GEN IV International Forum

Expertise | Collaboration | Excellence

Generation-IV International Forum

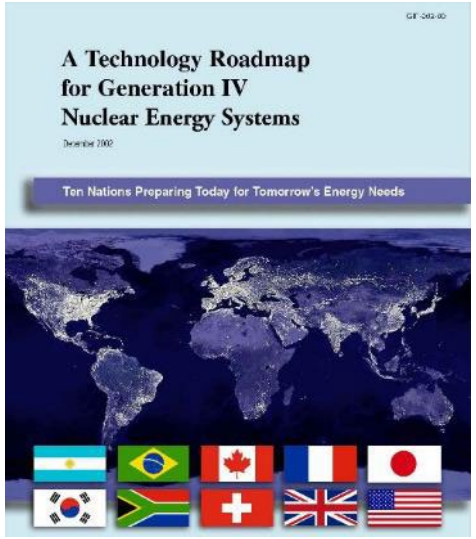
Hideki KAMIDE

Japan Atomic Energy Agency

GIF Chair

Genesis of Generation IV Concept

- In 1999, low public and political support for nuclear energy
  - Oil and gas prices were low
- USA proposed a bold initiative in 2000
  - The vision was to leapfrog LWR technology and collaborate with international partners to share R&D on advanced nuclear systems
  - 9 Countries and EU joined USA in developing the initiative
  - Oil prices jumped soon thereafter
- Gen IV concept defined via technology goals and legal framework
  - Technology Roadmap released in 2002
    - 2 year study with more than100 experts worldwide
    - Nearly 100 reactor designs evaluated and down selected to 6 most promising concepts
  - First signatures collected on Framework Agreement in 2005; first research projects defined in 2006



"This may have been the first time that the world came together to decide on a fission technology to develop together."
William Magwood IV, First Chairman of the Generation IV International Forum

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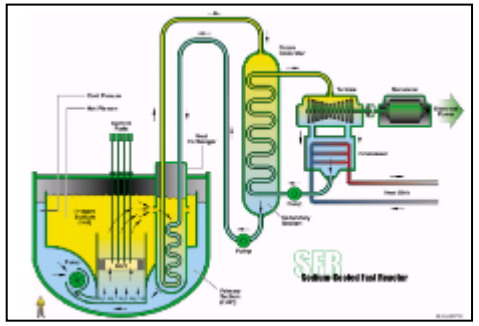
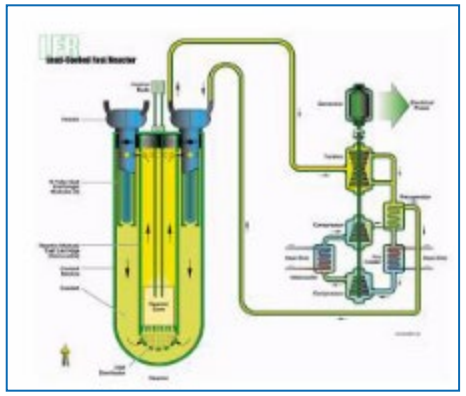
GIF Goals for Generation-IV Reactor Systems

- Sustainability
  - Long term fuel supply
  - Minimize waste and long term stewardship burden
- Safety & Reliability
  - Very low likelihood and degree of core damage
  - Eliminate need for offsite emergency response
- Economics
  - Life cycle cost advantage over other energy sources
  - Financial risk comparable to other energy projects
- Proliferation Resistance & Physical Protection
  - Unattractive materials diversion pathway
  - Enhanced physical protection against terrorism

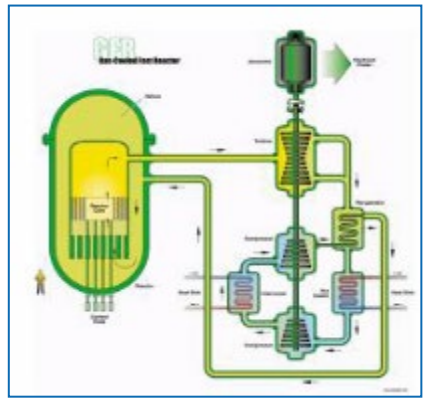
Gen-IV Nuclear Reactor Systems



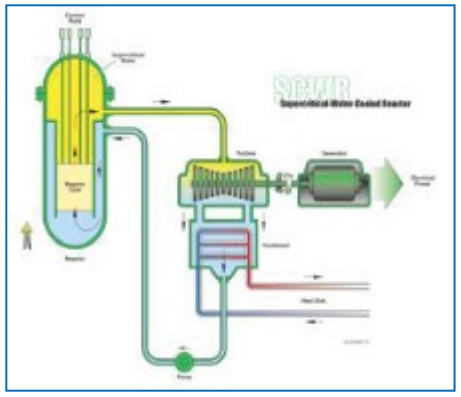
Sodium-cooled Fast Reactor (SFR)



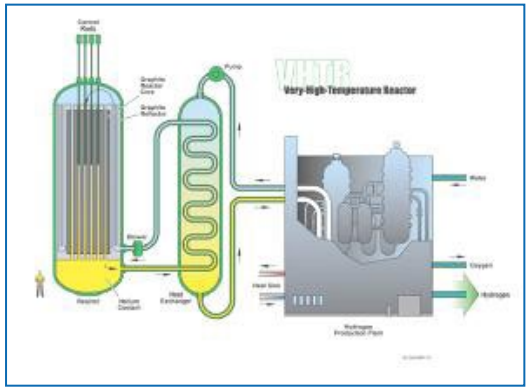
Lead-cooled Fast Reactor (LFR)



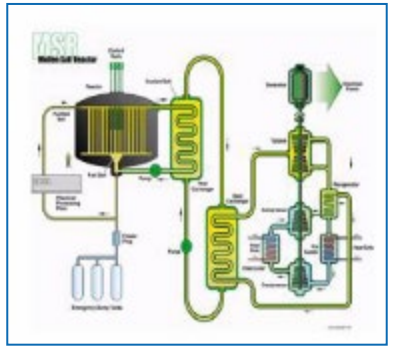
Gas-cooled Fast Reactor (GFR)



Supercritical Water cooled Reactor (SCWR)



Very High Temperature Reactor (VHTR)



Molten Salt Reactor (MSR)

Comparisons of Major Specifications

System	Neutron Spectrum	Coolant	Outlet temp. (Degree C)	Fuel cycle
Sodium-cooled Fast Reactor (SFR)	Fast	Sodium	500-550	Closed
Lead-cooled Fast Reactor (LFR)	Fast	Lead	480-570	Closed
Gas-cooled Fast Reactor (GFR)	Fast	Helium	850	Closed
Molten Salt Reactor (MSR)	Thermal/ Fast	Fluoride/Chloride salts	700-800	Open/ Closed
Supercritical Water-cooled Reactor (SCWR)	Thermal/ Fast	Water	510-625	Open/ Closed
Very High Temperature Reactor (VHTR)	Thermal	Helium	900-1000	Open

Involvement of GIF Members in R&D on Gen-IV systems

SFR			●	●	●	●	●			●	●	●
VHTR	●	●	●	●	●	●			●	●	●	●
LFR			●		●	●	●			●		●
SCWR		●	●		●		●					●
GFR				●	●							●
MSR	●	●		●			●		●	●		●

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Non active members

Missions of GIF (2019-2021)

- Market Opportunities and Challenges for Deployment
  - Enhanced interaction with industry, incl. with SMR vendors
- Safety and Regulation
  - Increased interaction with the regulators, e.g. in the frame of the NEA Working Group on Safety of Advanced Reactors (WGSAR) and IAEA
  - Development of system-specific Safety Design Criteria (SDC) and Guidelines (SDG)
- Enhancement of R&D cooperation
  - Use of R&D infrastructures to improve international collaboration - R&D Infrastructure TF
- Improved communication of GIF Results to Citizens, Policy makers, Regulators, Industry
  - Network with CEM (NICE Future Initiative), IFNEC, WNA….
  - New GIF newsletters and GIF visual branding, GIF Webpage
- Enhanced Education & Training as well as Knowledge Management

GIF Organization

Policy Group (PG)

Expert Group (EG)

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Senior Industry Advisory Panel

Policy Director and Technical Director
Technical Secretariats

Methodology / Opportunity Working Group (WG)

- Risk and Safety WG (RSWG)
- Proliferation Resistance and Physical Protection assessment methodology WG (PRPPWG)
- Economic Modelling WG (EMWG)
- Education & Training WG (ETWG)

Task Force (TF to solves specific issue)

- Advanced Manufacturing and Material Engineering TF (AMME-TF)
- Research & Development Infrastructure TF (RD-TF)
- Non-Electric applications of Nuclear Heat interim TF (NEaNH-iTF)

System Steering Committees

- Sodium-cooled Fast Reactor (SFR)
- Very High Temperature Reactor (VHTR)
- Supercritical-water-cooled Reactor (SCWR)
- Gas-cooled Fast Reactor (GFR)
- Lead-cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)

Project Management Boards

- System Integration Assessment
- Advanced Fuel
- Safety and Operation
- Component Design & Balance-Of-Plant

- Fuel and Fuel Cycle
- Code Verification
- Materials
- Hydrogen Production
- (System Integration Assessment)

- Thermal-hydraulics and Safety
- Water Chemistry and Materials
- (System Integration Assessment)

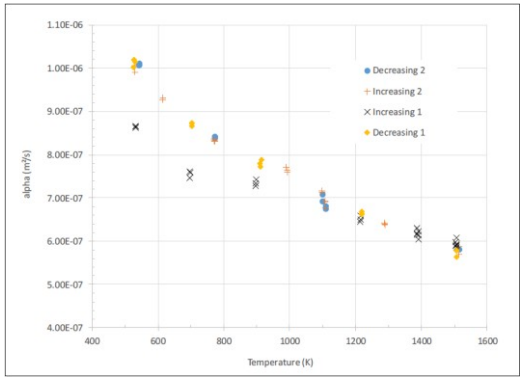
- Conceptual Design and Safety
- (Fuel and Core Materials)

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-ANL 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/

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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
- **Europe**: Euratom collaboration project **GEMINI+** project is ongoing, in which partners are working together towards the demonstration of high temperature nuclear cogeneration with an HTR in Poland – cf. presentation of D. Hittner (NC2I) and M. Fütterer (JRC) in Session 5

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/

Advanced Manufacturing and Material Engineering (AMME) Task Force

- AMME is a key for cooperation with Industry (SMR Vendors…)
  - Innovation for Safety and Economy of construction, operation, and maintenance, inspections. AI is also significant issue
- Advanced Manufacturing Workshop held at NEA in Feb. 2020
- AMME-TF is newly launched in GIF
  - Requirements Capture
    - Given the rapid change in advanced manufacturing, this group will work to identify the needs of the community.
  - Qualification, Demonstration and Deployment
    - New approaches and methods for qualification are key to the deployment of advanced manufacturing. The first focus is to identify these commonalities in qualification across different reactor systems.
  - Design and Modelling
    - Meeting the need to capture and share processes and methodologies for ensuring product quality by a) collecting experience, b) sharing, and c) benchmarks (including data driven AI approaches).

Workshop

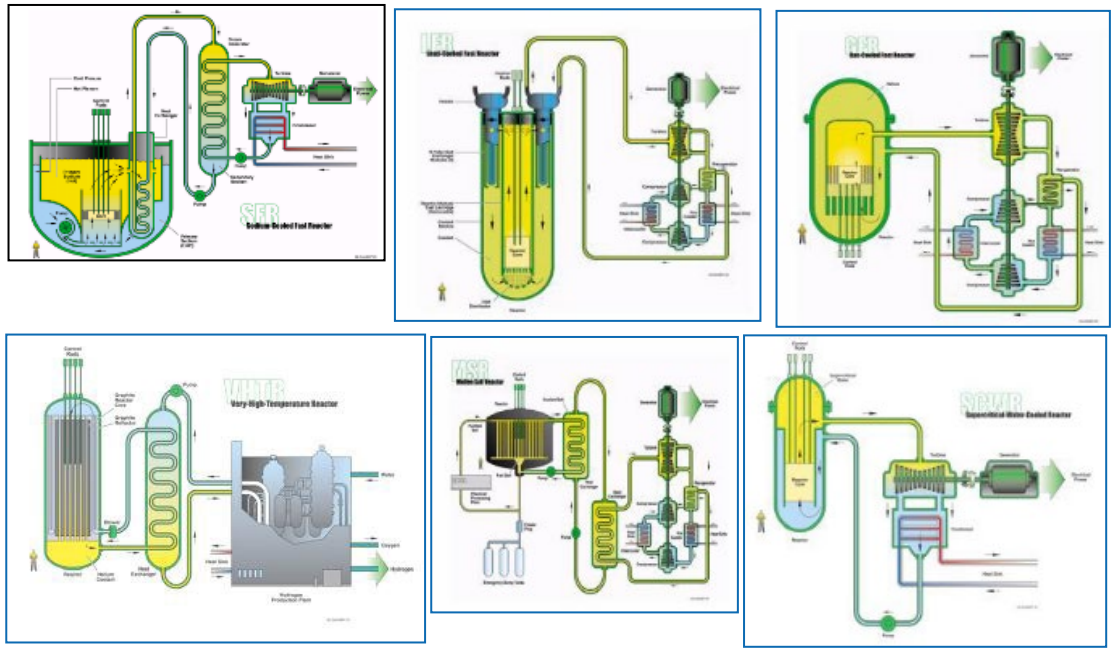
Small Group discussions

Non-electric Application of Nuclear Heat (NEaNH)

New Task Force of NEaNH for higher Flexibility to cover all Gen-IV systems and required R&Ds

- Heat application will be a key for Nuclear to contribute to the Carbon Neutral

Reactor Types



SFR, LFR, GFR
VHTR, MSR, SCWR

(High Temperature Systems)

X

Reactor Size

Power Reactor
SMR
Micro Reactor

X

Applications

- ✓ Cogeneration application
- ✓ Hydrogen production
- ✓ Seawater Desalination
- ✓ Process heat
- ✓ Synthetic Fuel and Chemicals
- ✓ Cooling application
- \+ Heat Storage

Matrix of 6 x 3 x 6

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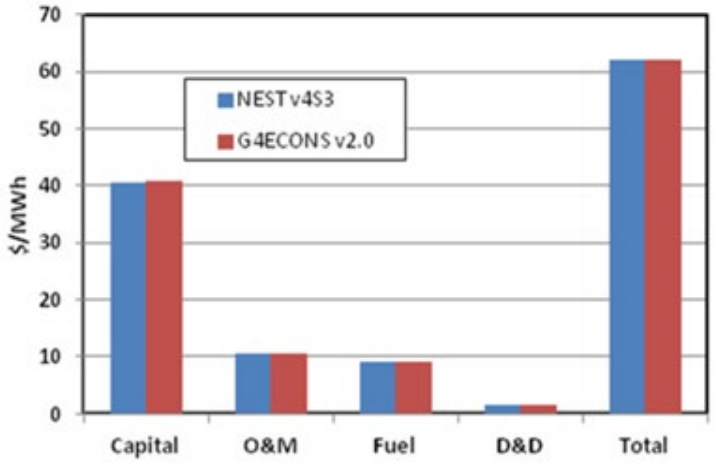
GIF Methodologies

EMWG – Economics Modelling WG

- Developed the G4ECONS software (freely available)
  - Assess the costs of Gen IV designs and identify cost drivers
- Approaches on life-cycle cost reduction
- Financial Issues on Gen-IV systems deployments
  - Report on Nuclear Energy: an ESG Investable Asset Class

https://www.gen-4.org/gif/jcms/c_9364/economics for "Cost Estimating Guidelines", "Impact of Increasing Share of Renewables", and "Nuclear Energy: An ESG Investable Asset Class"



Benchmarking (G4ECONS vs. IAEA NEST)

PRPPWG – Proliferation Resistance and Physical Protection WG

- Through a case study, developed a methodology to evaluate & facilitate the introduction of PRPP features at the earliest possible stage of design
- With SSCs, white papers on the six GIF systems

ACCIDENT INITIATORS → SYSTEM RESPONSE → CONSEQUENCES

THREATS → SYSTEM RESPONSE → OUTCOMES

- ***Safety and PR&PP should be considered from the earliest stages of design***
  - ***Flow diagrams: preliminary safety hazard and PR&PP target identification and categorization***
  - ***Physical arrangement: external events shielding, access control***

https://www.gen-4.org/gif/jcms/c_9365/pr-pp for "Evaluation Methodology Report", "Workshop materials", and "Case Study Report of ESFR"

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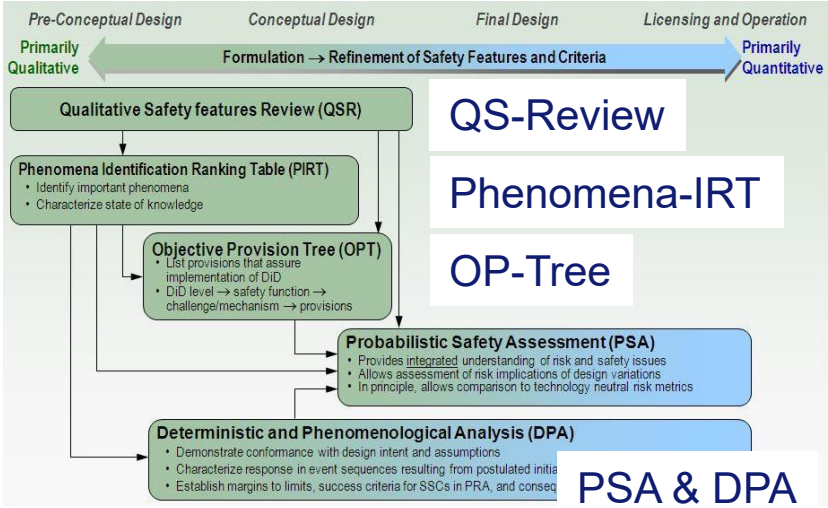
GIF Methodologies

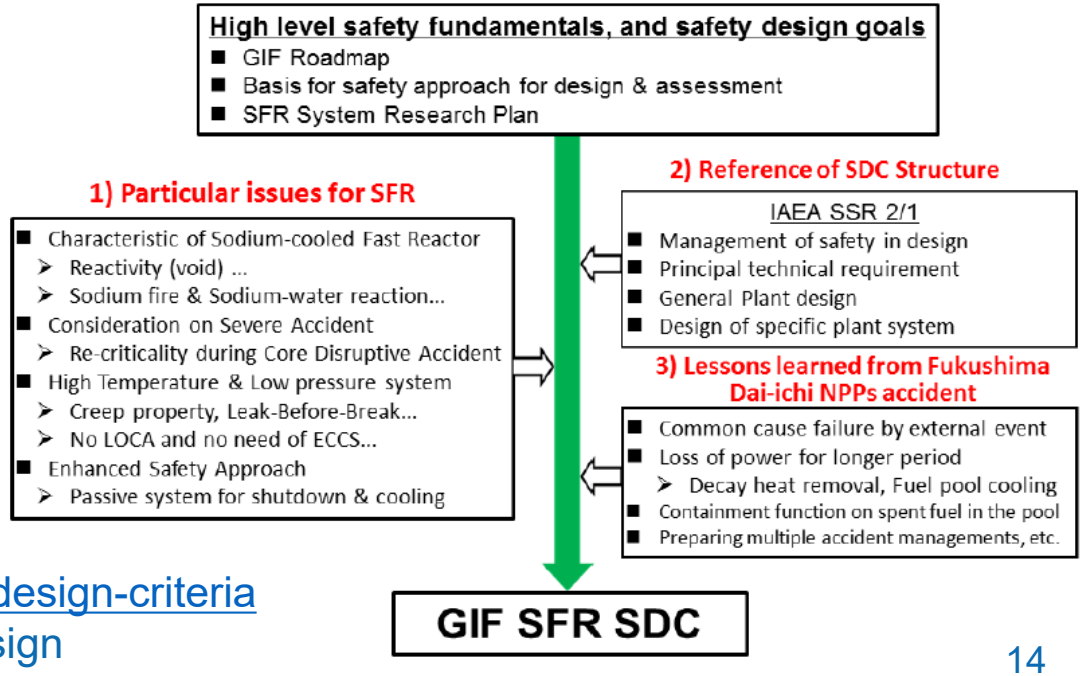
RSWG – Risk and Safety WG

- Develop "Basis for the Safety Approach for Design and Assessment of Generation IV Nuclear Systems"
- Developed white papers on Integrated Safety Assessment (ISAM) implementation & safety systems

https://www.gen-4.org/gif/jcms/c_9366/risk-safety for "ISAM Guideline" and "Safety Assessment Reports: 5 Systems"



- Safety Design Criteria (SDC)
  - Develop SDC and Safety Design Guidelines (SDGs) for the sodium-cooled fast reactor (SFR)
    - ✓ Reviewed by IAEA, OECD/NEA (WGSAR), and Regulatory Bodies of several countries
  - Extension to other GIF systems (LFR, VHTR, MSR…)



https://www.gen-4.org/gif/jcms/c_93020/safety-design-criteria for "SFR SDC" & "Safety Approach and Design Conditions, SFR SDGs"

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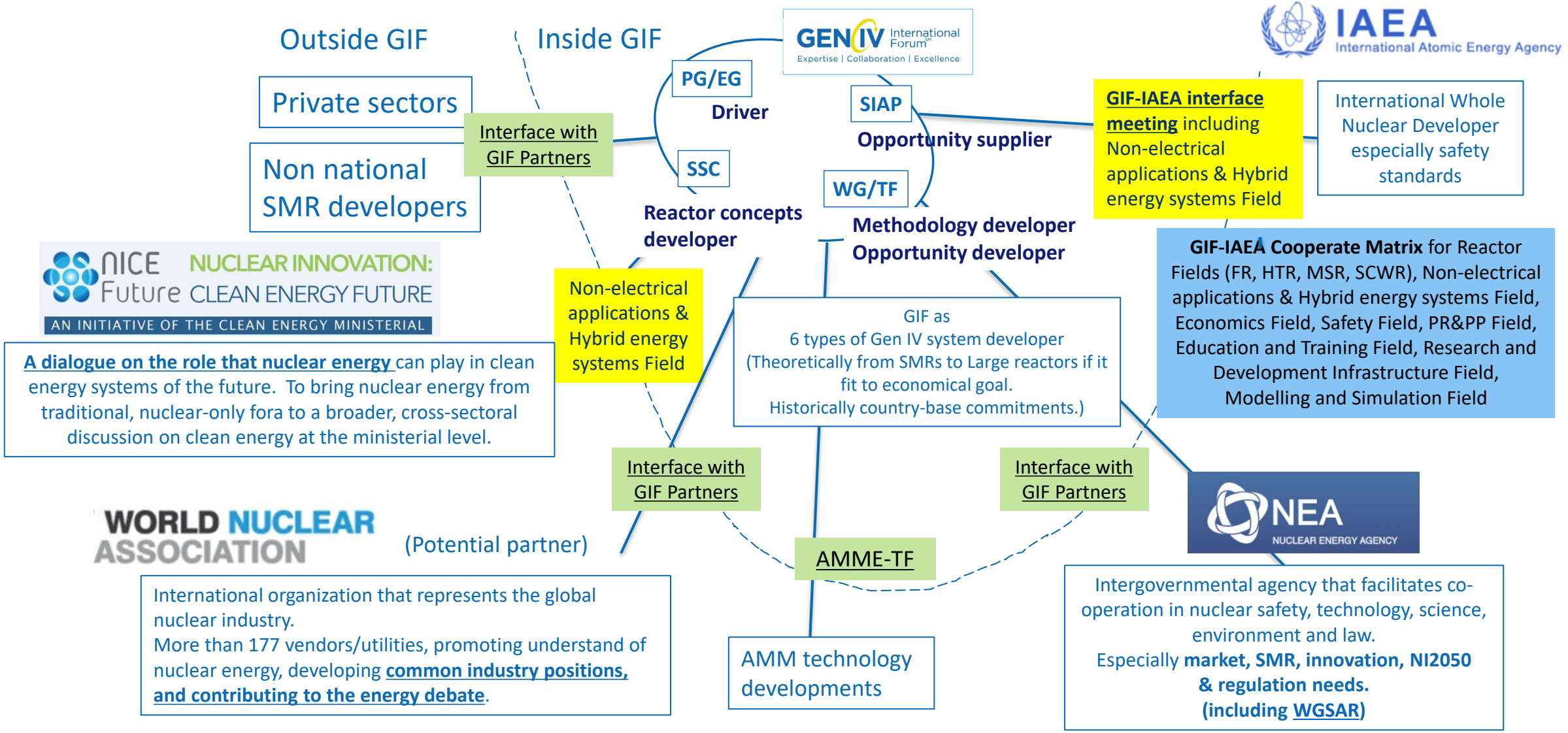
Enlargement of Cooperation with world Organizations



Cooperation with CEM: NICE Future Initiative

- Clean Energy Ministerial (CEM)
  - NICE Future Initiative (Nuclear Innovation: Clean Energy Future)
    - CEM10: Breakthroughs event-Panel (Vancouver, 2019)
    - Report: Flexible Nuclear Energy for Clean Energy Systems (2020)
      - 13 Generation IV International Forum: Delivering Next Generation Nuclear Systems
    - Booklet: Pathways to net zero using nuclear innovation (2021)

Message from GIF

- Gen-IVs can contribute to Carbon Free Society through the flexibility associated by high temperature systems

Pathways to net zero using nuclear innovation

2.1 Generation-IV International Forum (GIF)

The six most promising nuclear energy systems identified by GIF are:

Sodium-cooled Fast Reactor (SFR)

Very High Temperature Reactor (VHTR)

Gas-cooled Fast Reactor (GFR)

Molten Salt Reactor (MSR)

Lead-cooled Fast Reactor (LFR)

Super Critical Water-cooled Reactor (SCWR)

The Generation-IV International Forum (GIF) is a multinational co-operative endeavor organized to foster the research and development needed to accelerate the deployment of the next generation of nuclear reactor systems. Since its foundation in 2000, GIF has identified six nuclear energy systems being the most promising to meet its objectives, assuming a deployment horizon beyond 2030.

As well as the GIF Goals of sustainability, safety, Proliferation, Risk, and Physical Protection (PRPP) and, economics, the flexibility characteristics are becoming increasingly recognised as essential attributes for future energy sources. In the NICE Future initiative's "Flexible Nuclear Energy for Clean Energy Systems" report, GIF set out the flexibility characteristics of Gen IV reactors in Chapter 13.

Sustainability is a key issue of Generation-IV reactor systems, as these technologies enable stable and long term utilization of nuclear across a broader clean energy system. These new designs aim to efficiently use uranium resources and further minimize waste and environmental load. The minimization of environmental load means not only being CO_2-free but also reducing the amount of high level radioactive waste by means of burning of long term radioactive nuclides of Minor Actinides in the spent fuel.

One particular benefit of the Generation-IV reactor systems is higher outlet temperatures ranging 700 to 950°C (i.e., VHTR, GFR, LFR, and MSR), and ~550°C (SFR). This high temperature brings flexibility of energy use. This includes non-electrical applications of their nuclear heat, such as hydrogen production, industrial process heat to chemical processing facilities, and efficient heat storage.

Hideki Kamide
Chair of GIF

26

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Cooperation with IAEA

❑ GIF-IAEA Interface meeting

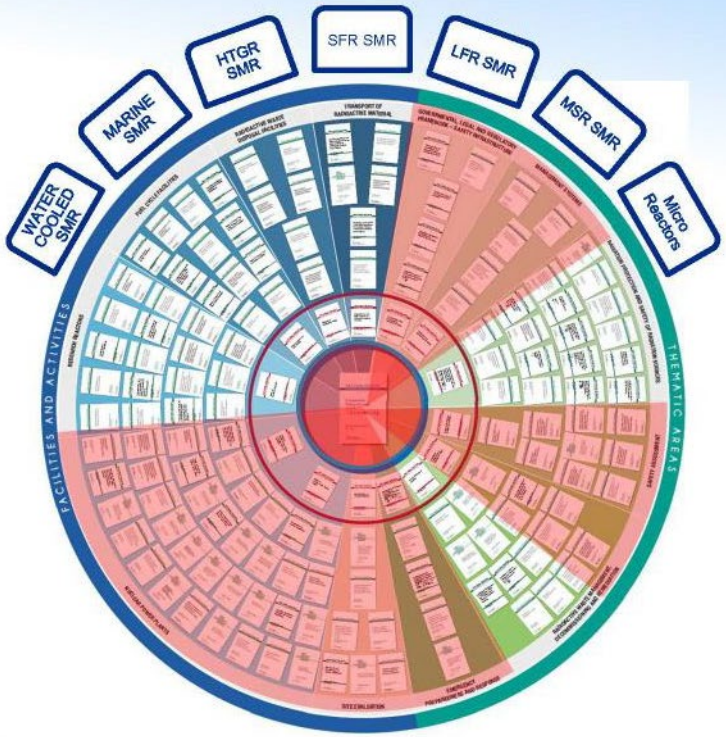
- 2021 July: The IAEA and the Generation IV International Forum (GIF) have agreed to expand their cooperation to include areas in the field of integrated energy systems, nuclear heat applications and hydrogen production, and advanced manufacturing. (IAEA Website news)

❑ Regulatory issues of Gen-IV systems

- GIF-IAEA LMFR safety workshop
  - ✓ Reviews of SFR SDC/ SDG and LFR SDC by IAEA
- SMR safety documents development in IAEA
  - ✓ SMR Regulators Forum
  - ✓ GIF members have joined several consultancy meetings

Scope

- Developing a framework of application of IAEA safety standards to all types of SMR
- A high-level mapping of areas of the safety standards applicability to SMRs
- Interface between safety security and safeguards will also be addressed



iaea_smr_safety_webinar_presentation_29_october.pdf, Page 8

Education & Training WG Activities

Series of Gen-IV webinars

A series of Generation-IV webinars has been launched in September 2016 and is currently offered once a month:

- 1 hour online lecture on one GIF system or cross-cutting topic from top-level experts
- **57 webinars have been presented as of today**
- Archived with flyers, slides, and **YouTube Video**.

https://www.gen-4.org/gif/jcms/c_82831/webinars

Pitch Your Generation IV Research Competition

Short video presentations; tinyurl.com/wwauk74

https://www.gen-4.org/gif/jcms/c_173421/pitch-your-research-competition

Summary

- ❑ Generation-IV Reactor Systems in GIF
  - SFR, LFR, GFR, MSR, VHTR, SCWR
  - GIF Goals; Sustainability, Safety and Reliability, Economy, PRPP (Security)
- ❑ Methodology Working Groups and Task Forces
  - New gates to cooperate with Private sectors
    - ✓ Non-electric Application of Nuclear Heat; NEaNH TF
    - ✓ Advanced Manufacturing and Material Engineering; AMME TF
  - Safety Design Criteria and Guideline; SFR and extended to other systems
  - Cost reduction measures on plant life cycle
  - Education and Training; Webinars and Knowledge managements
- ❑ Cooperation with other Organizations
  - Safety and Regulatory Issues
    - ✓ SMR safety standards by IAEA and OECD/NEA RSWG
  - Messages to COP26
    - ✓ Booklet of CEM, NICE future
    - ✓ Report on Nuclear Energy: an ESG Investable Asset Class
    - ✓ Cooperation with WNA

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 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**: The licensing of the BREST LFR research demonstrator is currently being completed with site preparations ongoing 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**

Site preparations for the BREST-OD-300 construction

GEMMA

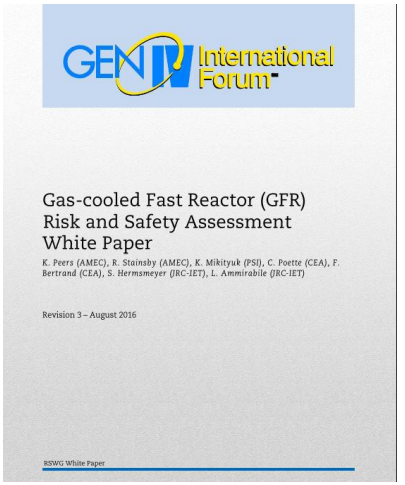
PATRICIA

PASCAL

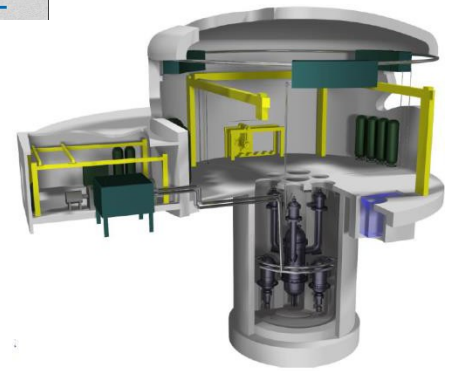
https://www.gen-4.org/gif/upload/docs/application/pdf/2020-06/gif_lfr_ssa_june_2020_2020-06-09_17-26-41_202.pdf
https://www.riatomsk.ru/article/20201109/seversk-brest-300-sroki/
http://www.eera-jpnm.eu/gemma/
https://patricia-h2020.eu/
https://cordis.europa.eu/project/id/847715
https://cordis.europa.eu/project/id/945341

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



ALLEGRO concept

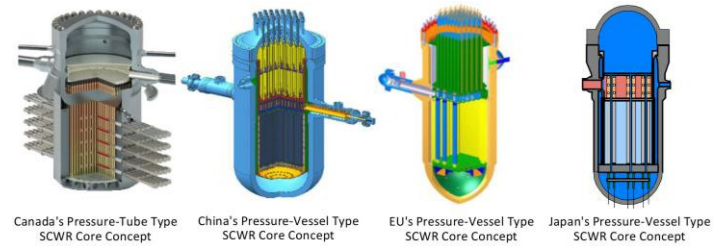


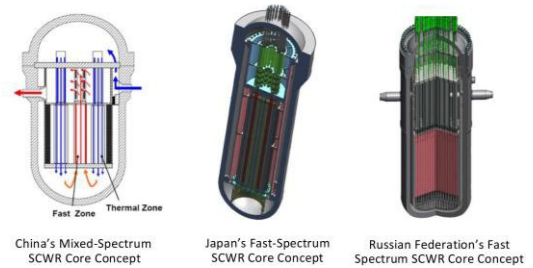
https://www.gen-4.org/gif/upload/docs/application/pdf/2016-10/rswg_gfr_white_paper_final_2016.pdf

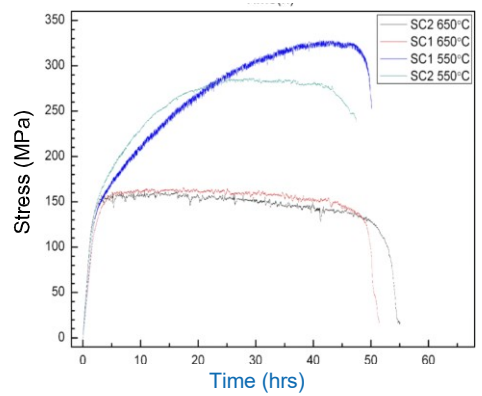
https://cordis.europa.eu/project/id/945041

Highlights related to 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 – cf. subsequent presentation of Markéta Krýková (CV Řež) in this session
- **10th International Symposium on SCWRs**
  - Scheduled in March 2021
  - Will be organized as videoconference or webinar







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 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 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

https://samosafer.eu/

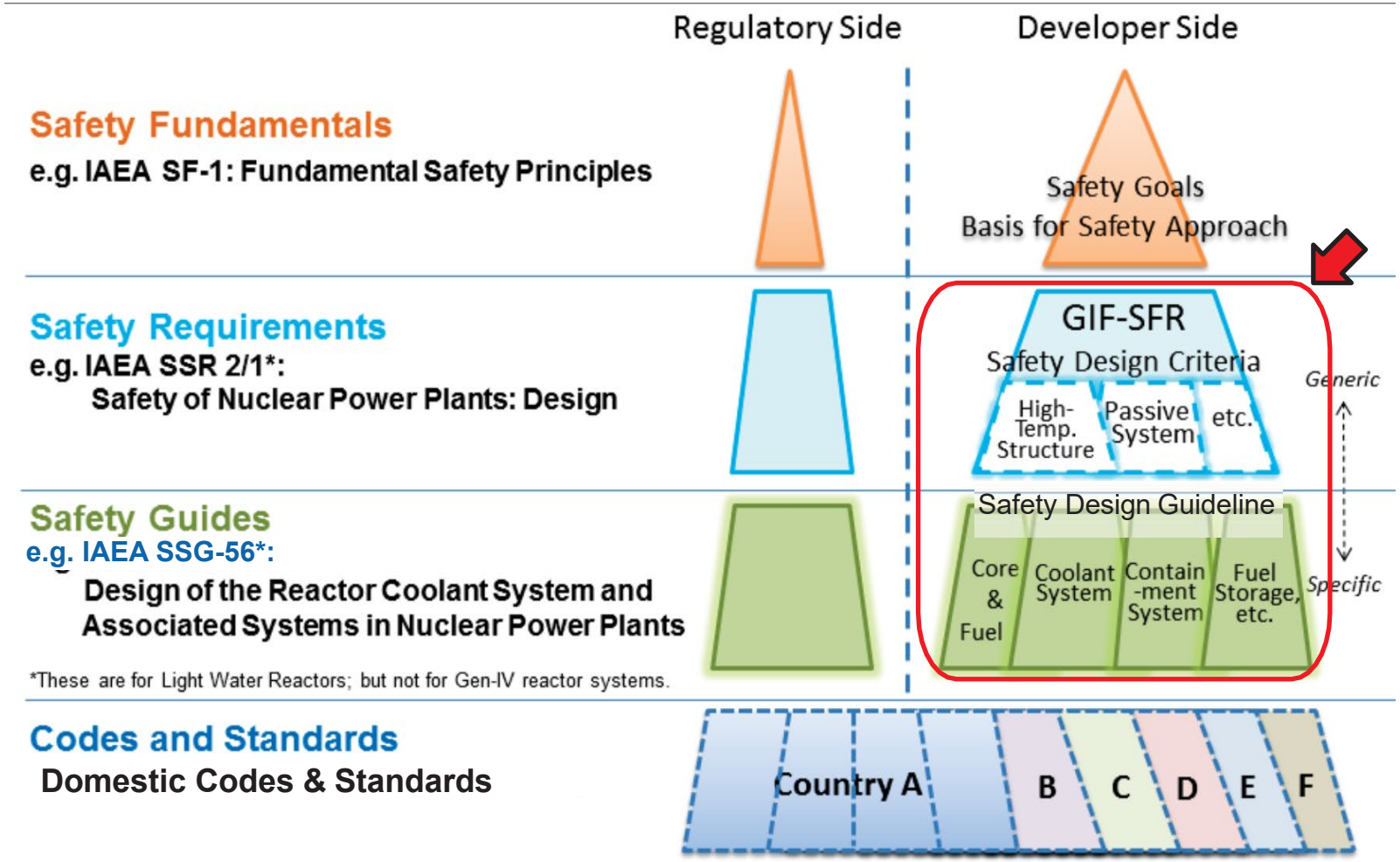
TMSR-LF1

SAMOSAFER

Successful synthesis of UCl_4 at JRC Karlsruhe

Safety Design of Gen-IV reactors and World Standardization

Safety Design Criteria and Guideline of Sodium cooled Fast Reactor



- SFR Safety Design Criteria (SDC) development was proposed at GIF Policy Group in 2010
  - Realization of enhanced safety designs common to SFR systems,
  - Preparation for the forthcoming licensing in the near future
- SDC was formulated in 2013, external review and update
  - IAEA
  - OECD/NEA WGSAR
  - Regulatory bodies in SFR developing countries
- Safety design guidelines (SDG) for GIF SFR started in 2013.

GEN IV International Forum
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Safety document development for GIF reactor systems

- SDC/SDG are extended to the other reactor systems.

	White Paper on ISAM Implement.	System Safety Assessment	Safety Design Criteria/Guidelines*
SFR	Completed	Completed https://www.gen-4.org/gif/jcms/c_9366/risk-safety	SDC-Completed 1st SDG-Completed 2nd SDG-under review
VHTR	Completed	Completed	GIF is observing IAEA-CRP for SDC
LFR	Completed	Completed	SDC-under preparation SDC Report submitted to IAEA for review in 2021
SCWR	Completed	Completed	Not needed
GFR	Completed	Completed	SDC-under preparation
MSR	Under preparation	Under preparation	Under planning

* https://www.gen-4.org/gif/jcms/c_93020/safety-design-criteria