement signed for 10 years on March 2007**
- **New Advanced Project Arrangement signed for 10 years on April 2018**
- **Amendment to be signed soon:**
  - **For UK new membership,**
  - **With Project Plan Update (including Partners commitments)**

Members:

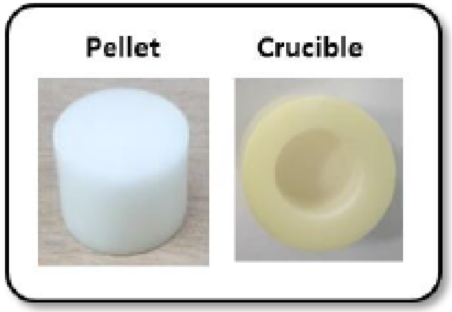
China (CIAE) *EURATOM (JRC)* *France (CEA)*

Japan (JAEA) *Korea (KAERI)* *RF (Rosatom)* *US (USDOE)*

Joining Member: *United Kingdom (BEIS)*

Top Advanced Fuel Project Objectives:

- **Selection of high burn-up Minor Actinide bearing fuel(s)**
- **Selection of cladding and wrapper withstanding high neutron doses and temperatures**
  - **Candidates:**
    - Non Minor-Actinide Driver fuels (Oxide, Metal, Nitride & Carbide)
    - Inert Matrix Fuels & Minor Actinide Bearing Blankets
    - Core materials:
      Ferritic/Martensitic & Oxide Dispersed Strengthened (ODS) steels
  - **Scopes**
    - Fabrication
    - Behavior under irradiation



RoK: Reusable crucible development for metallic fuel casting process

RF: High-Voltage Compaction Method for production of Fuel Pellet (Lab-Scale)

Main Outcomes of the Advanced Fuel Project phase 1 (2007-2017) (1)

2009: Report on ‘Advanced Sodium Fast Reactor (SFR) Fuel Comparison’

2015: Revision 1 of the report ‘Advanced Sodium Fast Reactor (SFR) Fuel Comparison’

- The internal GIF report includes:
  - the choice and direction of researches, development and qualification
  - Knowledge on fuel under study and development
    - Oxide, metal, nitride, and carbide fuels
- Main Goals (and challenges) for development of transmutation in SFRs:
  - To achieve high burn-up
  - For Operation at high temperature
  - With incorporation of Minor Actinides
- Main Physical limitations to meet these goals:
  - Fuel swelling
  - Cladding inner oxidation
  - Dimension stability of core materials (mainly due to dose rate)

Main Outcomes of the Advanced Fuel Project phase 1 (2007-2017) (2) Fuel Type Recommendations (1)

2015: Report ‘Advanced Sodium Fast Reactor (SFR) Fuel Type Recommendation’ including revision 1 of ‘Advanced Sodium Fast Reactor (SFR) Fuel Comparison’

- **Gives recommendations regarding preferred driver fuels and transmutation fuel types:**
  - Confirms the Advanced Fuel Comparison report dated 2009
  - Fuel type selection, for each country, is dependent upon multiple domestic factors:
    - Country experiences
    - Infrastructures
    - Domestics policies

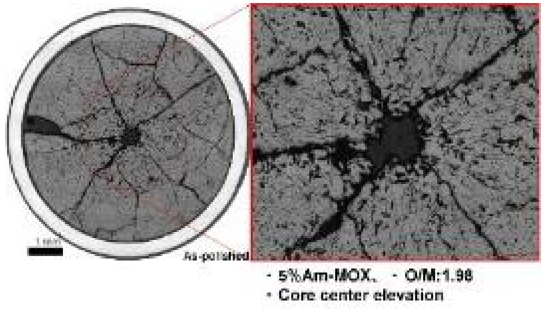
China: CEFR – A platform for R&D International Cooperation on Fast Reactors

Main Outcomes of the Advanced Fuel Project phase 1 (2007-2017) Fuel Type Recommendations (2)

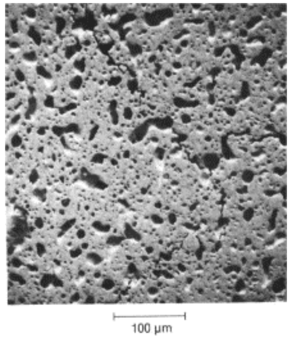
2015: Report ‘Advanced Sodium Fast Reactor (SFR) Fuel Type Recommendation’

Main Conclusions on Fuel R&D and readiness (1)

- **Oxide Fuel**
  - Highest technical readiness level; Demonstration of adequate performances:
    - For high burn-up for fuel at assembly level
    - For transmutation fuel at the fuel pin level
- **Metallic Fuel**
  - Substantial experience demonstrated at the assembly level
  - Issues identified regarding high-burn-up and transmutation have technical solutions that are being assessed via in-pile testing



Japan: Photomicrograph of 5% Am MOX fuel from the AM 1 10 minute irradiation in Joyo



US: Fission gas pore morphology of irradiated U 10Zr fuel

Main Outcomes of the Advanced Fuel Project phase 1 (2007-2017) Fuel Type Recommendations (3)

2015: Report ‘Advanced Sodium Fast Reactor (SFR) Fuel Type Recommendation’

Main Conclusions on Fuel R&D and readiness (2)

- **Nitride/Carbide Fuel:**
  - fairly extensive and adequate performance demonstrated at the pin, sub-assembly and assembly (nitride) level for driver fuel
    - High burn-up and transmutation; no critical issues identified; technologies in early stage of assessment
- **Target Fuel system dedicated to transmutation**
  - Early stage of development and assessment
  - Potential issues that have been identified being assessed via in-pile testing

Euratom: MA-bearing transmutation oxide-based fuel synthesis device using Hydrothermal Decomposition

Main Outcome of the Advanced Fuel Project phase 1 (2007-2017) Fuel Type Recommendations (4)

2015: Report ‘Advanced Sodium Fast Reactor (SFR) Fuel Type Recommendation’

Main Conclusions on Fuel and Clad/Wrapper Material Selections

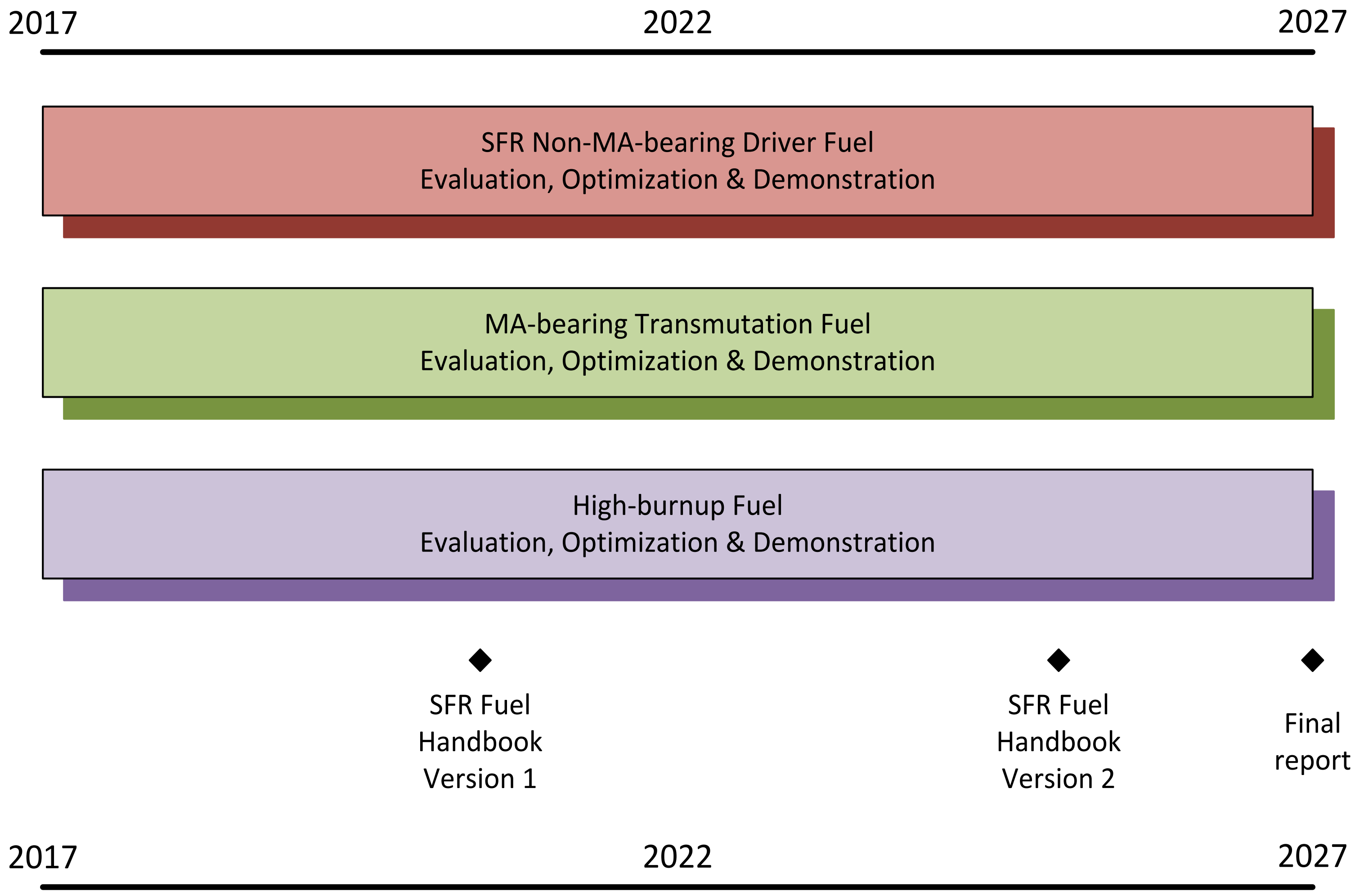
- **Fuel Selection:**
  - China, France, Japan and Euratom selected oxide fuel, at least for initial SFR start-up
  - US and Republic of Korea are working to start-up with metal fuel
  - Russia has selected nitride fuel for BN-1200
- **Clad/Wrapper selection: Partners’ recommendations**
  - Start with ferritic/martensitic clad/wrappers
  - In a longer time, switch to other advanced alloys such as oxide dispersed strengthened steels

Advanced Fuel Project Plan (2017-2027)

Continuation of 2007-2017 Project Plan with additional evaluation, optimization and demonstration of selected fuel candidates

- Advanced Fuel development efforts on three research items (see figure)
  - Investigation of specific knowledge gaps on oxide and metal fuel (highest technical readiness level)
  - Continuation of evaluation of nitride, carbide and inert matrix as medium and long term options

- AF Project Output: SFR Fuel Handbook
  - Current state of science and technology

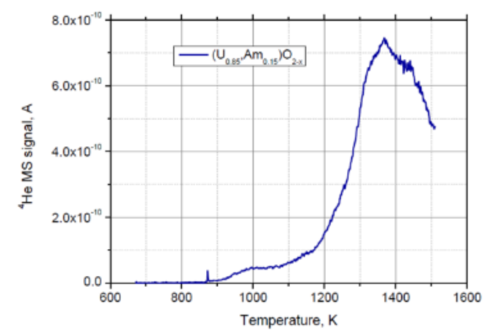


Examples of 2020 outcomes from the GIF SFR Advanced Fuel Project

Given in the GIF Annual Report 2020

- **WP2.1: SFR non-MA-bearing driver fuel evaluation, optimization and demonstration**
  - CIAE: For irradiation tests, fabrication of dummy assemblies and out-of-pile hydraulics tests
  - CEA: Characterization of the PAVIX-8 axially heterogeneous pins irradiated at intermediate Linear Heat Rate in PHENIX and assessment of GERMINAL V2 code against the experimental results
  - JAEA: Technology development (nanoparticle coating) for minimizing fuel retention in glove box
- **WP2.2: MA-bearing transmutation fuel evaluation, optimization and demonstration**
  - Euratom: Investigation of He release mechanisms from $(U,Am)O_2$
  - JAEA: Development and evaluation of simplified pelletizing process for MA-bearing MOX
  - KAERI: Analyses of interaction Casting/U-10%Zr with Rare-Earth; Alternative crucibles and mould demonstrated using a casting of the U-Zr-Rare-Earth alloy
  - Rosatom: Developments of manufacturing process for Am-burning element (heterogeneous scenario)

Helium release measured by KEMS from $(U_{0.85}, Am_{0.15})O_2$



- **WP2.3: High-burn-up fuel evaluation, optimization and demonstration**
  - CIAE: preparation of CN-1515 and CN-FMS material irradiation tests in the CEFR (Fabrication of claddings done)
  - CEA: Characterization of irradiated cladding tubes of 15-15Ti AIM1 from two different fabrication routes (GDMS, tensile tests)
  - JAEA: high- and ultra-high-temperature creep rupture tests of 9Cr-ODS steel clads and comparison with 11Cr-ferritic/martensitic steel clads
  - KAERI: technology development to suppress fuel-clad chemical interaction for the use of MA-bearing metal fuel (Cr plating)
  - Rosatom: Development and manufacturing of BN-600 irradiation assemblies

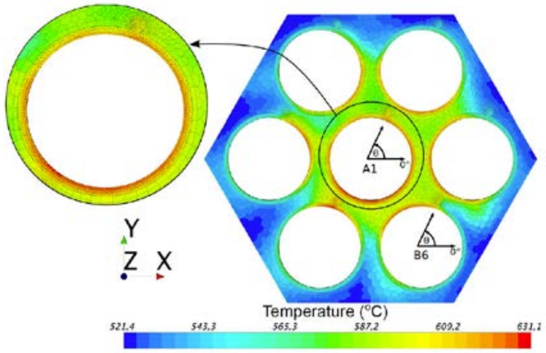
2020: Synthesis on GIF SFR Advanced Fuel R&D (for Oxide, Metal and Nitride Fuels)

GIF Contribution to OECD/NEA/WGSAR report on Fuel Qualification of Advanced Reactors
To be presented and issued in proceedings of Fast Reactor *

- **Introduction:** Advantages of each fuel candidates
- Typical Fuel element description
- Role in Safety Cases
- Challenges for Fuel Qualification
- **Conclusions:**
  - Acquisition of fuel performance is the most common and effective method to qualify the integrity of fuel pins and fuel subassemblies
  - A variety of irradiation experiments for SFR oxide, metal and nitride fuels were identified
  - Today, Fast Spectrum irradiation capabilities are very limited internationally
  - Fuel testing campaigns can require a great deal of time and expense

  ⇒ Advanced fuel modeling techniques simulating the fuel irradiation behavior will play a significant role in future fuel qualification

    - With the main challenge validating the predictability of complex fuel performance phenomena identified for each type of fuel



France: Simulation of 3-D pin deformation with thermomecanical (Domajeur2) and Thermohydraulics (STAR-CCM+) coupled codes

***REFERENCE FUEL OPTIONS FOR GENERATION-IV SODIUM-COOLED FAST REACTORS,** F. SERRE[1], N. CHAUVIN[1], M. PELLETIER[1], P. GAUTHE[1], R. N. HILL[2], T. SOFU[2], T. E. SOWINSKI[3], S. OKAJIMA[4], K. ISHII[4], S. KUBO[4], S. MAEDA[4], , J-W YOO[5], J CHANG[5], J CHEON[5], I. PAKHOMOV[6], L. ZABUDKO[7], N. J. BARRON [8], H. TSIGE TAMIRAT[9], L. REN[10]
[1]CEA (FR), [2]ANL, (US) [3]DOE (US), [4]JAEA (JP), [5]KAERI (ROK), [6],SSCRF (RF), [7]JSC PRORYV (RF), [8]NNL (UK), [9],EURATOM (EU), [10]CIAE (China)

Some general conclusions on SFR design and Fuel R&D

- **A huge amount of knowledge has been accumulated and on SFRs, coming from several decades of operation and studies,**
- **Liquid sodium is a mastered coolant but its handling requires a specific know-how**
- **Preservation of knowledge and training of new generation are key issues**
- **SFR technology, which is quite mature, has a big potentiality to meet future needs of energy production and sustainability in case of rapid nuclear sector expansion**
- **In preparation of its deployment, following issues require further R&D : Passive safety systems, Severe accident countermeasures, CAPEX reduction, Flexibility, Lifetime extension and Fuel performance**

A key organization to deal with these Challenges:

GEN IV International Forum
Expertise | Collaboration | Excellence

- **As other SFR projects, AF Project allows the GIF partners to share R&D national progresses, to discuss/benchmark the results for further R&D orientation, and to gather the state of the art in joint documents**