GEN IV International Forum
Expertise | Collaboration | Excellence

Prospects and Challenges of Gas cooled Fast Reactor (GFR) Technology

Dr. Petr Vacha, UJV, Czech Republic

02 October 2024

cea
Argonne NATIONAL LABORATORY
Pacific Northwest NATIONAL LABORATORY
NATIONAL NUCLEAR LABORATORY
OAK RIDGE National Laboratory
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens
ÚJV

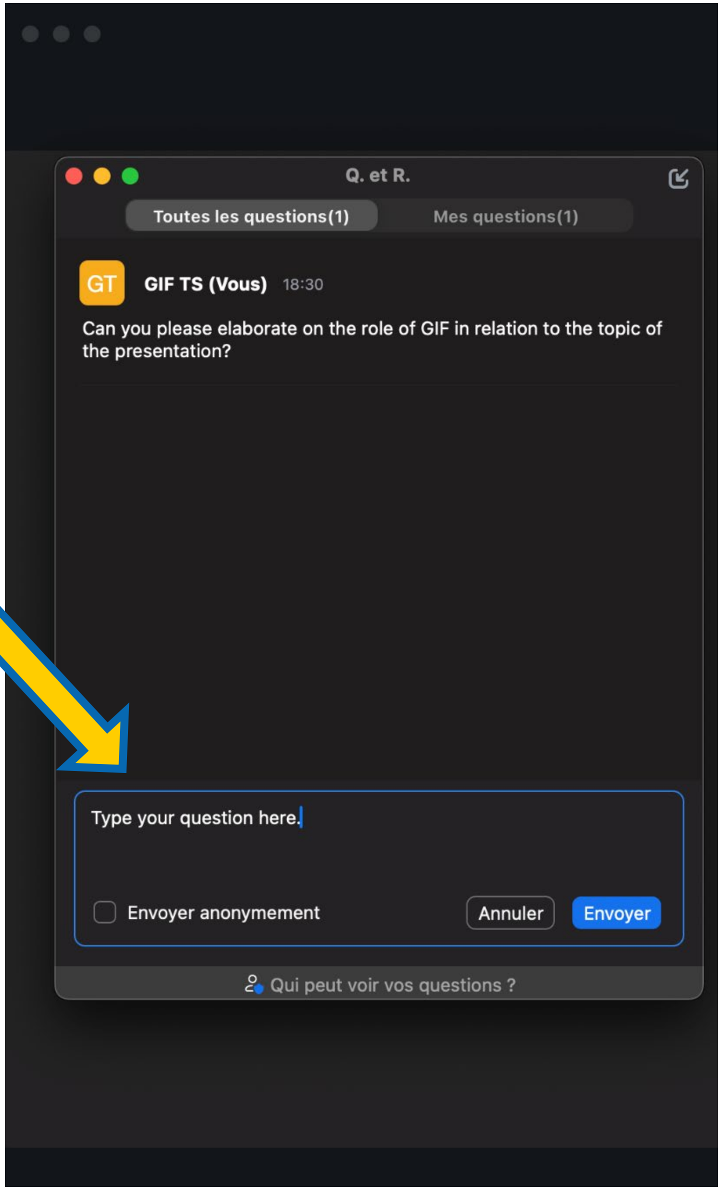
Some Housekeeping Items

Listen through your computer	Please select the "use computer audio" option and check that your speakers/headphones are not muted.
Technical Difficulties	Search the Zoom Webinars Support https://support.zoom.com/hc/en/article?id=zm_kb&sysparm_article=KB0064143
To ask a question	Select the "Q&A" pane on your screen and type in your question
Share with others or watch it again	A video/audio recording of the webinar and the slide deck will be made available at www.gen-4.org
Please take the survey	A brief online survey will follow the webinar.

To Ask a Question – Use the Q&A function

Click the Q&A buton in the zoom menu.

You will then see a window that will allow you to type your question.



International Forum
Expertise | Collaboration | Excellence

Prospects and Challenges of Gas cooled Fast Reactor (GFR) Technology

Dr. Petr Vacha, UJV, Czech Republic

02 October 2024

Meet the Presenter

Mr. Petr Vacha is head of the Advanced Reactor R&D in UJV Rez, Czech Republic, and has over 10 years of experience in design and safety assessment of gas-cooled fast reactor technology,

As the lead designer of the HeFASTo GFR concept, he is leading a team of almost 30 scientists and engineers.

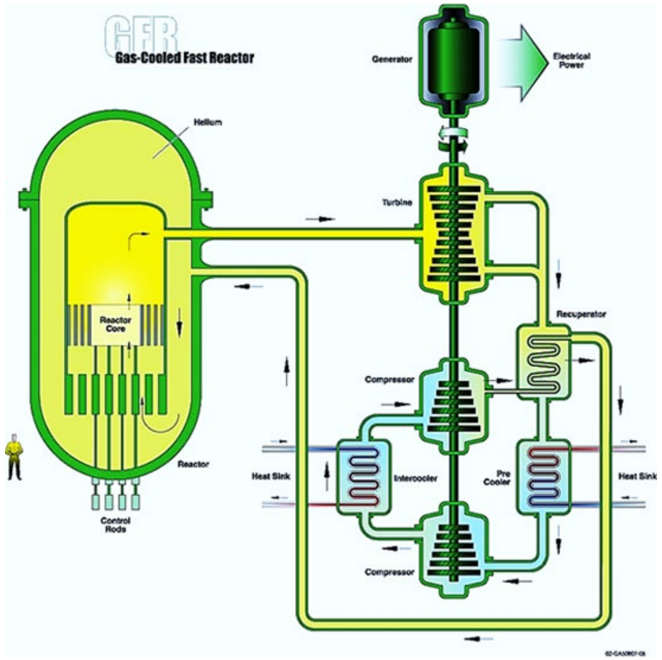
Mr. Vácha holds BSc and MSc degrees in nuclear reactors and energetics from the Czech Technical University in Prague. During his time at UJV Rez, he has established technical expertise in fast reactor design, thermal-hydraulics of gas-cooled systems, and severe accident prevention and mitigation of GFRs.

Email: petr.vacha@ujv.cz

Outline

- What is GFR, how long it has been researched and why it is still a relevant technology in the 21st century
  - Overview on actively developed concepts
- GFR technology challenges and our approach to overcome them
  - Inherent coolant properties
  - Materials
  - Reactor operation
  - Path towards the FOAK reactor
- Prospects of using GFR
  - High-temperature heat production
  - Nuclear waste minimization and other advantages of a fast reactor

GFR in a nutshell

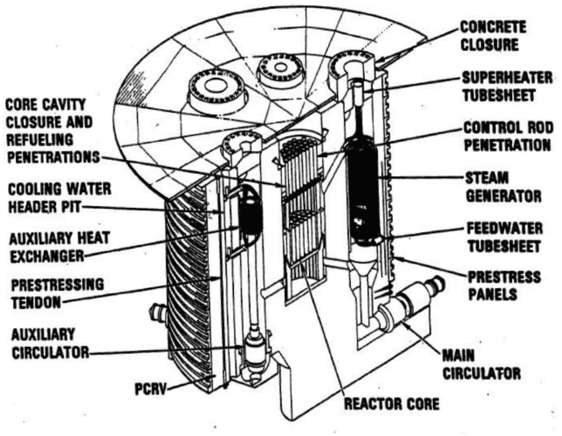


Source: www.gen-4.org

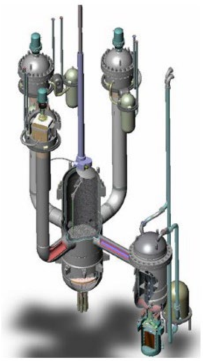
- **Combination of FAST and HIGH-TEMPERATURE reactor**
  - Potential to close the fuel cycle
  - Waste minimalization
  - High-potential heat production, electricity production with very high efficiency
- **Main features:**

+ High core outlet temperature (>850 °C)
+ Good neutronic safety (for a fast reactor)
+ Transparent, chemically inert coolant
+ Very effective breeder or burner
- Less effective cooling (than water, molten metals or salts)
- Extreme demands on material properties
- Never tested on a non-zero power scale

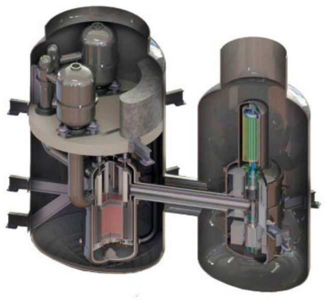
History of GFR research



70's - Concept GCFR 300 MWth, General Atomics



2002 – ETDR, CEA



2009 – EM², General Atomics

- **Surprisingly rich:**
  - Dates back to the 60's – first wave of fast reactor development
  - Concepts developed in Europe, USA, USSR, Japan
  - Never built – too ambitious and demanding on materials and technologies of the era + success in SFR development

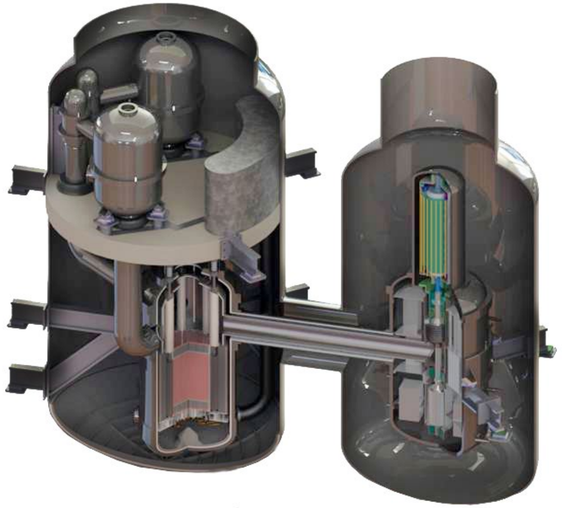
- **Modern Era**
  - GFR as one of the GIF technologies for the 21st century
  - R&D Focused in Europe, USA and Japan
  - ETDR -> ALLEGRO
  - EM^2 -> FMR

Overview of GFR concepts under development

- **ALLEGRO**
  - Intended as FOAK demonstrator/research reactor
  - Main goal is to serve as a showcase of the technology and testbed for GFR-related technology
  - Developed by V4G4 CoE (Europe)

www.allegroreactor.eu

- **Fast Modular Reactor (FMR)**
  - Concept of a commercial GFR
  - 50 MWe, direct cycle
  - Developed by GA and Framatome (USA)

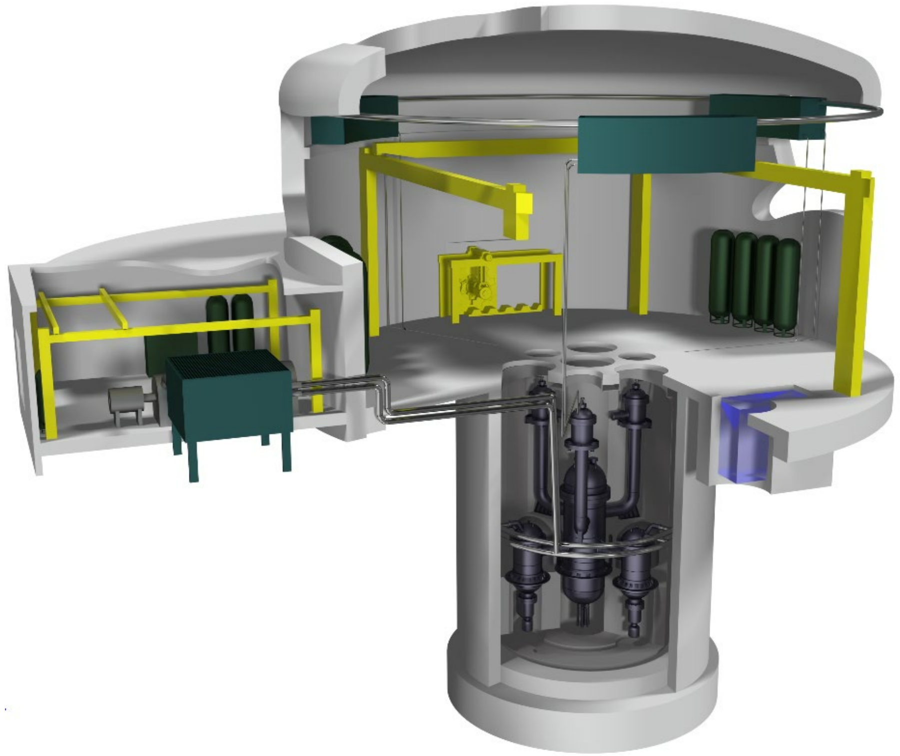


https://www.ga.com/general-atomics-and-framatome-collaborate-to-develop-a-fast-modular-reactor

- **Helium-cooled Fast Reactor (HeFASTo)**
  - Concept of commercial GFR
  - 200 MWth, indirect cycle
  - Developed by UJV Group (Czechia)

www.hefasto.eu

ALLEGRO 1/2

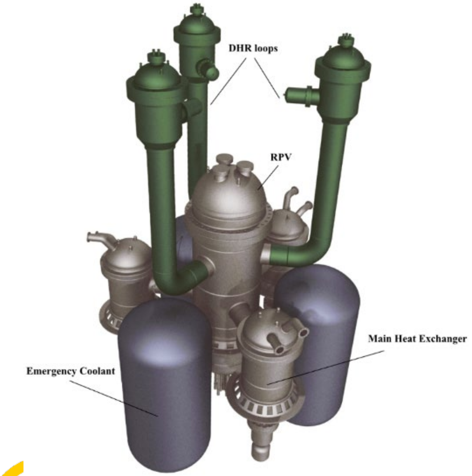


- **Two consecutive core configurations**
  - Driver core – MOX/UO2 pin-type fuel in steel cladding, experimental positions for fuel qualification
  - Refractory core – (U,Pu)C pin-type fuel in SiC-SiCf cladding <- GFR reference fuel
- **Target core outlet temperature 850°C**
- **Power density up to 100 MW/m3**
- **Focus on fully passive safety to meet GENIV objectives**

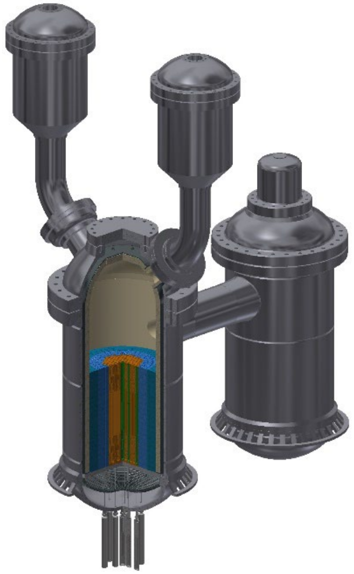
ALLEGRO main characteristics	
Nominal Power (thermal)	75 MW
Driver core fuel/cladding	MOX(UO2) / 15-15ti Steel
Experimental fuel/cladding	UPuC / Sic-Sicf
Fuel enrichment	35% (MOX) / 19.5% (UO2)
Power density	100 MWth/m3
Primary coolant	He
Primary pressure	7 MPa
Driver core in/out temperature	260°C / 530°C
Experimental fuel in/out T	400°C / 850°C

ALLEGRO 2/2

- **ALLEGRO should achieve:**
  - Demonstration of viability of the GFR technology
  - Proof of concept – ability to deliver high-potential heat while remaining safe and reliable
  - Testbed– qualification of materials and technologies in prototypical conditions
- **Ultimate goal – Qualification of the GFR technology for commercial application**

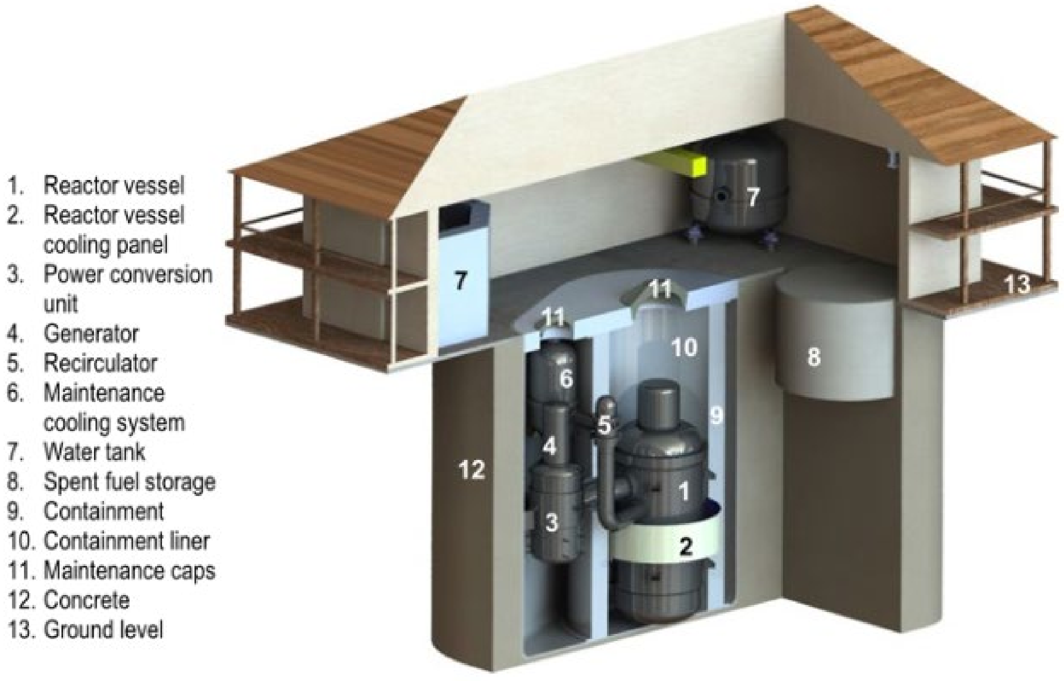


ALLEGRO → Commercial GFR



Fast Modular Reactor (FMR)

- **Formerly developed as EM²**
  - Highly-innovative concept featuring direct cycle power conversion cycle
  - Major innovations in fuel and core materials development
  - Aiming at providing a highly-efficient nuclear reactor for electricity production

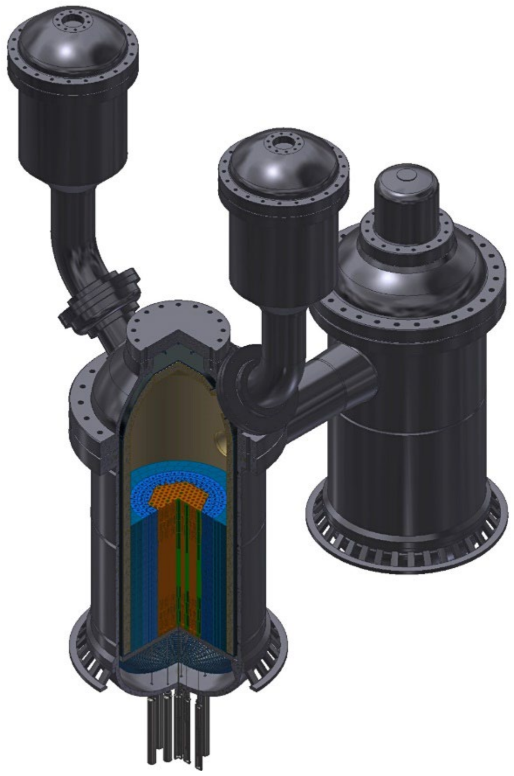


Parameter	Value	Unit
Thermal power	112	MWth
Core inlet/outlet temperature	500 / 800	°C
Primary coolant	He	-
Primary pressure	7,0	MPa
Secondary coolant	None – direct cycle	-
Fuel	UO2	-
Fuel enrichment	19,75	%

Helium-cooled Fast Reactor (HeFASTo) 1/2

- **A concept of Advanced Modular Reactor based on the GFR technology:**
  - Developed by ÚJV Řež, a. s. since 2021
  - Closed fuel cycle actively counting with reprocessing of spent fuel from PWRs
  - High level of modularity and very long fuel campaign – increase in economic competitiveness
  - Fully passive safety and proliferation resistance compliant with GENIV goals

Helium-cooled Fast Reactor (HeFASTo) 2/2



- **Main Features of HeFASTo**
  - Indirect power conversion cycle – modularity of the secondary circuit
  - Two-layer containment protecting from external hazards and release of RN
  - Placed partially underground – only 18m above ground
  - 5 years of operation without the need for fuel handling

Parameter	Value	Unit
Thermal power	200	MWth
Core inlet/outlet temperature	450 / 900	°C
Primary coolant	He	-
Primary pressure	7,5	MPa
Secondary coolant	N2+He	-
Secondary pressure	8,0	MPa
Fuel	UC or(U,Pu)C	-
Fuel enrichment	UC - 19,5 (U,PU)C - 30	%
Operation time without outage	5	years
Load factor	>95	%

GFR challenges – coolant properties

GFR challenges – coolant properties

Property (unit)	**Helium** (550°C / 70bar)	**Sodium** (550°C / 1bar)	**Lead** (550°C / 1bar)
Density (kg/m^3)	4.217	820	10 300
Specific heat capacity (kJ/kg.K)	5.19	1.25	0.14
Thermal conductivity (W/m.K)	0.310	67	20.2
Dynamic viscosity (Pa.s)	3.1e^{-5}	2.2e^{-4}	1.6e^{-4}
Melting point (°C)	-272	97.5	327
Boiling point (°C)	-269	883	1775

- **Helium as a nuclear reactor coolant**
  - Advantages: transparent, inert, no phase change, excellent specific properties
  - Disadvantages: extremely low density
  - Conclusions: need for either very high thermal capacity of the core combined with low power density (HTR), or **keeping a steady coolant flow through the core at all times (GFR)**

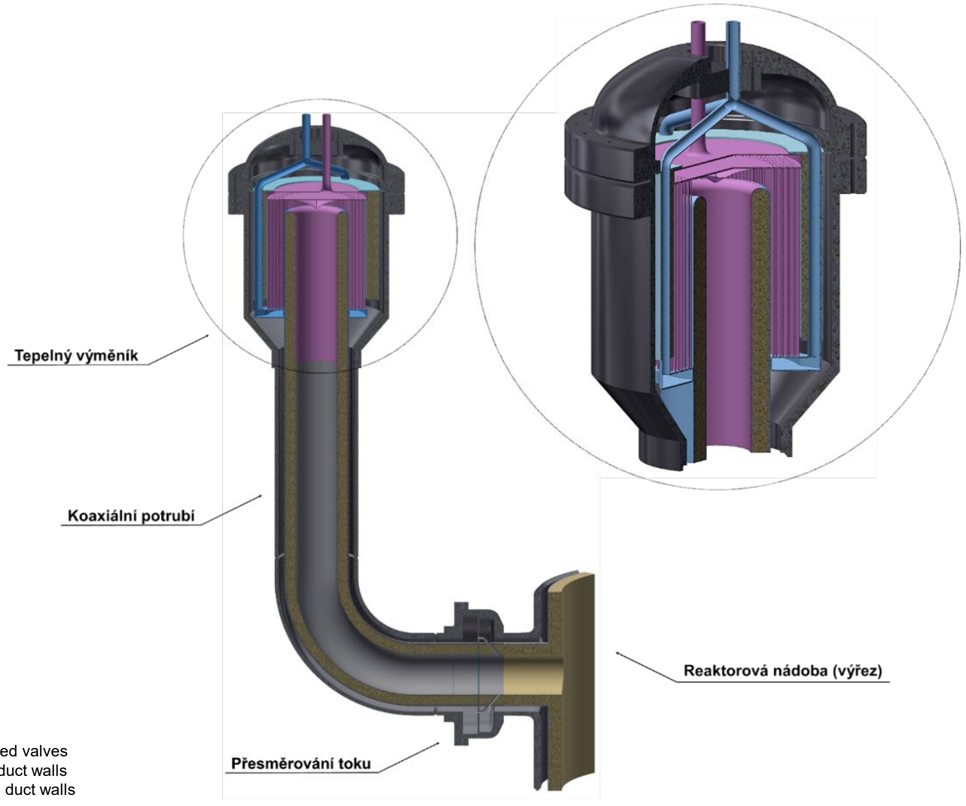
GFR SAFETY approach

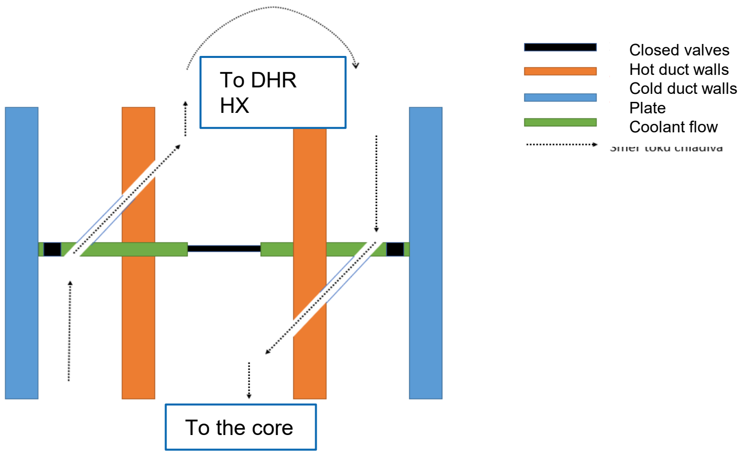
- **Passive safety**
  - **Three main passive safety systems:**
    - Dedicated Decay Heat Removal system – natural convection
    - Emergency coolant injection system – actuated by pressure difference
    - Primary containment – enhancing natural convection by keeping elevated residual pressure in LOCAs

- **Main goals of the safety concept**
  - Practical elimination of severe accidents
  - Minimalization of core damage even in very improbable situations like combination of station blackout and LOCA
    - Goal is to be able to remove even slightly damaged core as a one piece in the envelope
  - The result is complete elimination of radionuclides release outside of the plant

Decay Heat Removal system (DHR)

- **Dedicated system:**
  - Fully passive, based on natural convection
  - Continuously pre-conditioned during normal reactor operation with a small controlled primary coolant flow
  - Key safety systems in LOFA
  - 2 x 100 % loops
  - Patented in the Czech Republic, international patent pending

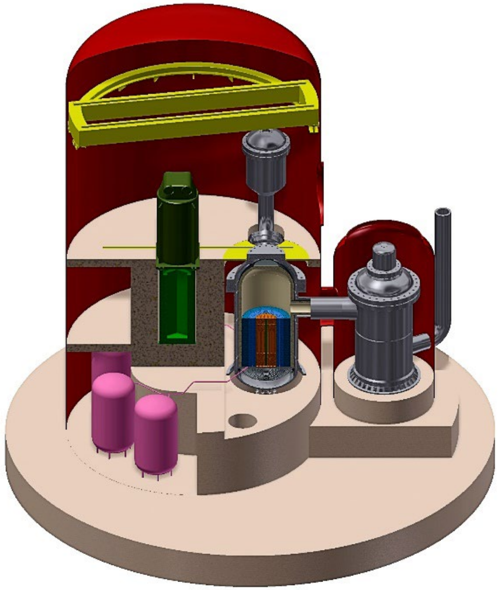




System in the pre-conditioning settings

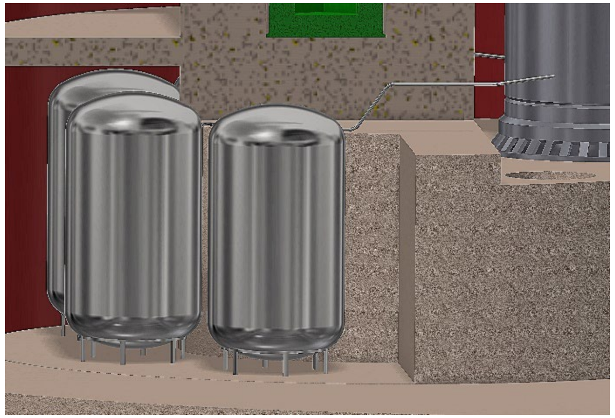
Containment

- **Primary containment**
  - Leak-tight steel envelope of the primary circuit, equipped with filtered ventilation system
  - Keeps elevated residual pressure in case of LOCA



- **Secondary containment**
  - Steel-lined concrete envelope of the whole system
  - Protection from external hazards
  - Large water pool on the top as the ultimate heat sink for decay heat removal

Emergency Coolant Injection system



- **Features:**
  - System of interconnected tanks with pressurized coolant connected to the RPV
  - Can be fully passive, actuated by pressure difference
  - During reactor operation – separated only by an overpressure membrane
  - If the primary pressure unexpectedly drops – the membrane is torn and emergency coolant starts flowing into the primary circuit
  - Key safety system in LOCA

GFR challenges - Materials

GFR challenges – materials

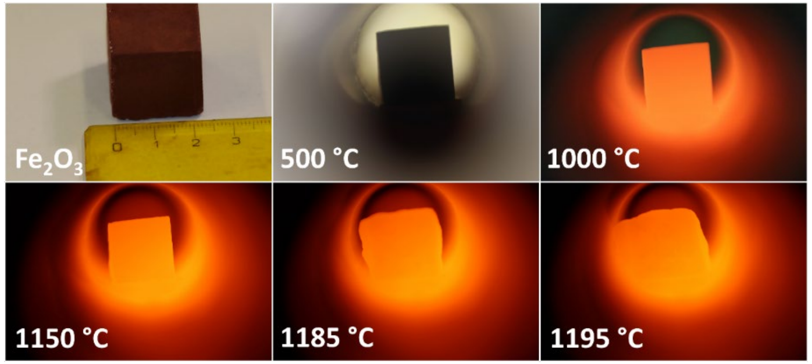
- **Major R&D topic for GFR deployment**
  - In the USA: extensive development of the fuel and core internals materials
  - Japan: Development of fuel cladding and composite structural materials
  - Europe: Large R&D program on development, testing, and standardization of various materials for GFRs
- **A lot of work on standardization is needed before a GFR can be built**

GFR material R&D for GFR in Europe (1)

- **Czech R&D program on GFR materials:**

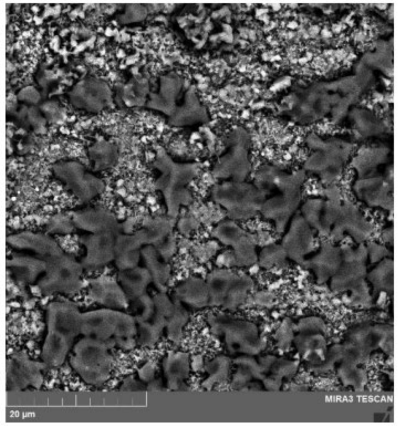
- Several ongoing targeted R&D projects

Name	Duration	Main goals
NOVA	2018-2022	Development of core-catcher sacrificial materials
MATPRO	2020-2024	New refractory and radiation-resistant geopolymers for containment internals
SODOMA-He	2019-2024	Complex testing of construction materials and cladding in relevant enviroments
VELEMLOK	2022-2025	Development and testing of high-temperature resistant construction materials
RENFRI	2024-2025	Start of fuel development and qualification

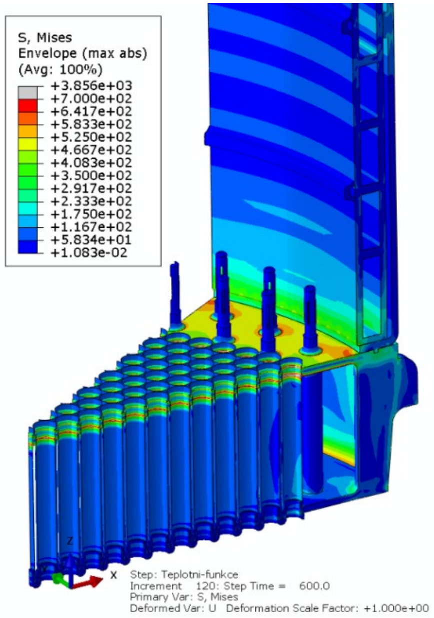


GFR material R&D for GFR in Europe (2)

- **H2020 SafeG project**
  - 2020-2024
  - 15 organizations from 8 countries (Europe + Japan)
  - WP2 dedicated to material R&D
  - Outcomes comprising development of additive manufacturing processes development, material R&D and design work
  - www.safeg.eu



Cr oxides – 15-15Ti;

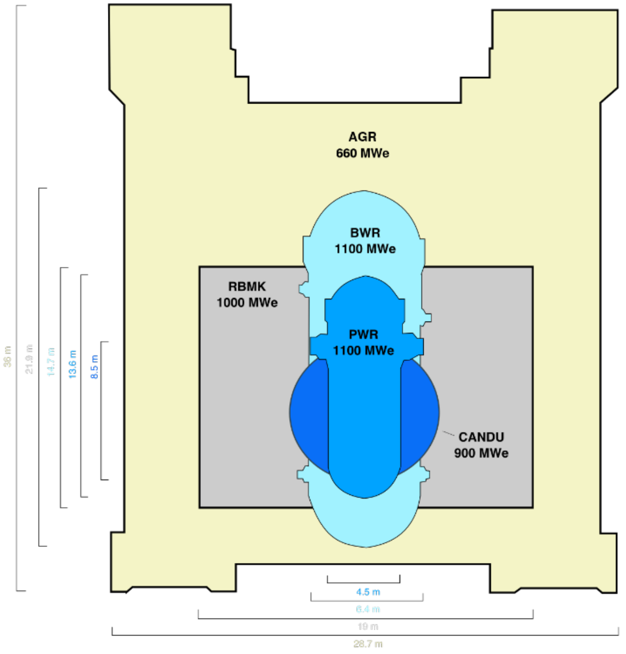


SafeG Demonstrator – Reduced scale full HX

GFR challenges – Reactor operation

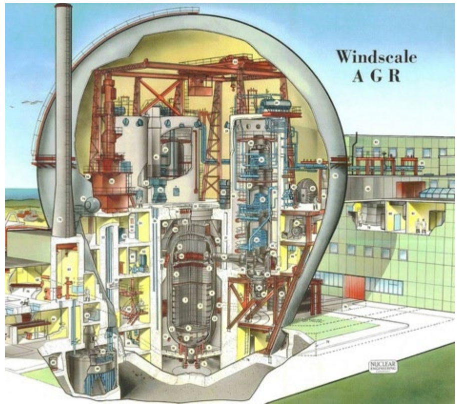
History – gas-cooled reactors

- **Gas-cooled reactors with moderator:**
  - Rich history of commercial operation (since the end of 50's)
  - MAGNOX and AGR in Great Britain
  - Helium-cooled reactors in Germany, USA, Japan, China
  - In total – more than 500 reactor-years of experience
  - Still under operation and new builds commissioned
  - Biggest drawback – very low power density (~ 4-10 MW/m^3)



1985 – THTR 300, thtr.de

2022 – HTR-PM, world-energy.org

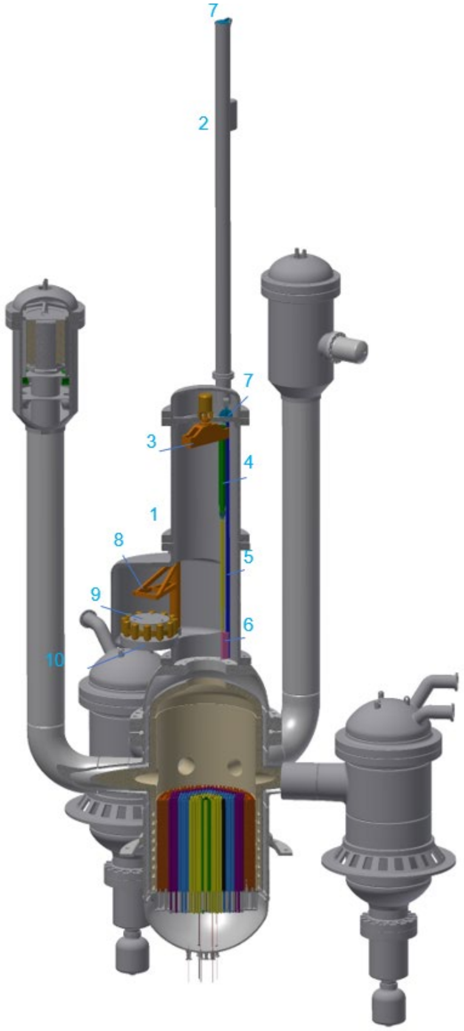


1965 – AGR, theengineer.co.uk

GEN IV International Forum
Expertise | Collaboration | Excellence

GFR specifics:

- **Some major differences from HTGRs:**
  - Fuel handling:
    - Needs to be done with pressurized primary circuit (as in block-type HTGR), however, much smaller diameter of fuel elements
  - Very low thermal inertia of the core:
    - More susceptible to oscillations of main parameters such as mass flow rate, power level etc.
    - Need for fast actuation of safety systems in transients -> preference of passive safety systems

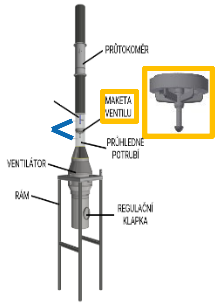


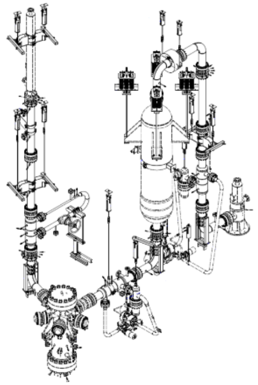
1) fuel handling assembly vessel
2) elevator shaft
3) fuel handling crane
4) telescopic arm
5) elevator rail
6) elevator driver
7) elevator hatches
8) cover manipulator crane
9) hot branch plug
10) inner cover

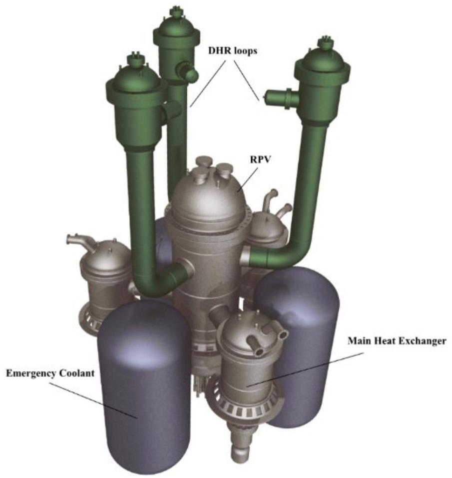
GFR challenges – Path towards FOAK reactor

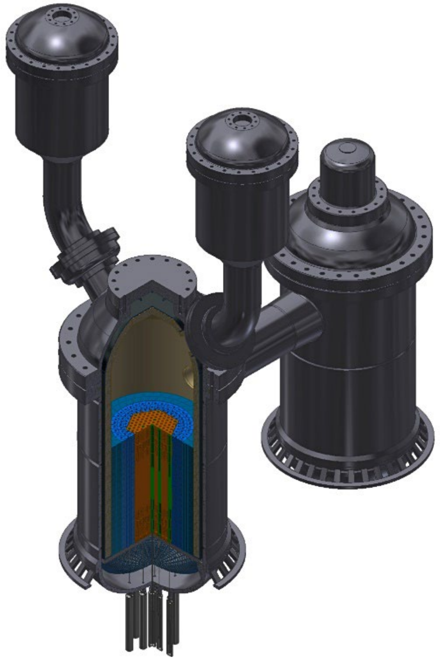
Milestones to GFR deployment

You are here









Start of development – „paper reactor“ only numerical simulations

Pre-conceptual phase

Small-scale experiments testing individual phenomena and components

Conceptual phase

Electrically heated scaled-down prototype

Conceptual and Basic design stage

Demonstration Nuclear reactor

Years of operation, testing qualification

Fully commercial nucelar reactor

GEN IV International Forum

Expertise | Collaboration | Excellence

S-ALLEGRO

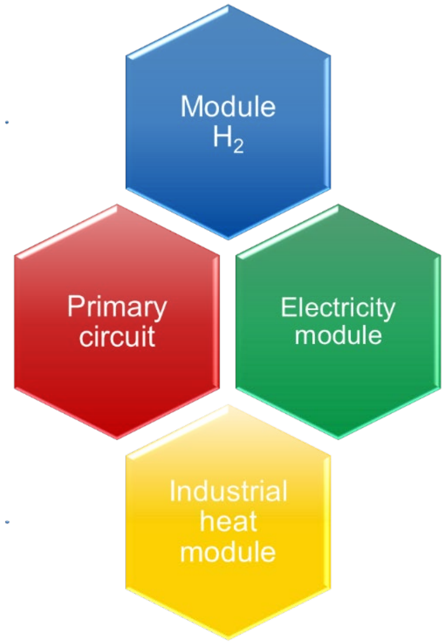
- 1MW electrically heated mock-up GFR, operated by CVR in Pilsen
- 850°C / 7MPa He

- **Main goals:**
  - Simulation of reactor operation and hypothetical accidents
  - Component testing
  - Technology testing

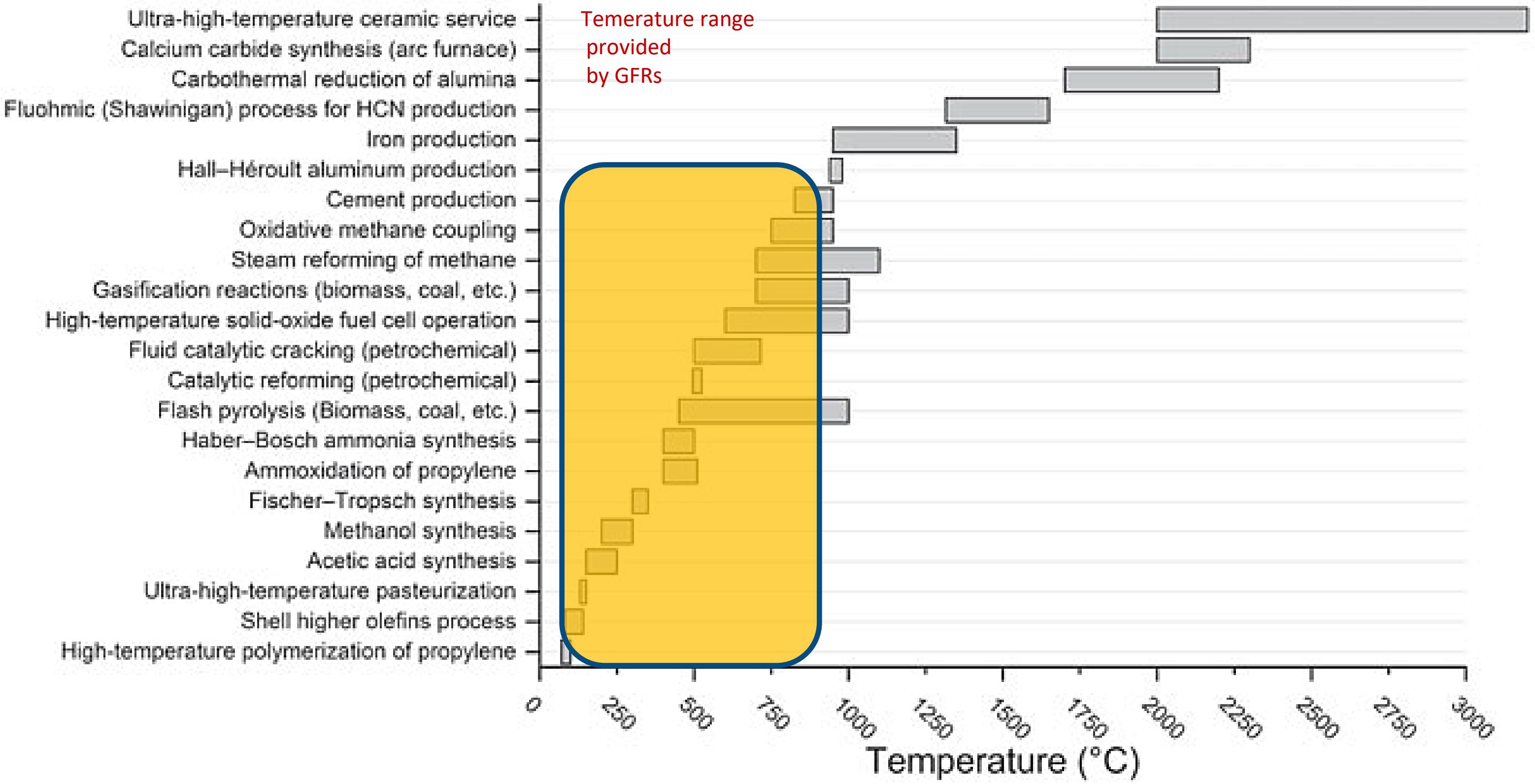
GFR prospects – High-temperature heat

Use of high temperatures from GFRs

- **ALLEGRO:**
  - Showcase unit for hydrogen and electricity production and high-temperature heat storage
- **FMR:**
  - Electricity production with extremely high efficiency (over 44 % net), long fuel campaigns and very high load factor
- **HeFASTo:**
  - Modular secondary circuit – electricity, hydrogen, direct heat supply



Potential applications in chemical industry



Kreider et. al: „High-Temperature Gas-Solid Reactions in Industrial Processes“, Reviews of Mineralogy & Geochemistry vol.84,2018

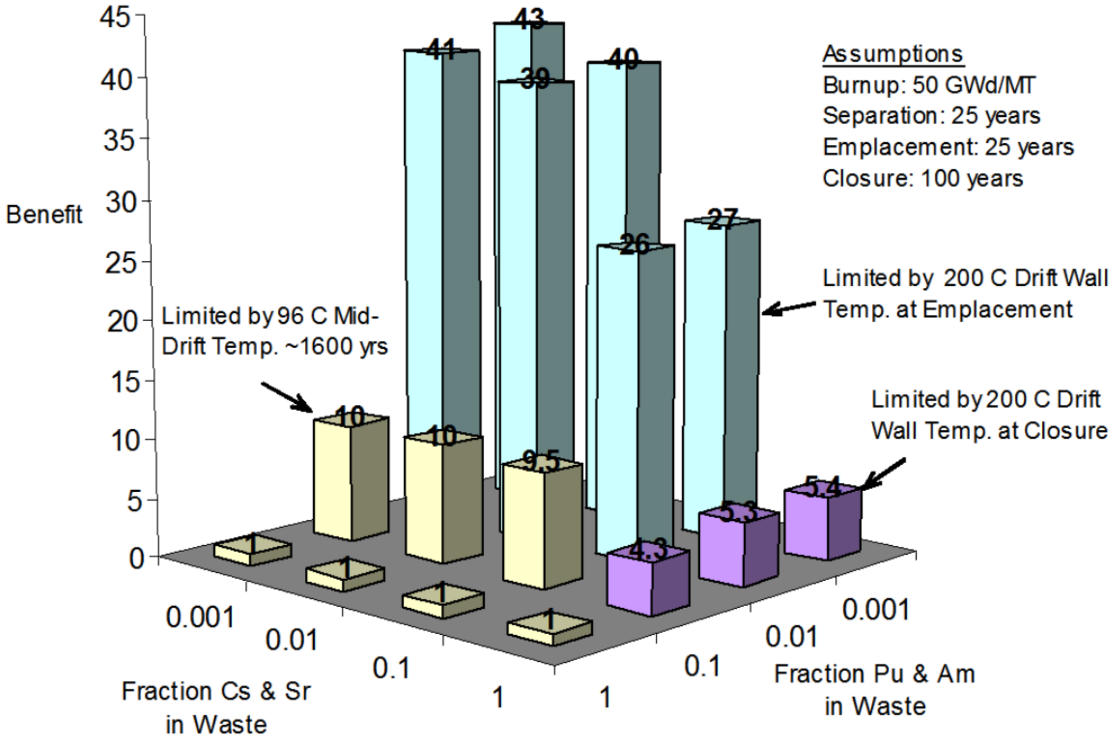
GFR prospects – waste minimization and other advantages of FRs

Incentives for using Fast Reactors (FRs)

- **Sustainable source of energy**
  - Residual fissile and fertile material can be recycled multiple times into new fuel
  - Potential for „limitless“ fuel through breeding
  - Very cost- and labour-intensive
- **Waste management**
  - Superior storage and/or disposal forms relative to thermal-spectrum reactors
  - Possibility to „burn“ long-term parts of spent nuclear fuel from LWRs
- **Efficiency**
  - Possibility to use very long fuel campaigns and reach very high fuel burnups, exceeding 100 MWd/kg

Waste management using FRs

sitory “Densification” Factors



R.A. Wigeland, et al., Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository, Nuclear Technology, 154 (2006).

Summary

- **GFRs comes with several crucial challenges unique to the technology**
  - They are well knowna and large R&D programs are underway to prove the proposed solutions
  - Needs to be further experimentally tested before accepted as suitable for use in a nuclear reactor
- **Several reactor concepts under development**
  - In Europe and in the USA
  - Growing interest from governments and public institutions as well as industry
- **Rationale to use fast reactors**
  - Waste management, electricity and heat supply with high efficiency, closing the fuel cycle

Dedication

Ing. Branislav Hatala, Ph.D.
1972 - 2024

To the memory of Branislav „Brano“ Hatala,
Chairman of GIF GFR SSC,
leading GFR expert, and a good friend.

Upcoming Webinars

Date	Title	Presenter
26 November 2024	Overview and update of SCWR within GIF	Armando Naval, CNL, Canada
December 2024	Overview and Update of LFR Activities within GIF	Andrei Moiseev, Rosatom, Russia
January 2025	Overview and Update of MSR activities within GIF	Jiri Krepel, PSI, Switzerland