Overview and Update of the GIF VHTR Activities

Dr. Gerhard Strydom
Idaho National Laboratory, USA

February 19, 2025

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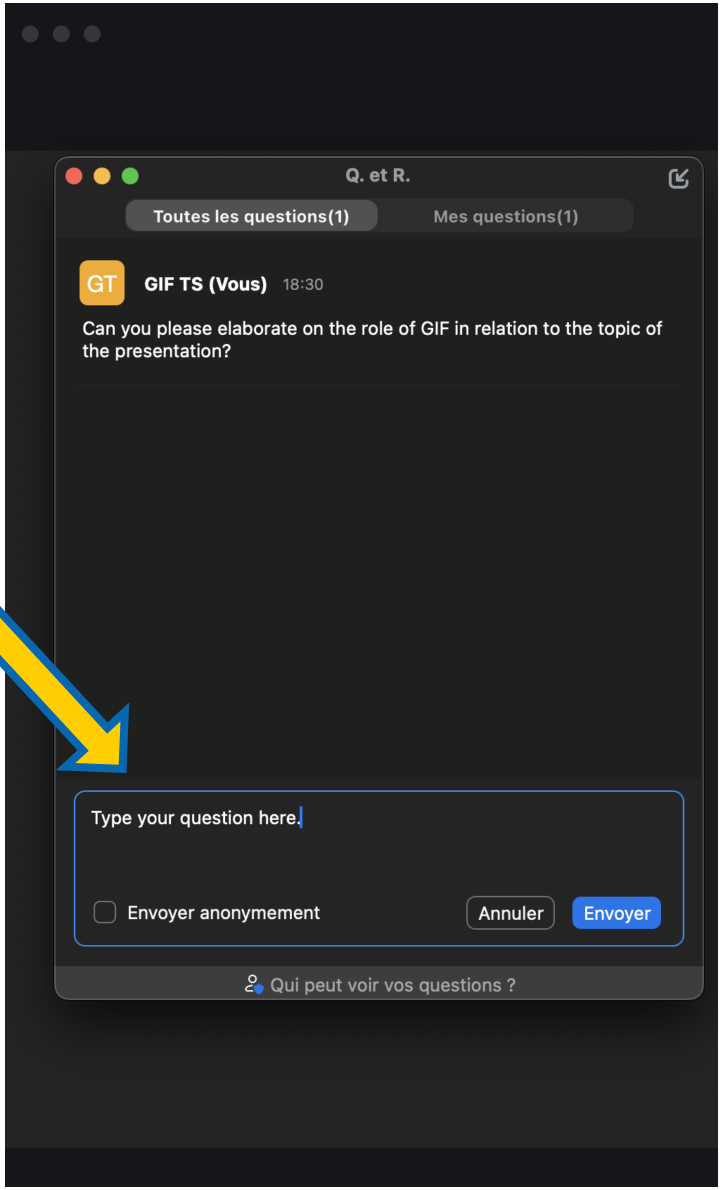

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Meet the Presenter

Dr. Gerhard Strydom is the National Technical Director for the United States Department of Energy's (DOE) Advanced Reactor Technologies (ART) Gas-Cooled Reactors (GCR) campaign. He is responsible for overseeing the ART GCR program activities on graphite and high-temperature materials qualification, as well as GCR methods development and code validation.

He represents the US DOE on the IAEA GCR Technical Working Group (TWG) and the Generation-IV Forum (GIF) Expert Group since 2016. Until October 2024, he served for 4 years as the Chair of the GIF Very High Temperature Reactor (VHTR) System Steering Committee.

He is the author of more than 80 technical publications, including 53 journal and conference papers, and received his Ph.D. on the development of a multi-phase and multi-physics uncertainty assessment methodology for prismatic GCRs in 2020.

Email: Gerhard.Strydom@inl.gov

Outline

- (V)HT(G)R Basics: Family Members, History, and Main Technical Attributes
- Current International HTGR Deployment Landscape
- Examples of HTGR R&D Activities and Collaborations within the GIF VHTR Framework
- Questions and Discussion

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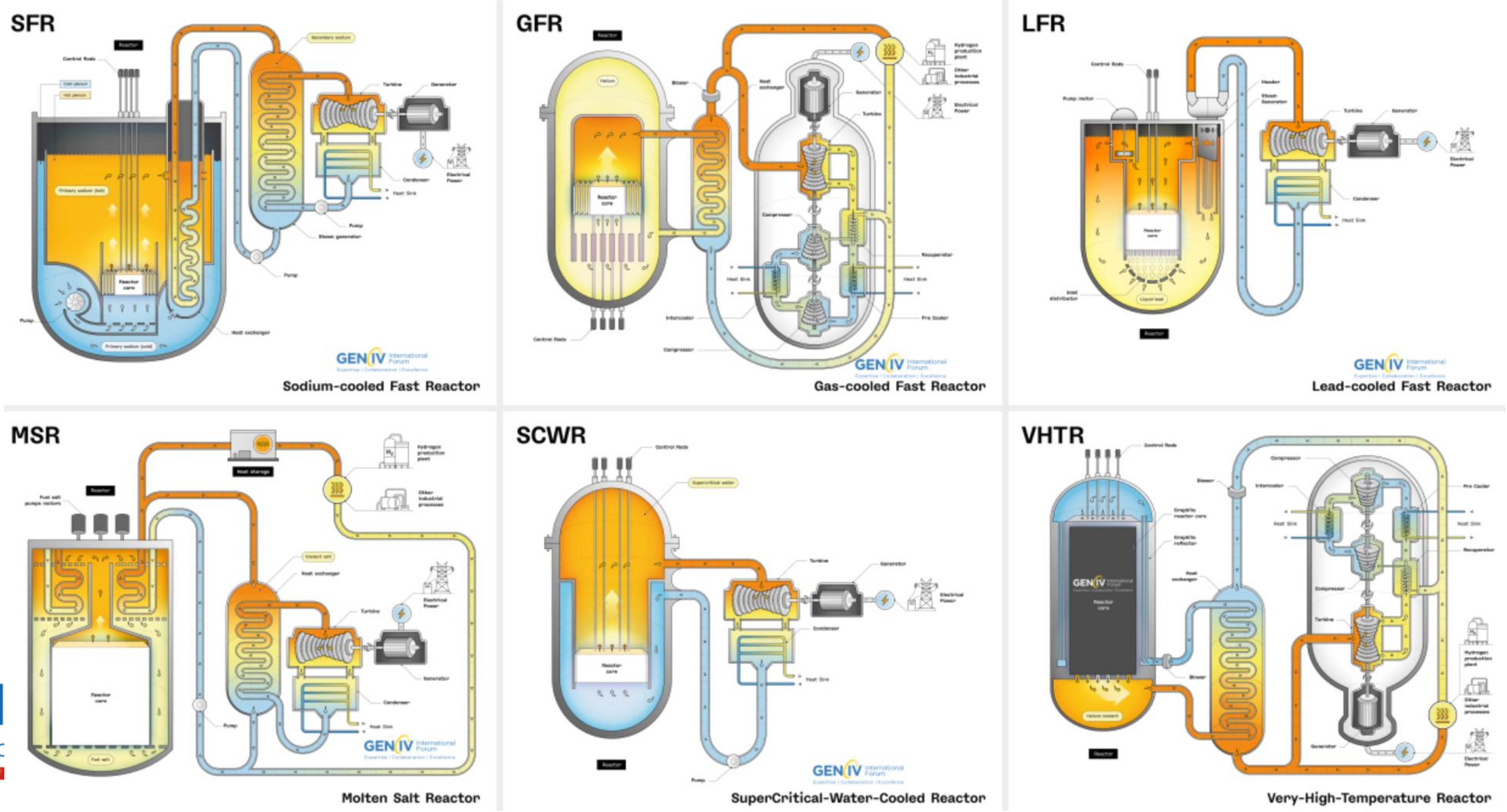
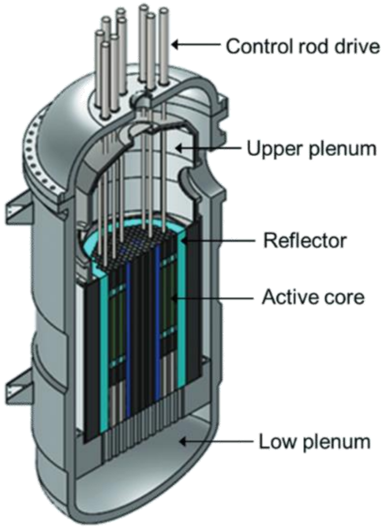
Spot the Difference: Which One Is *Not* a “High-Temperature” Reactor?

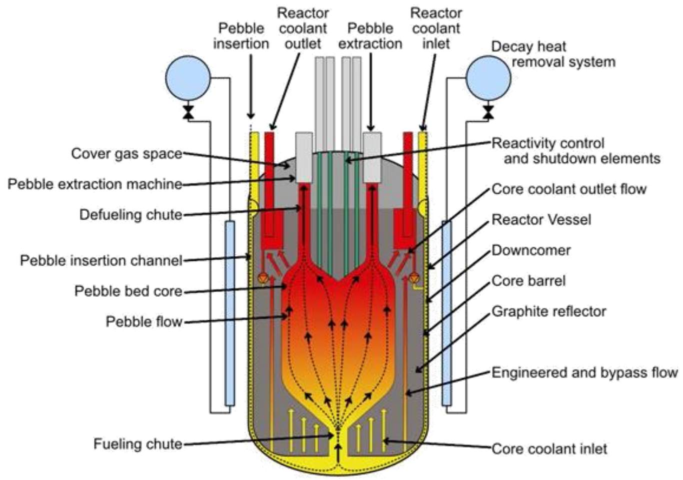


Source: Choi, Hangbok, et al. "Preliminary Neutronics Design and Analysis of the Fast Modular Reactor." Nuclear Science and Engineering (2023): 1-11.

VHTR vs. HTGR vs. GCR vs. HTR?

- High-Temperature Reactors (HTRs) are a general class of non-water-cooled reactors utilizing gas or liquid coolants
- Can be fast or thermal spectrum
- **Gas**-Cooled Reactors (GCRs) include:
  - AGR: British Advanced Gas Reactors, reactor outlet temperatures 600ºC, UO_2 rods, CO_2 cooled, graphite moderator
  - HTGR: Reactor outlet temperatures <950ºC*, TRISO fuel, helium (mostly) cooled, graphite moderator
  - GFR: Higher temperature systems, UO_2 pellets fuel in cylindrical silicon carbide (SiC) cladding, helium cooled, no moderator
  - VHTR: Reactor outlet temperatures >950ºC, TRISO fuel, helium cooled, graphite moderator





Source: Kairos Pre-Application Activities, https://www.nrc.gov/reactors/new-reactors/advanced/who-were-working-with/licensing-activities/pre-application-activities/kairos.html

** Some sources use >750ºC, some >800ºC, some >1000ºC…*

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950ºC*,

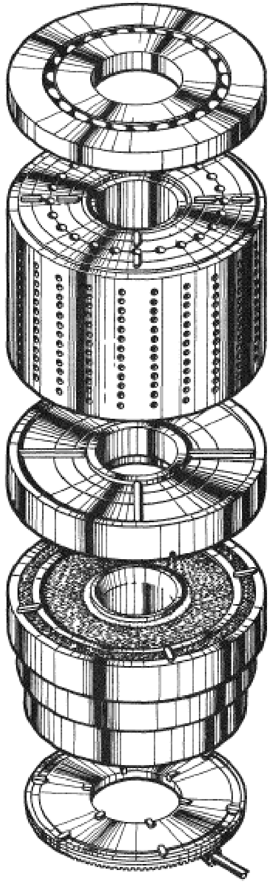
Do VHTRs Even Exist?

Yes! They used to…and now again in space applications

(But they require refractory metals for vessels)

Ultra High Temperature Reactor Experiment (UHTREX) Los Alamos 1959-1970

- *3 MWt, helium cooled with 1316°C outlet temp @ 3.45 MPa*
- *1420°C average fuel temp; 1582°C maximum*
- *Uncladded 93% UC_2 fuel*
- *Graphite moderated with articulated control rods for reactivity control*
- *Capable of fuel insertion and removal at operating conditions*



Space propulsion fuel particle in TRISO testing 'first'

Wednesday, 15 March 2023

A coated particle fuel for nuclear thermal propulsion applications, fabricated by TRISO-X LLC, has undergone testing in extreme conditions representing those experienced in space.

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Source: https://www.world-nuclear-news.org/Articles/Space-propulsion-fuel-particle-in-TRISO-testing-fi

Why GIF VHTR?

- While the original Gen-IV approach 20 years ago focused on VHTRs' very high outlet temperatures for hydrogen production, recent research and market assessments suggest:
  - Lower outlet temperatures in the 700-950°C range are sufficient for many industrial applications,
  - Lower temperatures also limit material challenges associated with near-term deployment. We currently do not have alloys qualified for commercial use at VHTR conditions.
- So, I'll use the more common "HTGR" for the rest of this presentation

ASME Alloy 617 Allowable Stress as function of temperature and pressure

- At 540°C, the allowable stress is 106 MPa
- At 650°C, the allowable stress is 105 MPa
- At 760°C, the allowable stress is 45 MPa
- At 815°C, the allowable stress is 26 MPa
- At 925°C, the allowable stress is 9 MPa
- At 980°C, the allowable stress is 5 MPa

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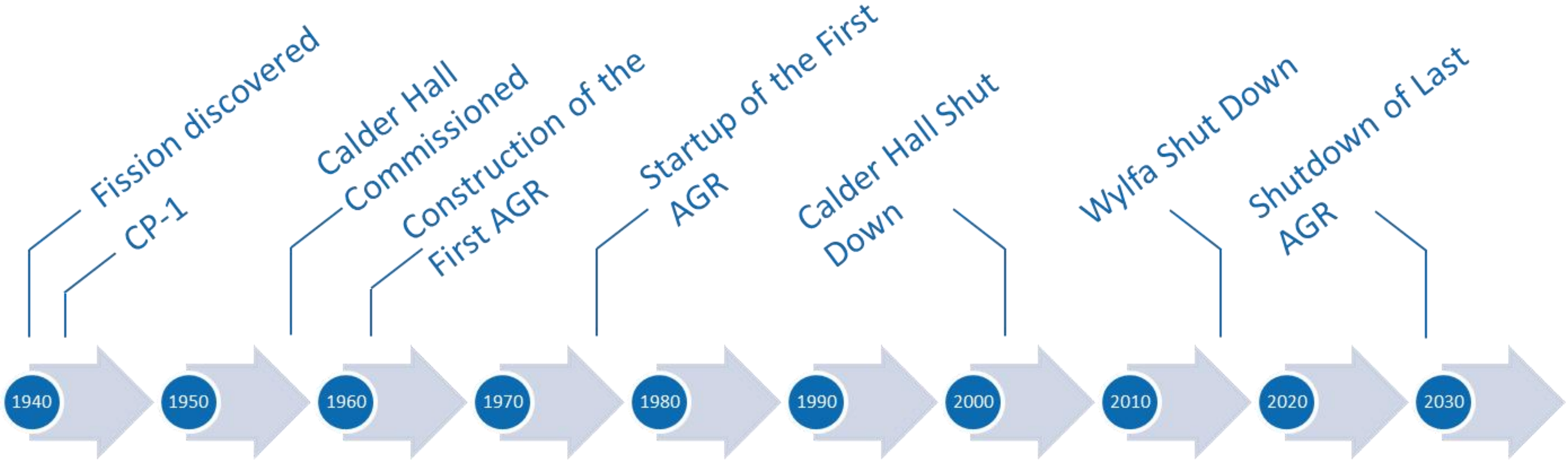
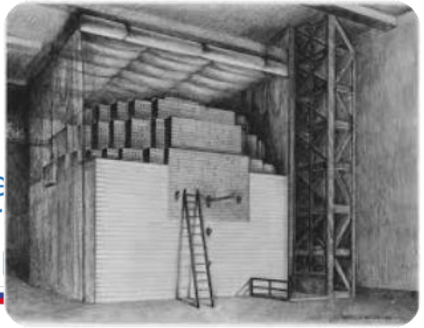
Source: https://virgamet.com/offer/alloy-inconel-haynes-617-na50-24663-nicr23co12mo-n06617#:~:text=High%2Dtemperature%20Allowable%20stress%20according,980%C2%B0C:%205%20MPa

Graphite-Moderated, Gas-Cooled Reactors Are Not New!

- 1942: Chicago Pile (CP-1) (USA, Air-Cooled)
- 1950s+: Production/Power Reactors (CO_2 cooled): MAGNOX (UK), UNGG (Fr), AGR (UK)





1942 Chicago Pile-1

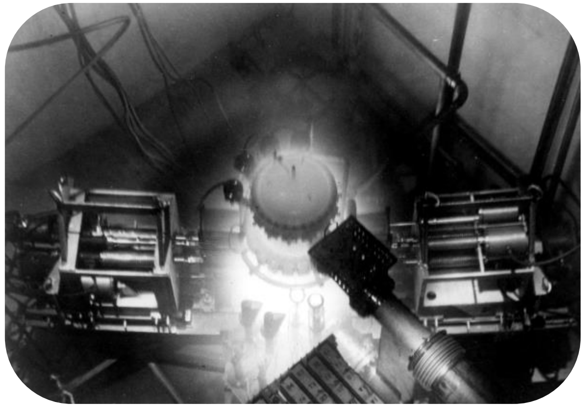
1956 Calder Hall NPP

1988/1989 Two AGRs Torness NPP

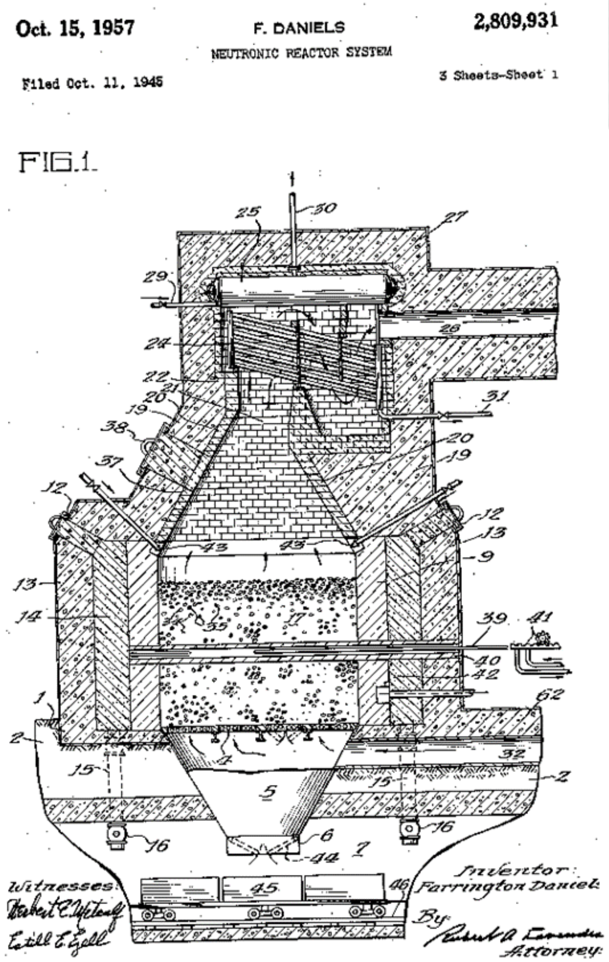
HTGR Evolution

- Daniels' Pile (1945)
  - F. Daniels (ORNL); Graphite or BeO moderated
  - He cooled, 732°C outlet
  - Closed Brayton cycle, UC_2 or UO_2 in cladding
- Actual Experimental reactors followed
  - GCRE, ML-1, EGCR…
- Coated Fuel Particle
  - UKAEA, Battelle idea (~1957)
  - Superior retention of fission products at elevated temperatures (especially the TRISO version)

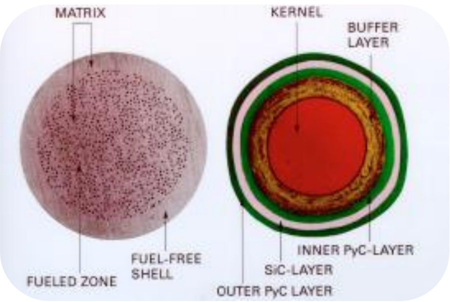
1962 Gas Cooled Reactor Experiment (GCRE)



1945 Daniels' pile



1960s TRISO particle



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1961 ML-1

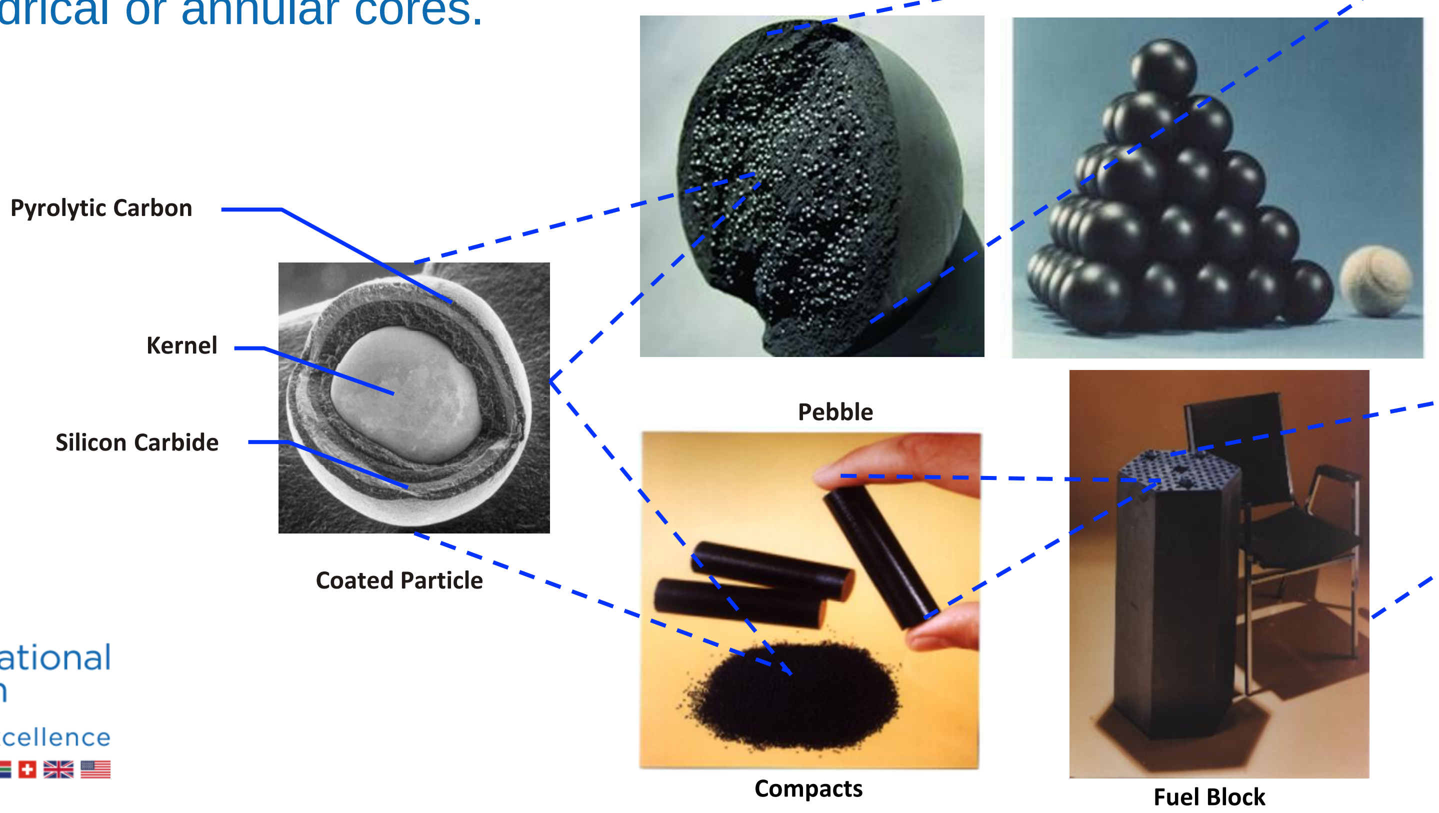
Test and Prototypes HTGRs

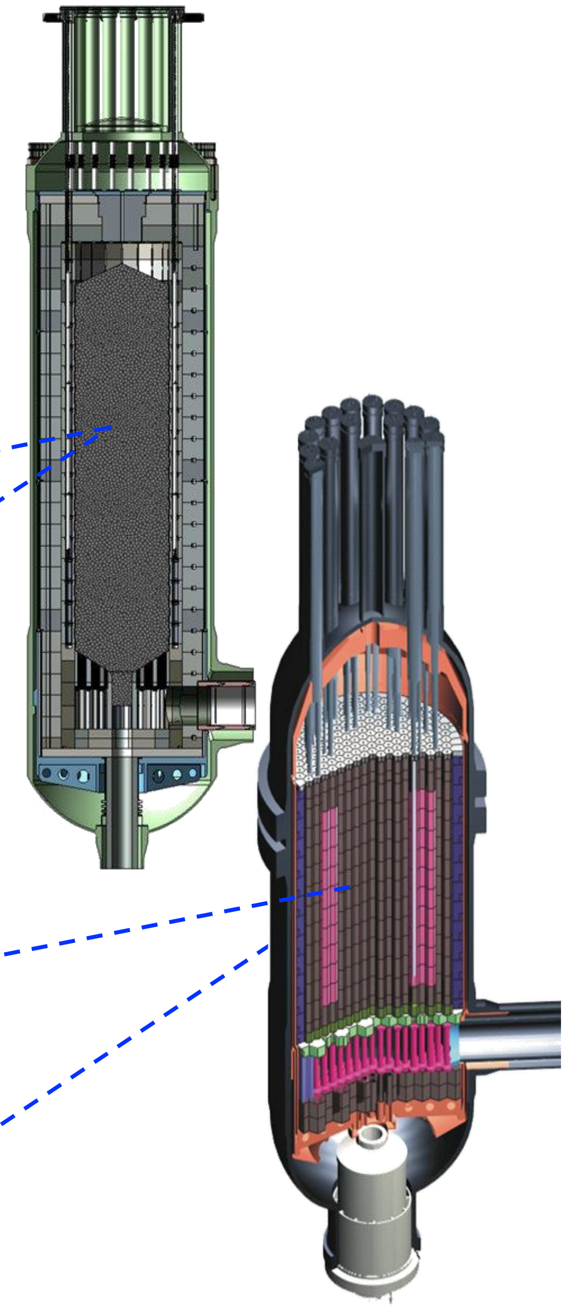
	Test HTGRs				Prototype HTGRs		
	Dragon	**AVR**	**HTTR**	**HTR-10**	**Peach Bottom**	**FSV**	**THTR-300**
Country	UK (OECD)	Germany	Japan	China	USA	USA	Germany
Period of operation	1963-76	1967-88	1998-present	2000-present	1967-74	1976-89	1986-89
Reactor type	Tube	Pebble	Prismatic	Pebble	Tube	Prismatic	Pebble
Thermal power, MWt	21.5	46	30	10	115	842	750
He coolant outlet temp., °C	750	950	950	700	725	775	750
Coolant pressure, MPa	2	1.1	4.0	3.0	2.25	4.8	3.9
Electrical output, MW	-	13	-	2.5	40	330	300
Process heat output, MW	-	-	10	-	-	-	-
Process heat temp., °C	-	-	963	-	-	-	-
Core power density, W/cm³	14	2.6	2.5	2	8.3	6.3	6.0
Fuel particle	UO_2	$(Th/U, U)O_2$, C_2	UO_2	UO_2	ThC_2	$(Th/U, Th)C_2$	$(Th/U)O_2$
Kernel coating	TRISO	BISO & TRISO	TRISO	TRISO	BISO	TRISO	BISO

Source: Alina Constantin, "IAEA activities on HTGR technology development", IAEA, 2024.

Modular HTGRs

- UO_2 or UCO fuel kernels.
- Tristructural isotropic (TRISO) fuel form.
- Pressed into a semi-graphitic matrix and shaped into either compacts (“prismatic” HTGR) or pebbles (“pebble bed” HTGR).
- Hexagonal, cylindrical or annular cores.





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What About Micro-HTGRs?

Developer	Name	Type	Power Output (MWe/MWth)	Fuel	Coolant	moderator	refueling interval	PCU
Antares Industries		Heat Pipe	1.2 MWth	TRISO	sodium	graphite		Brayton Cycle
BWXT	BANR	HTGR	17 MWe/50 MWth	TRISO	Helium	graphite	5 years	Brayton Cycle
General Atomics	GA Micro	HTGR	1-10 MWe		gas			?
HolosGen	HolosQuad	HTGR	13 MWe	TRISO	Helium/CO2		10 years	Brayton Cycle
NuCube	Nu3	heat pipe	1 MWe/3 MWth	TRISO	sodium	graphite	10+ years	
NuGen, LLC	NuGen Engine	HTGR	2-4 MWe	TRISO	Helium			Integral direct cycle
Radiant Nuclear	Kaleidos Battery	HTGR	1.2 MWe	TRISO	Helium	graphite	4-6 years	
Ultra Safe Nuclear	Micro Modular Reactor	HTGR	5 MWe/15 MWth	TRISO	Helium	graphite	20 years	Rankine
Westinghouse	eVINCI	heat pipe	5 MWe/15 MWth	TRISO	Sodium	graphite	8 years	Brayton Cycle
X-Energy	XENITH	HTGR	5 MWe/10 MWth	TRISO	Helium	graphite	3+ years	Open air Brayton Cycle

These are just the current US projects we're aware of…

HTGR Limits?

- Why don't we see more *micro* pebble bed HTGRs?
  - Maybe there is a lower limit on both size and power for a PBR to still be economical and technical feasible?
- Is there an *upper limit* to HTGR power levels?
  - General Atomics and the German program both designed ~3000 MW_t prismatic HTGRs
  - But …if you still want inherent safety and without active cooling systems during loss of cooling:
    - ~650 MW_t for prismatic (with central reflector). Framatome SC-MHTGR is 625 MW_t
    - ~250 MW_t for pebble bed HTGR (cylindrical), but with an annular core/central reflector, PBMR was 400 MW_t
- Have HTGRs been proposed for *non-terrestrial* uses?
  - Yes, for marine and space applications…

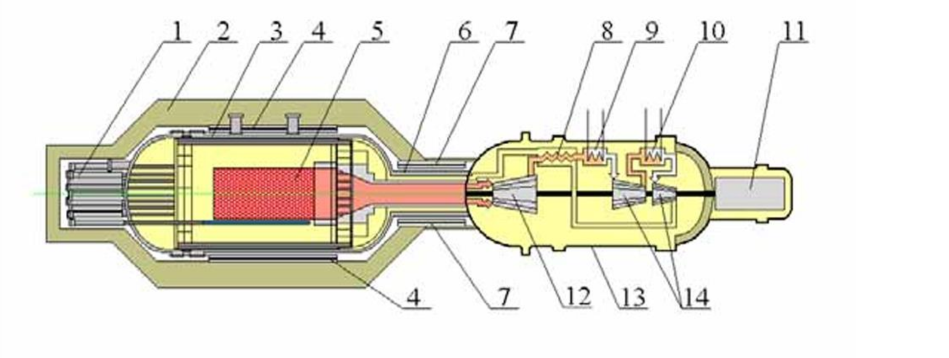

Fig.3 Conceptual layout of the marine nuclear power system
1- Control rode drive; 2- Radiation shield; 3- Pressure vessel; 4- Cavity cooling system; 5- Ordered bed core; 6- Connected tube; 7- Passive cooling system; 8- Recuperator; 9- Precooler; 10- Intercooler; 11- Generator; 12- Turbine; 13- Power conversion vessel; 14- Compressor;

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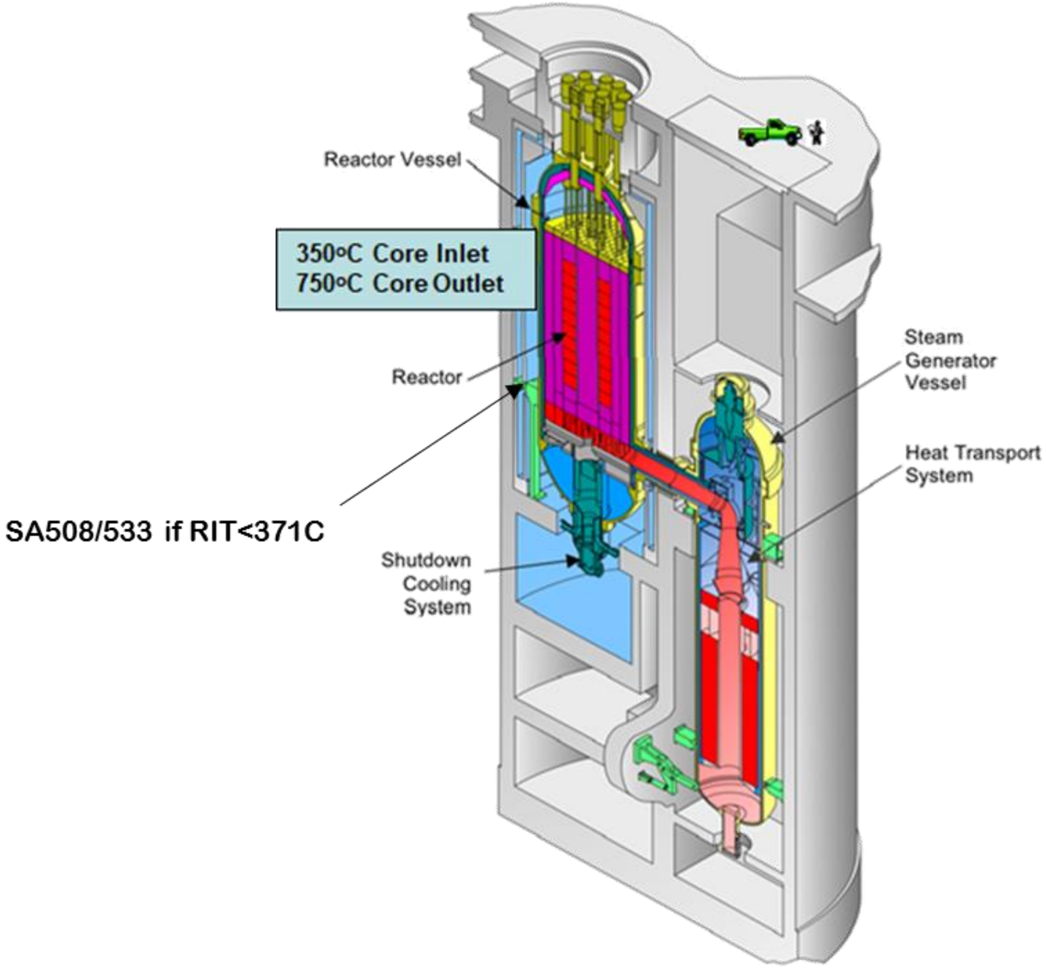
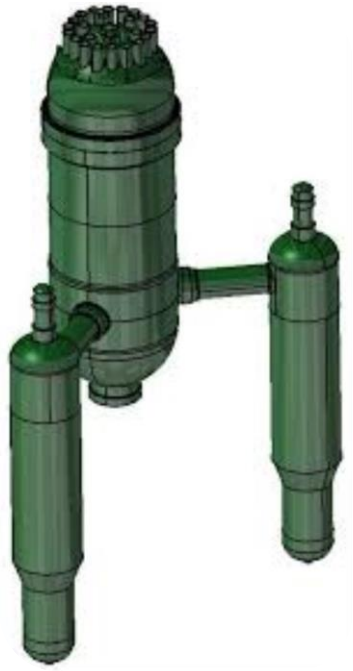
Source: Jiafu Tian, "A NOVEL CONCEPT OF THE MODULAR HTGR AND ITS NEW APPLICATION", Proc. Of HTR2008.

Primary Loop Features: Framatome SC-MHTGR

Parameter	
Fuel	TRISO (<20% LEU) in Compacts and Blocks
Core Geometry	102 columns,10 blocks per column
Reactor Power	625 MWt
Reactor Outlet Temperature	750ºC
Reactor Inlet Temperature	325ºC
Primary	He at 6 MPa
Secondary (x2)	Steam @ 16.7 MPa, 566ºC

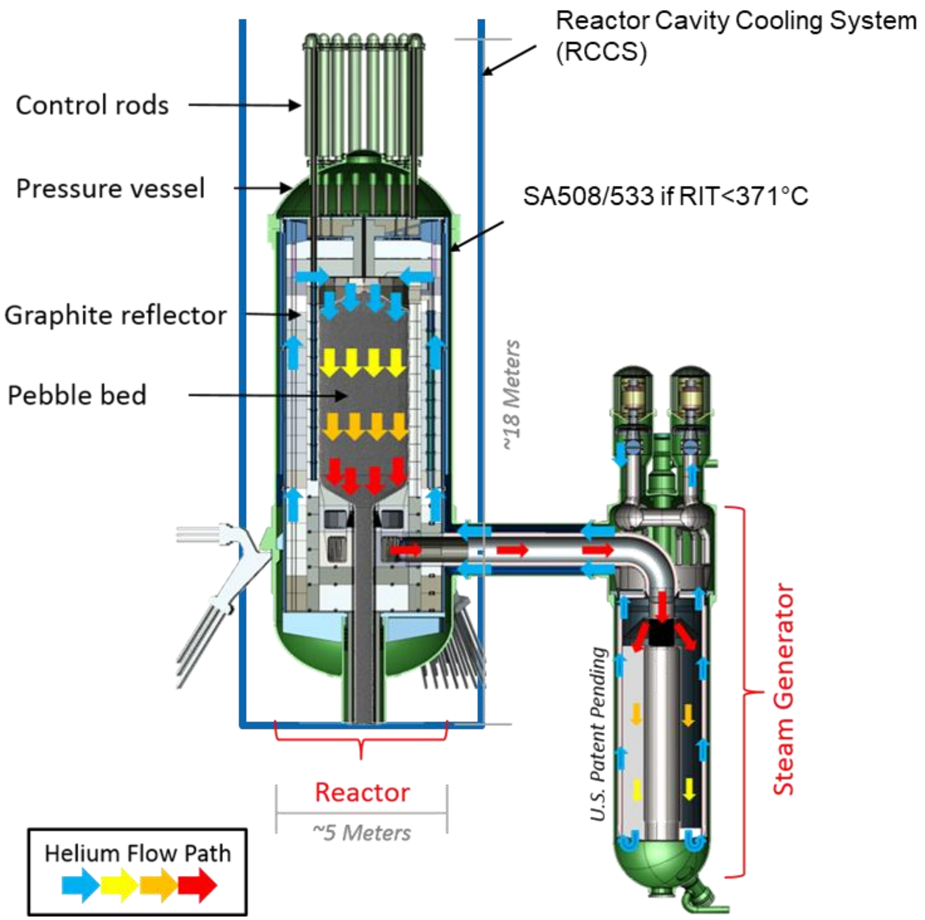




Source: https://inis.iaea.org/records/5d8yb-p1y81

Primary Loop Features: X-Energy Xe-100

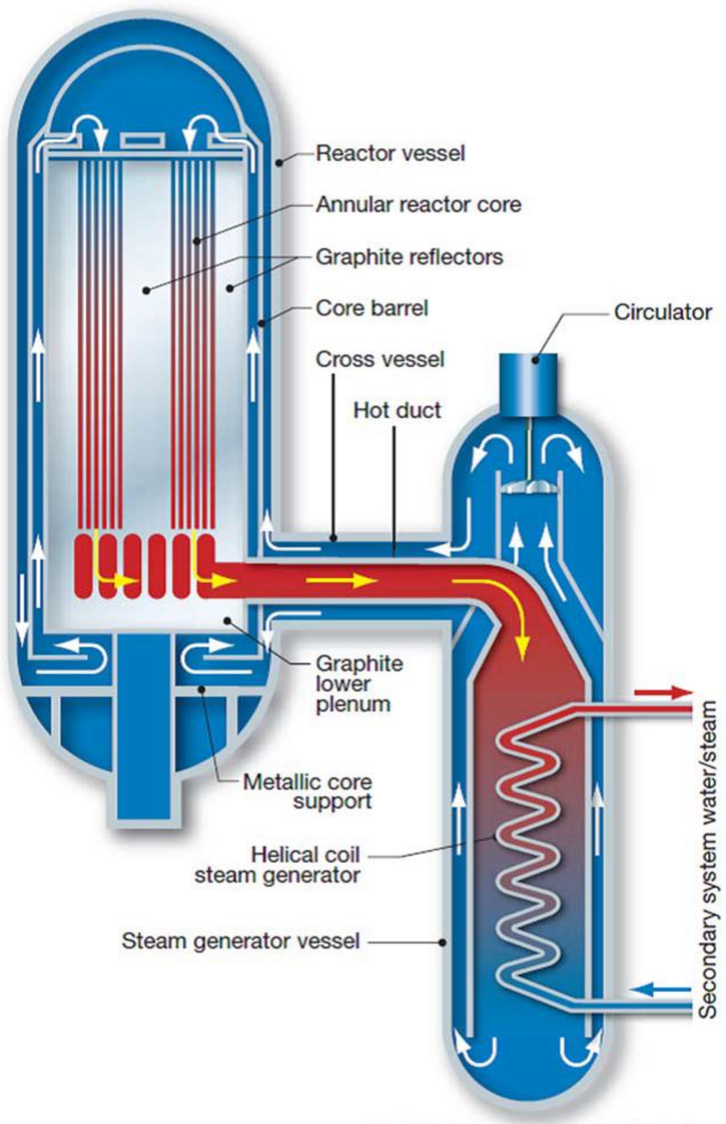
Parameter	
Fuel	TRISO (~15% HALEU) in Pebbles
Core Geometry	~200K Pebbles in a Cylindrical Bed
Reactor Power	200 MW_t
Reactor Outlet Temperature	750ºC
Reactor Inlet Temperature	260ºC
Primary	He at 6 Mpa
Secondary	Steam at 16.5 MPa, 565ºC



Source: Xe-100 200 MWt Pebble Bed HTGR (x-energy.com)

Attributes of Modular HTGRs

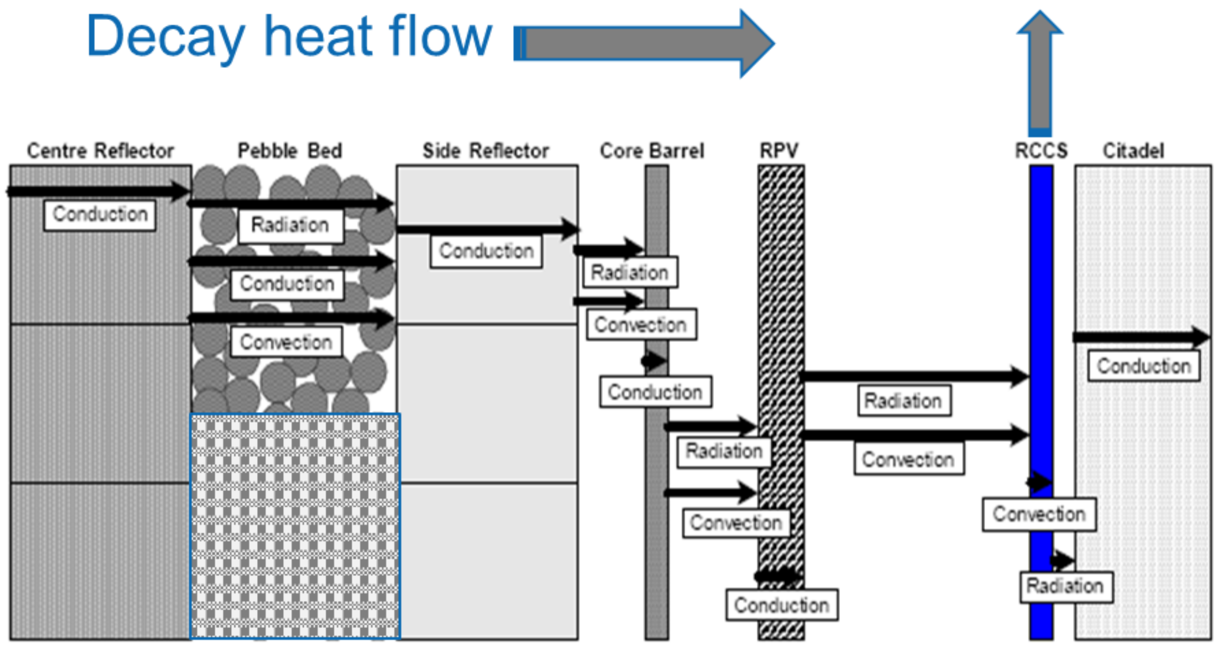
- Graphite-moderated and reflected.
- Cooled (usually) by helium (~7 MPa).
- Large ΔT (>400°C) across the core (top to bottom) compared to 30°C for an LWR.
- Fuel: TRISO fuel particles in a carbonaceous matrix.
- Uninsulated reactor vessel (not needed anymore for smaller designs).
- Large aspect ratio: heat escapes radially via conduction and radiation if forced cooling is lost.
- Slow temperature response during accidents (high heat capacity and low power density)



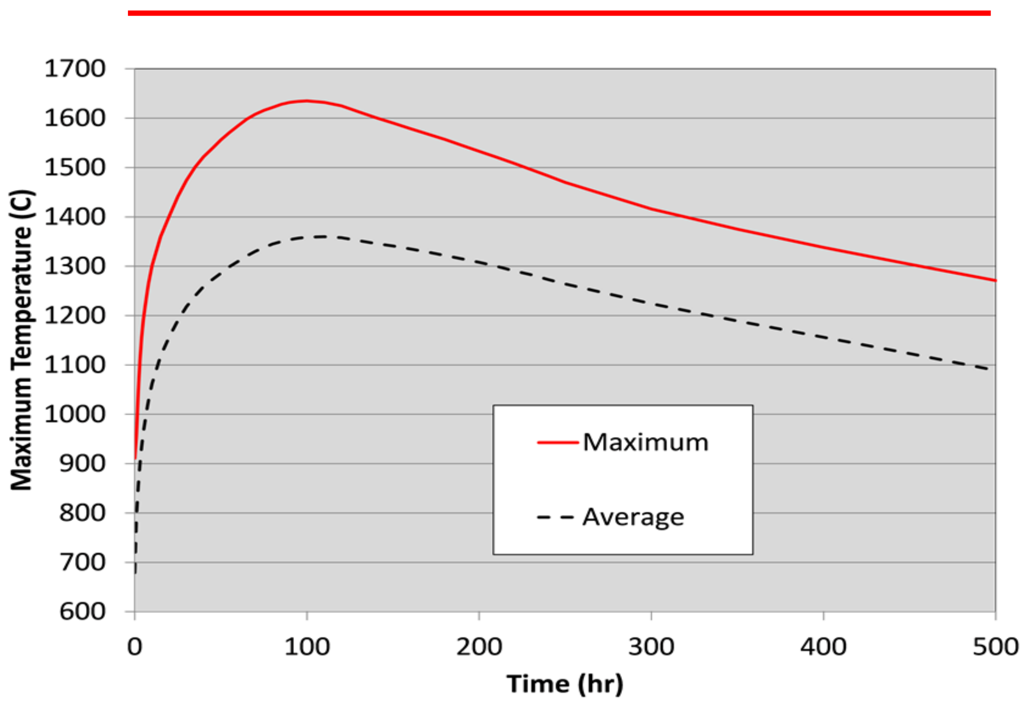
(1 of 2 steam generators shown)

Inherent Safety: Loss of Forced Flow

1800ºC – No appreciable UCO particle failures observed in AGR heating tests, although accelerated diffusion of certain FP (Sr, Cs, Eu) is observed.



Source (figure): F. Reitsma, IAEA



Source: "Core temperatures during a DLOFC", AREVA Technical Document 12-9251926-001, Summary Report-SC-HTGRE Demonstration Reactor.

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Modular HTGR Safety Design Approach

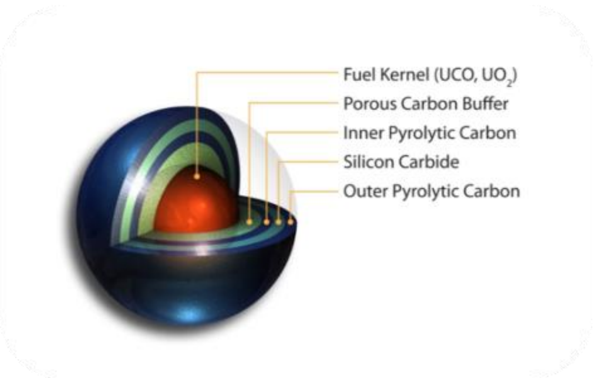
- Utilize inherent material properties as basis for safety
  - Helium coolant – neutronically transparent, chemically inert, low heat capacity, single phase
  - Ceramic coated (TRISO) particle fuel – high temperature capability, high radionuclide retention
  - Graphite moderator – high temperature stability, large heat capacity, long thermal response times
- Simple reactor design with inherent and passive safety features
  - Retain most radionuclides at the source (i.e., within fuel)
  - Shape and size reactor to allow passive heat removal from reactor core using uninsulated reactor vessel
    - Heat is still removed if system is depressurized due to breach in reactor helium pressure boundary (HPB)
    - Heat is radiated from reactor vessel to RCCS panels
  - Large negative temperature coefficient supports intrinsic reactor shutdown
  - No reliance on AC-power to perform required safety functions
  - No reliance on operator intervention; insensitive to incorrect operator actions or inactions

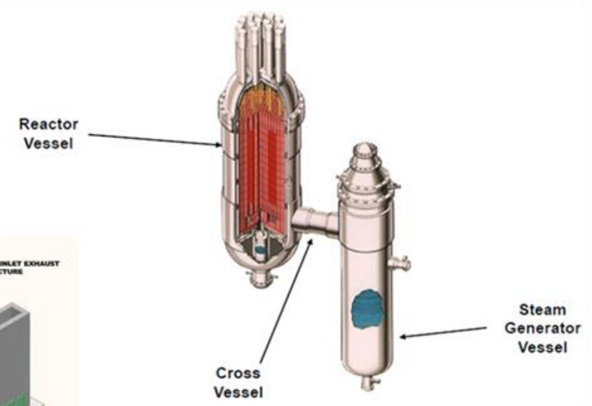
Modular HTGR Functional Containment

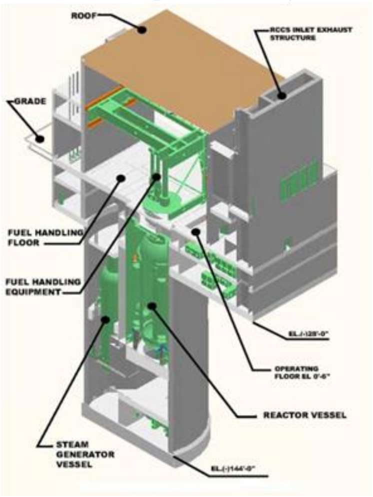
5 Radiological Release Barriers

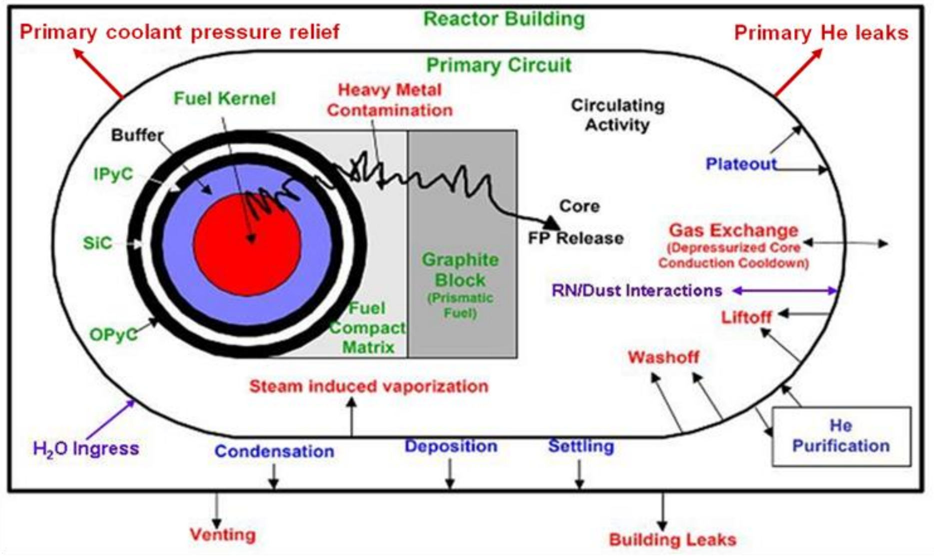
- **Fuel Kernel**
- **Fuel Particle Coatings**
- **Matrix/Graphite**
- **Helium Pressure Boundary**
- **Reactor Building**

Fuel Element









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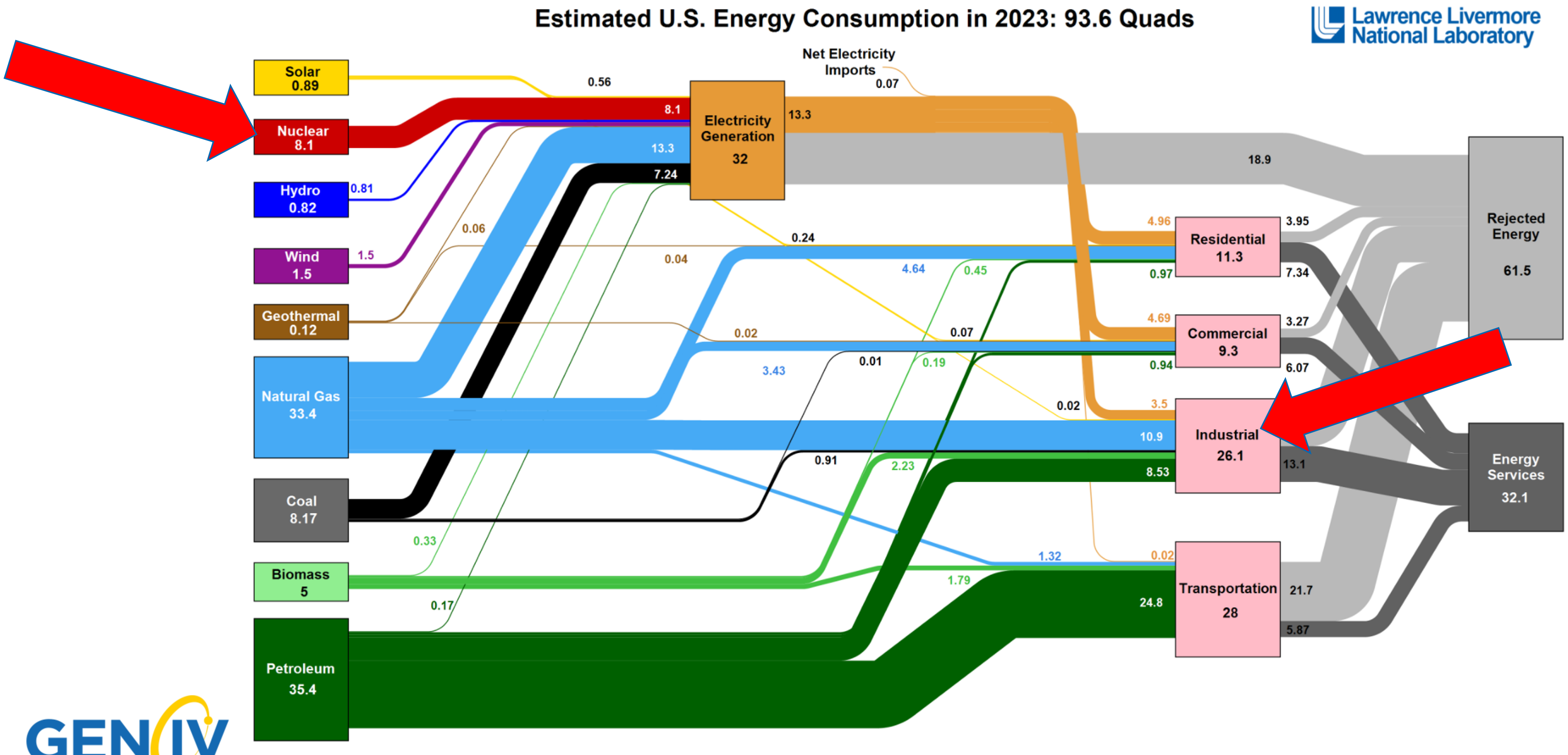
The Use Case for Non-Electric Industrial Applications



Source: LLNL October, 2024. Data is based on DOE/EIA SEDS (2024). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 49% for the industrial sector, and, 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Source: https://flowcharts.llnl.gov/sites/flowcharts/files/2024-10/energy-2023-united-states.pdf

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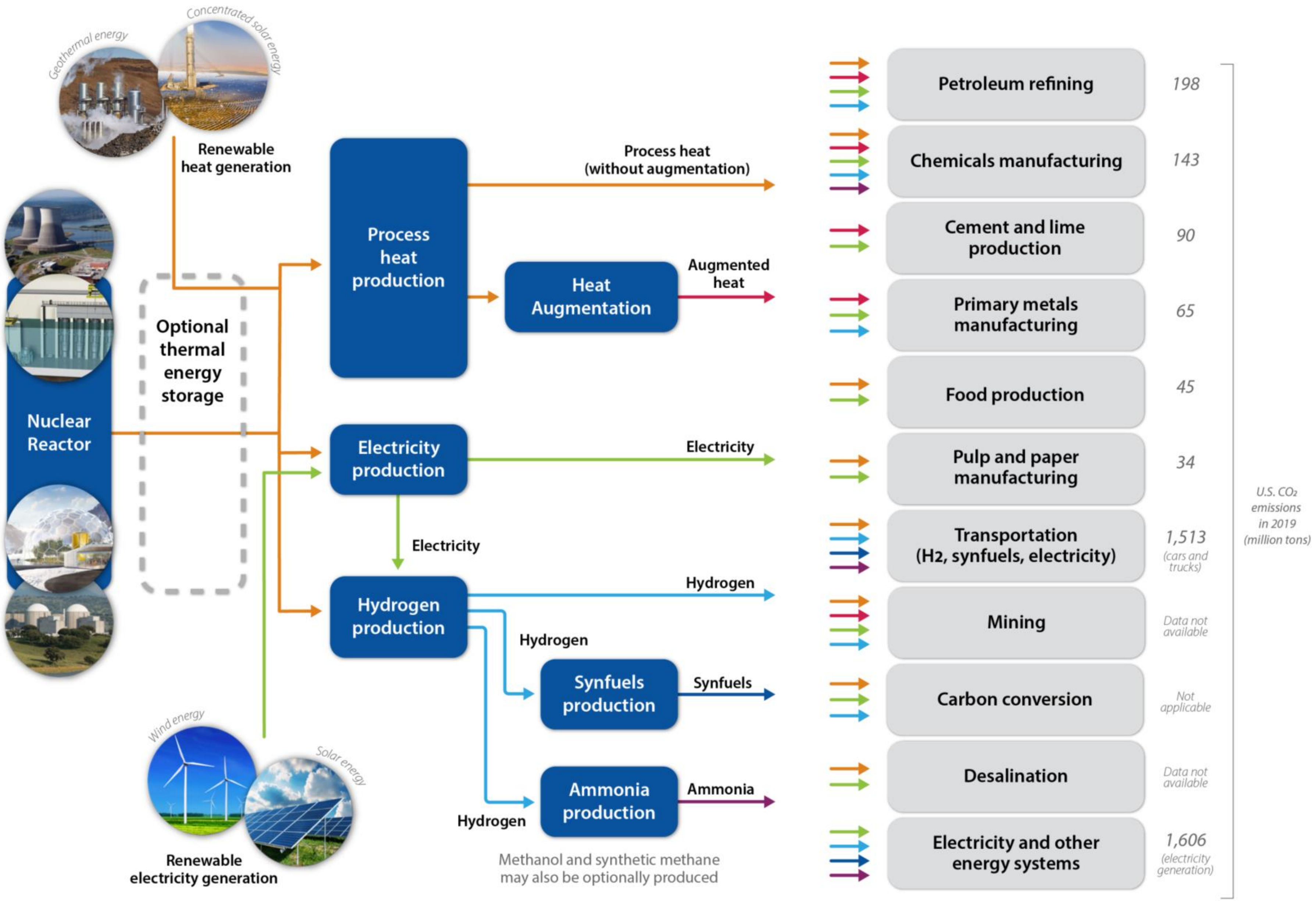
Potential Nuclear-Driven Integrated Energy System Opportunities

Reactor sizes align with the needs of each application; heat augmentation can be applied if needed to match process temperature demands.



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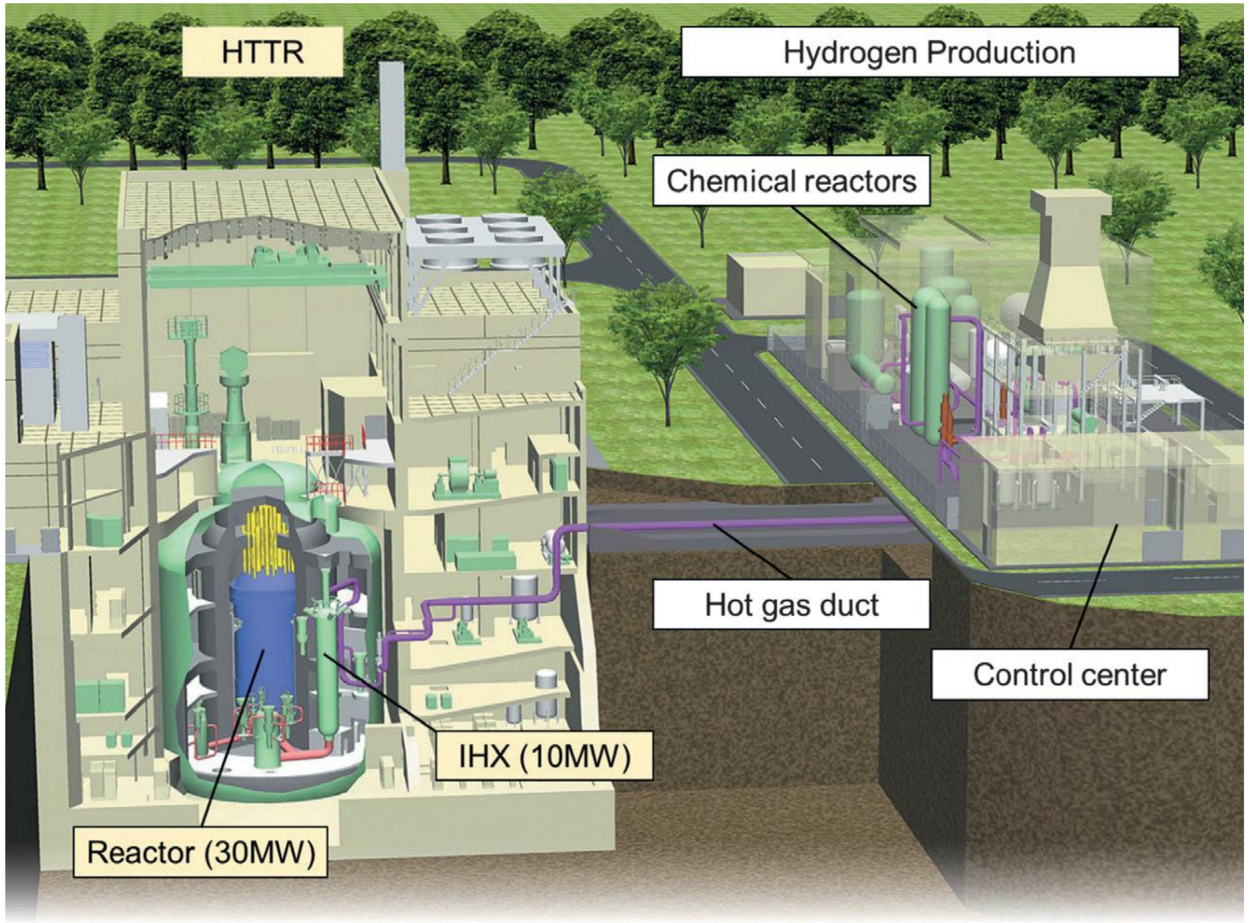
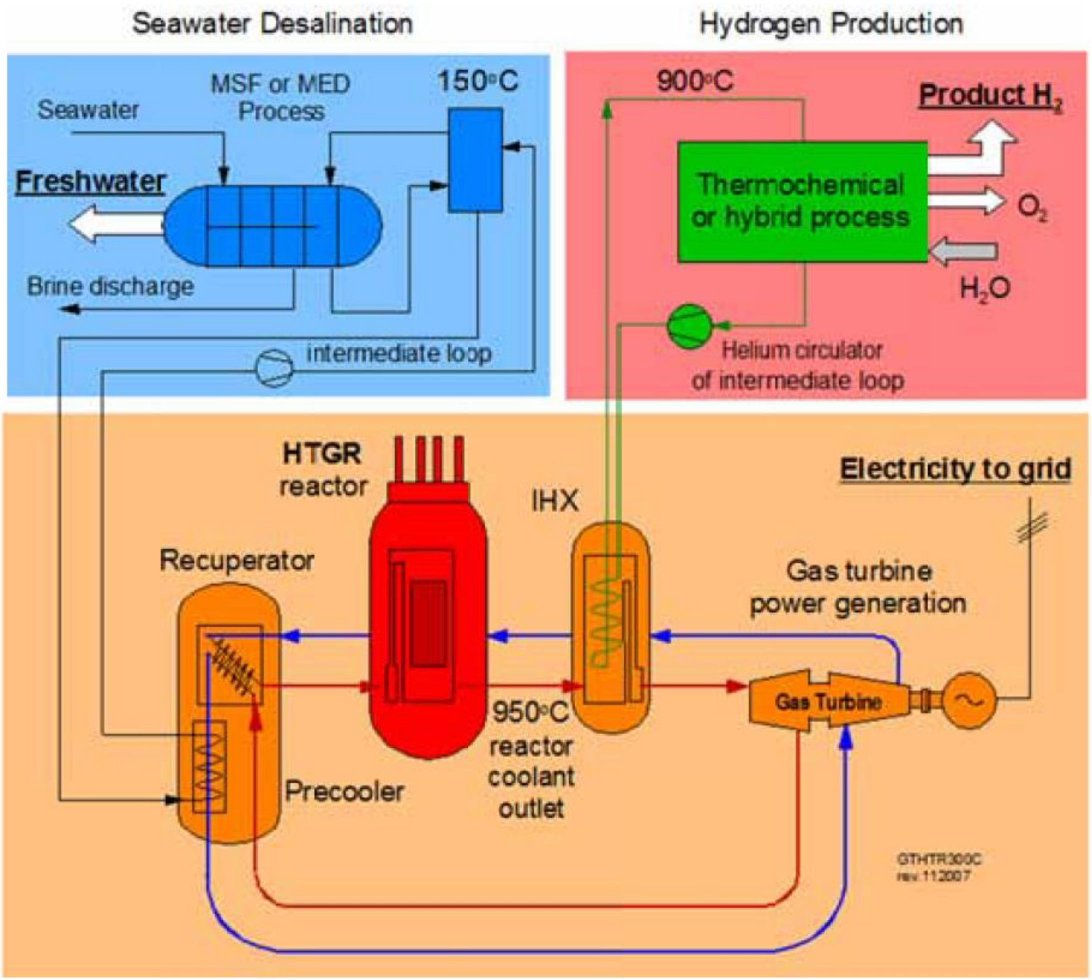
Source: Adapted from INL, National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs, April 2021

Hydrogen Production and Desalination with HTGRs: Japan





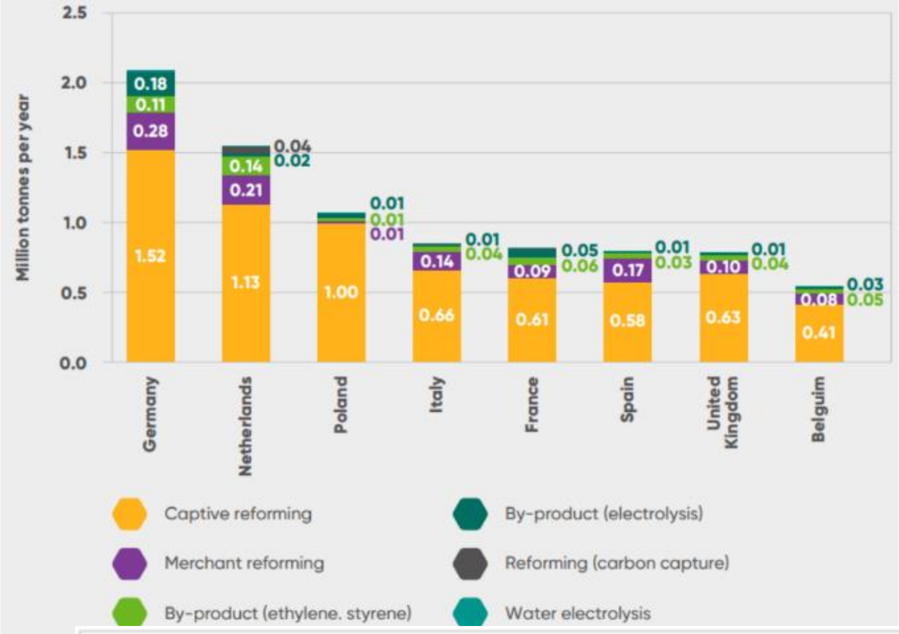
(Left) Fütterer, M., et al. 2020. The High Temperature Gas-Cooled Reactor. Encyclopedia of Nuclear Energy https://doi.org/10.1016/B978-0-12-409548-9.12205-5.

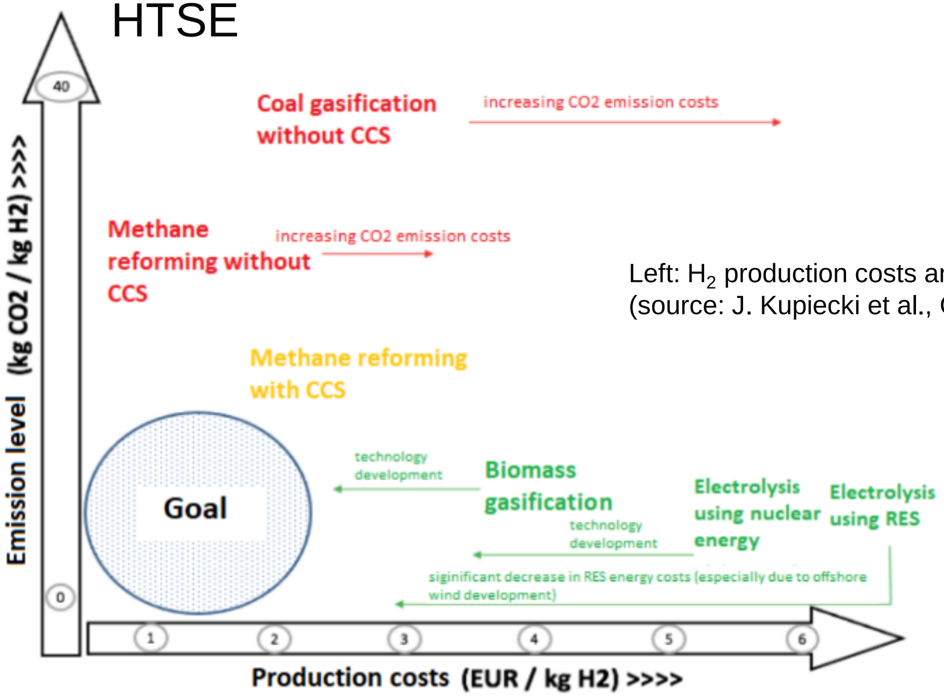
(Right) IAEA 2012. Advances in Nuclear Power Process Heat Applications. IAEA-TECDOC-1682.

Heat and Hydrogen Market: EU

- 7.8 Mt/year hydrogen consumed in the EU
- Most hydrogen is captive, i.e., directly consumed by refineries and fertilizer plants
- Heat, transport, synthetic fuels and Direct Reduced Iron (DRI) are seen as emerging hydrogen markets.
- A single HTR could generate up to 189 kT/year hydrogen with HTSE

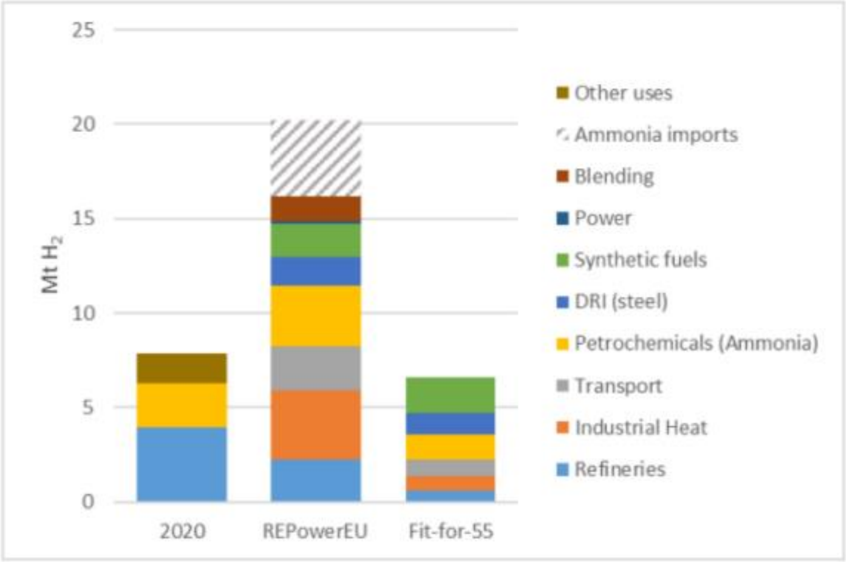
Total hydrogen production capacity of top 8 hydrogen producers (source: Hydrogen Europe, 2022)





Left: H_2 production costs and emissions of different technologies (source: J. Kupiecki et al., Centrum Technologii Wodorowych, 2021)

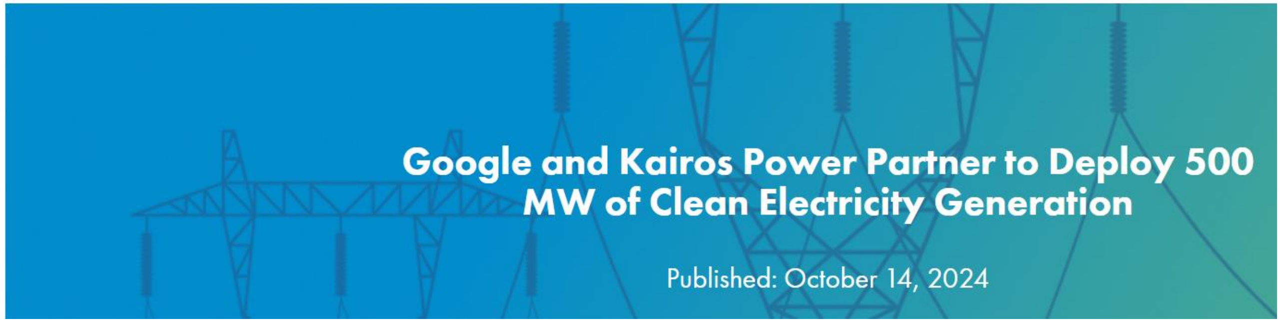
Right: Current and planned hydrogen consumption by sector in the EU (source: JRC, 2022)



HTGRs and Data Centers

Kairos Power

COMPANY TECHNOLOGY UPDATES MEDIA



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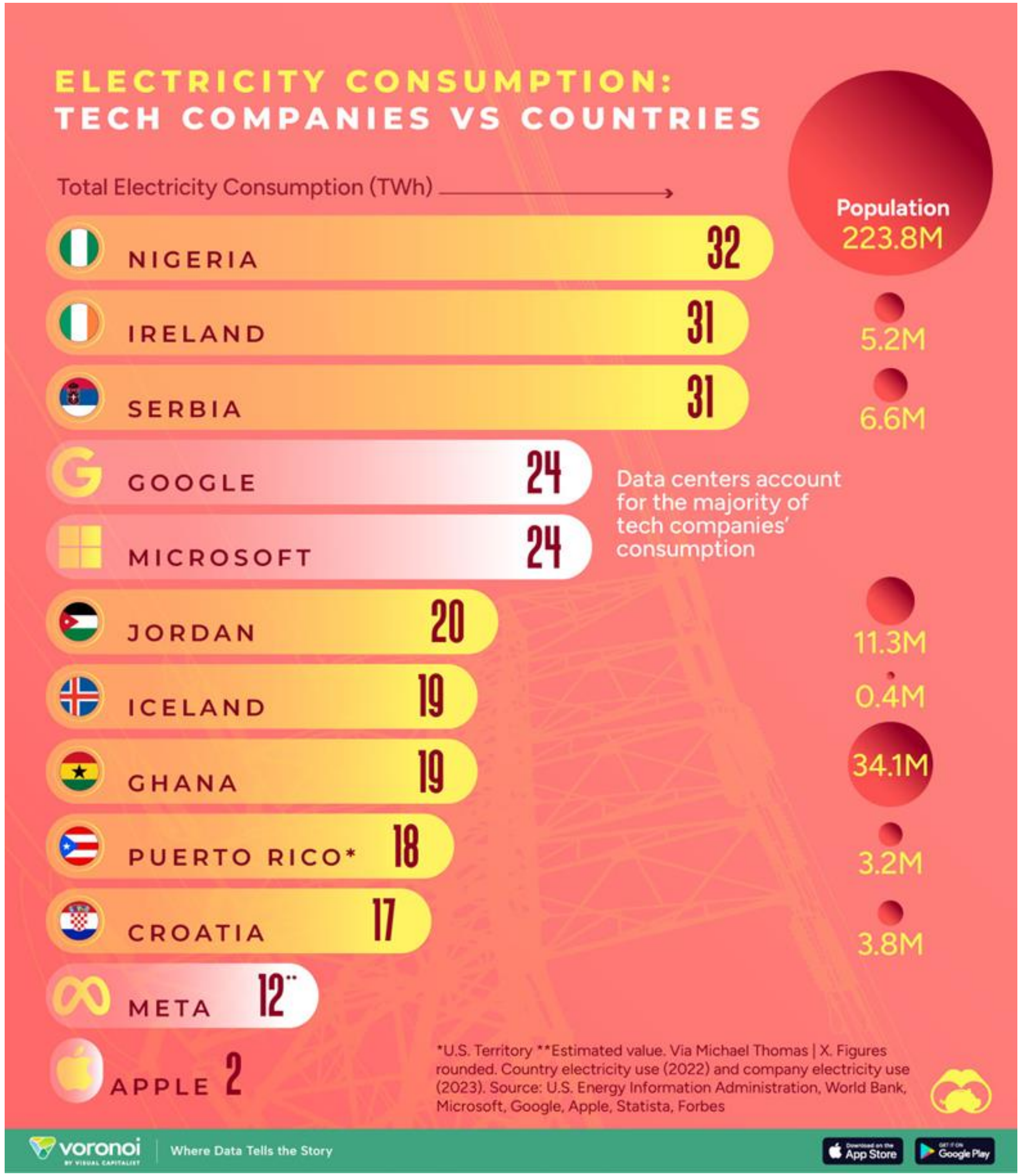
Amazon invests in X-energy, unveils SMR project plans

Wednesday, 16 October 2024

Amazon has announced it has taken a stake in advanced nuclear reactor developer X-energy, with the goal of deploying up to 5 GW of its small modular reactors in the USA by 2039.



https://kairospower.com/external_updates/google-and-kairos-power-partner-to-deploy-500-mw-of-clean-electricity-generation/
https://world-nuclear-news.org/articles/amazon-invests-in-x-energy-unveils-smr-project-plans
https://www.visualcapitalist.com/charted-big-tech-uses-more-electricity-than-entire-countries/

HTGR Projects: Canada

- OPG X-Energy framework agreement
- Saskatchewan Research Council - Westinghouse eVinci
- CNL Stage 3: Global First Power (USNC)

Saskatchewan government announces microreactor funding

Monday, 27 November 2023

The province is providing CAD80 million (USD59 million) for the Saskatchewan Research Council to pursue the demonstration of a microreactor in Saskatchewan, with plans for a Westinghouse-designed eVinci micoreactor to be operational in the province from 2029.

Canadian Nuclear Research Initiative (CNRI)

Supporting Technology Developers

- Program enables collaborative advanced reactor development and research projects
- The goal is to accelerate the deployment of safe, secure, clean, and cost effective SMRs in Canada and make CNL's technical capabilities and expert knowledge available and accessible
- Projects underway with several vendors, new projects in negotiation.
- New intake announced at G4SR-5
- Now including fusion
- www.cnl.ca/CNRI

Participants Including:

USNC ULTRA•SAFE•NUCLEAR; moltex clean energy; ARC CLEAN ENERGY; Kairos Power; TERRESTRIAL ENERGY; generalfusion; CLEAN CORE; Westinghouse

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

December 19, 2024 | In The News

StarCore Moving Forward in Manitoba

STARCORE NUCLEAR

In the week of December 9, several of the StarCore Nuclear team were in Manitoba to continue discussions with several parties who are participants in Project Whiteshell. Project Whiteshell is a 9.6 MWe HTGR which is intended to demonstrate StarCore's offering for off-grid sites in Canada.

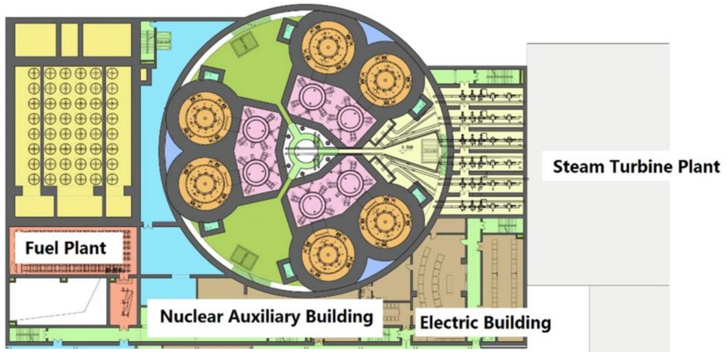
Project Whiteshell will closely follow the NGNP design developed at INL in the late 1990's and will incorporate the lessons learnt at sites who ran similar HTGR reactors, such as the ones at Fort St Vrain and Peach Bottom.

During last week the StarCore team held meetings with the Manitoba Provincial Government, Manitoba Hydro, The Mayor of Pinawa LGD, Blair Skinner, Southern Chiefs Organisation, the Brokenhead Ojibway Nation and other first nations groups. Davi Dabney – CEO, Leo Eskin – Director of Engineering and Joe Wiendl – Director of Corporate Strategy made good progress for StarCore and Project Whiteshell.

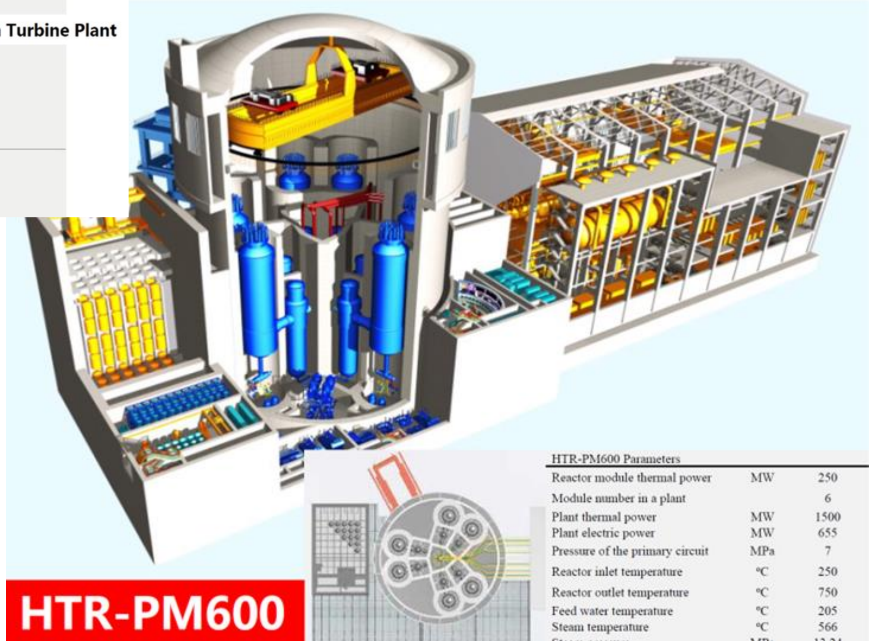
StarCore is expecting to commence licensing early in 2025 and work will include: discussions with CNL for siting of the demonstration plant at Whiteshell, initiating the Vendor Design Review with CNSC, engagement with contractors on various scopes of work, preparing the 19 focus areas for the VDR and early engagement for critical materials to meet schedule

Source: GIF VHTR Canada Member Dr Ali Siddiqui (ali.siddiqui@cnl.ca)
https://starcorenuclearpower.com/starcore-moving-forward-in-manitoba/
https://www.world-nuclear-news.org/articles/saskatchewan-government-announces-microreactor-fun

HTGR Projects: China



- HTR-PM (two ~110 MWe PBR units)
  - Commercial operation in December 2023, and District Heating for local community in March 2024, demonstrated viability and inherent safety of small-sized modular approach:
    - Total loss of primary system cooling demonstrated with no operator actions.
    - Standardized reactor and balance-of-plant approach (turbines, steam generators) ensure economics-of-scale and site flexibility



HTR-PM600 Parameters

Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	°C	250
Reactor outlet temperature	°C	750
Feed water temperature	°C	205
Steam temperature	°C	566

- Next phase: demonstrate economy of scale with much larger facilities
  - HTR-PM600: Electricity only (6-units = 655 MWe)
  - HTR-PM600s:
    - Cogeneration of steam and electricity for industrial use
    - Government approved 6-module plant in August 2024.
    - Three standard HTR-PM modules with optimized plant and site layout.
  - HTR-PM1000: Replacing GW-scale fossil power plant (12 units = 1,310 MWe)

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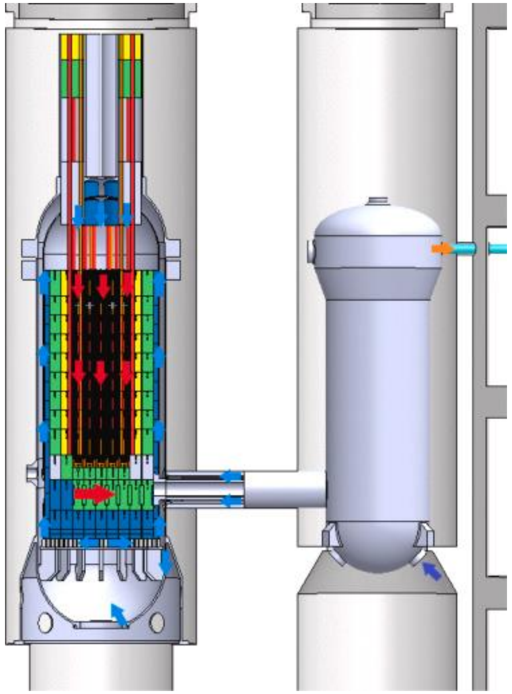
Source: GIF VHTR China Member Dr. LI Fu (lifu@mail.tsinghua.edu.cn)

HTGR Projects: Euratom

GEMINI 4.0 and HTGR-POLA

- Many industrial sites that use process steam also require hydrogen for full decarbonization of their processes.
- GEMINI 4.0 continues focus on cogeneration of steam and clean hydrogen.
- Recent core design activities looked at larger core size to mitigate initial high LOFC temperatures, and positioning of control rods.



- HTGR-POLA (POLish Atomic) project: basic design with a significant part of Preliminary Safety Report (PSR) completed
- This reactor will become basis for subsequent commercial HTGR reactors in the Polish industry.
- The fifteen largest Polish chemical plants require at least 6.5 GW of thermal power in the form of steam at 400-550C.
- Leverage GEMINI 4.0 progress for 30 MWt HTGR test project
- Next planned phases: preparation of detailed technical design (2 years), licensing (1 year+), construction (4 years) and commissioning (6-12 months).

Source: GIF VHTR Euratom Member Dr. Michael Fuetterer (Michael.FUETTERER@ec.europa.eu)

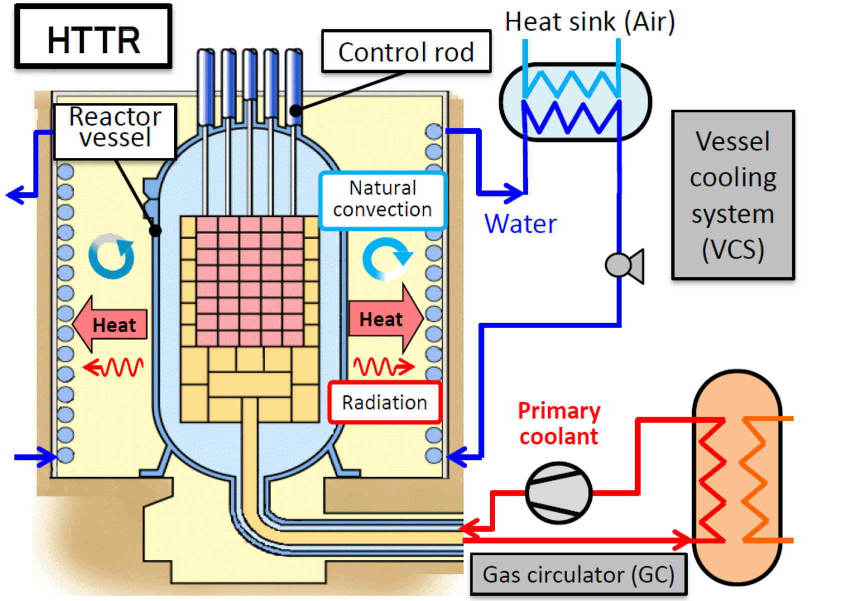
HTGR Projects: Japan

Safety Demonstration Test in HTTR

HTTR demonstrated its inherent safety features which decreases the reactor power against the loss of forced cooling (LOFC) in full power operation without scram.

Test conditions of OECD/NEA LOFC test

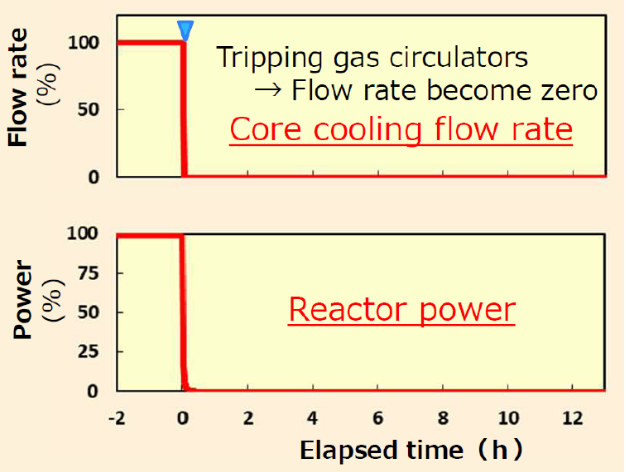
☑ Low power (30% (9MW)) (Shutdown of GC)	**LOFC (Run1)** (Completed in PY2010)
☑ High power (100% (30MW)) (Shutdown of GC)	**LOFC (Run2)** (Completed in March 27, 2024)
☑ Low power (30% (9MW)) (Shutdown of GC and VCS)	**LOFC (Run3)** (Completed in PY2021)



Test condition (Run2)

- Initial power: 100% (30MW)
- Reactor coolant flow: Stop
- VCS: Active
- Shutdown operation (scram): Not active

Test result[1] (Run2)



Obtained data will be used for validation of the analysis code.

[1] JAEA, "Success of Safety Demonstration Test in HTTR (High Temperature Engineering Test Reactor) – Confirmation of the Inherent Safety Feature of HTGR-", https://www.jaea.go.jp/english/news/press/2024/032801/

Source: GIF VHTR Japan Member Dr. Shoichiro Okita (okita.shoichiro@jaea.go.jp)

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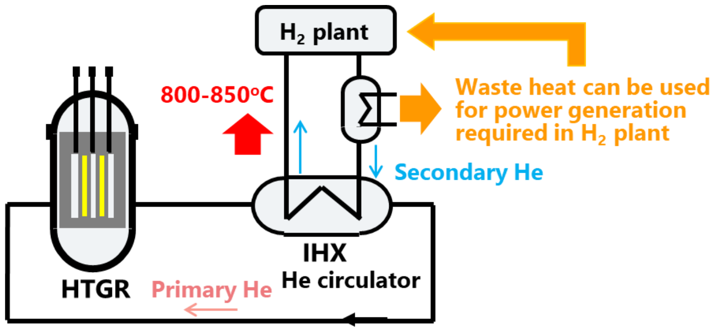
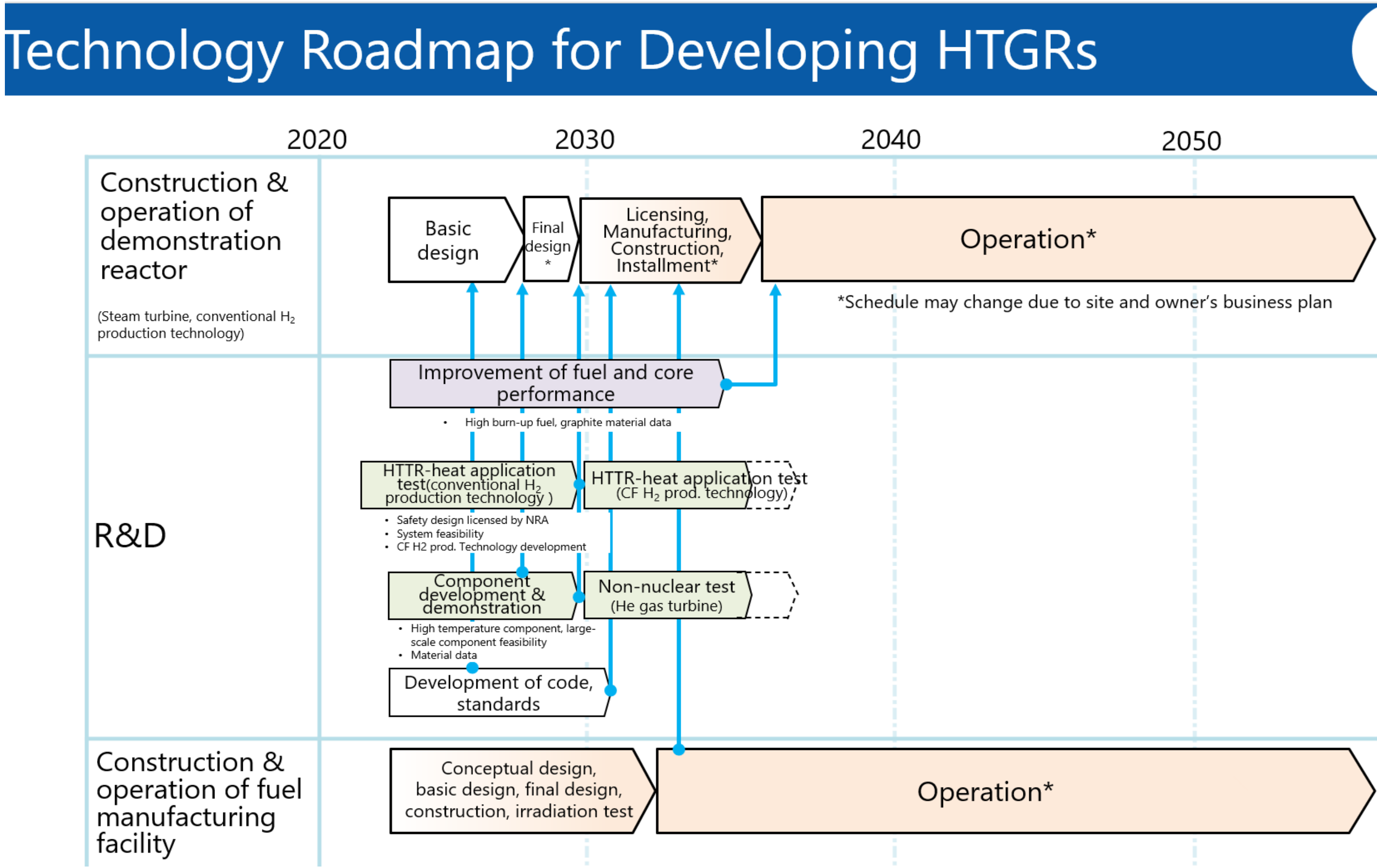
HTGR Projects: Japan

Prismatic HTGR Demonstration Reactor



- Japanese government approved development and construction of HTGR demonstration reactor to be operated in 2030's
- Reactor power 150-250 MW with outlet temperature 800C+ to supply hydrogen production plant.
- Estimated ~$3B funding, with Mitsubishi Heavy Industries, Ltd. (MHI) as prime contractor
- Will include fuel, core and system design, site evaluation



Source: GIF VHTR Japan Member Dr Takeshi AOKI (aoki.takeshi@jaea.go.jp)

HTGR Projects: Republic of Korea

- In July 2024, it was announced that Republic of Korea will spend $32 million to develop a prismatic HTGR by 2027.
- Public-private partnership: KAERI will design the nuclear reactor while five industrial firms will design and build the power plant (POSCO E&C Co., Daewoo Engineering & Construction, Lotte Chemical, SK Ecoplant and Smart Power).
- POSCO E&C is expected to use HGTR technology for steel-making; SK Ecoplant to commercialize high-temperature water electrolysis hydrogen production, and Lotte Chemical for its petrochemical business.

Public-Private Partnership Project for Advanced SMR

Yr	~'24	'24	'25	'26	'27	'28 ~	'34~
Classification	Government R&D	PPP Development Project				Demonstration Project	Commercialization Project
Leading Organizations	Government	Government 50 Private Sector 50					Private Sector
Project Details	Development of Technologies	(1st Phase) Conceptual Design		(2nd Phase) Basic Design		• PSAR · EIA, Detail Design (FSAR) • Site Selection · CP · OP	Business

Organization	Role
KAERI Korea Atomic Energy Research Institute	Core Design / System Design / Safety Analysis Fuel Design / Core Structure Design
POSCO E&C	Project Management / Plant Design (BOP)
SMART POWER	Electrical System Design for Plant
DAEWOO E&C	Radiation Protection System Design Radiative Waste Management System
SK ecoplant	SOEC System Design / Hydrogen Business Plan
LOTTE CHEMICAL	Process Heat System Design/ Process Heat Business Plan

KAERI 한국원자력연구원 Korea Atomic Energy Research Institute

Source: GIF VHTR ROK Member Dr Chan Soo KIM (kcs1230@kaeri.re.kr)

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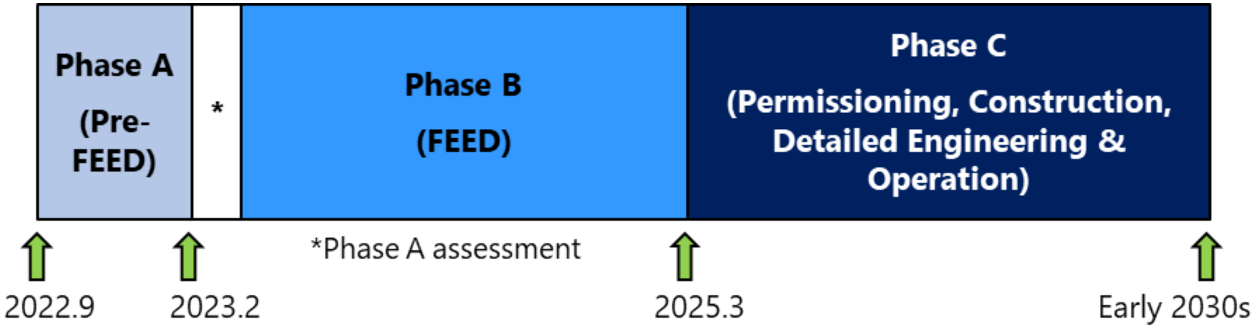
HTGR Projects: UK

- JAEA is collaborating with UK and Poland to accelerate deployment of HTGRs.
- The UK government aim to have a demonstration HTGR in operation by the early 2030s.
- National Nuclear Laboratory (NNL) and JAEA performed Front End Engineering Design (FEED) and supporting activity studies in July 2023. NNL selected Jacobs to review the initial designs and delivery plans for the HTGR in May 2024.



- UK government also launched a Coated Particle Fuel (CFP) program in conjunction with the HTGR demonstration reactor program.
- NNL was awarded UK CFP Program Step 1 in July 2023.
- JAEA and NNL signed Collaboration Memorandum on fuel manufacturing technology and License Arrangement in April 2024.
- NNL will take the role as integrator to develop the UK's first CPF Program, which will carry out R&D and prototype production activities to prepare the UK's first prototype TRISO fuel block for irradiation testing in April 2025. A match-funded grant of up to £16M has been awarded to NNL for this scope.

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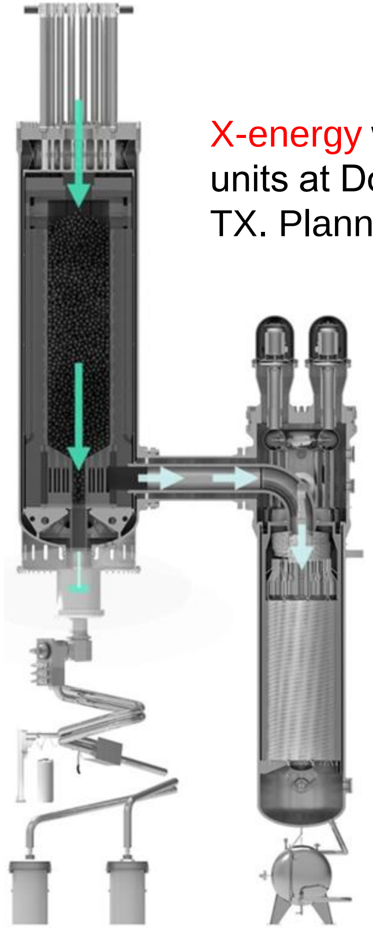
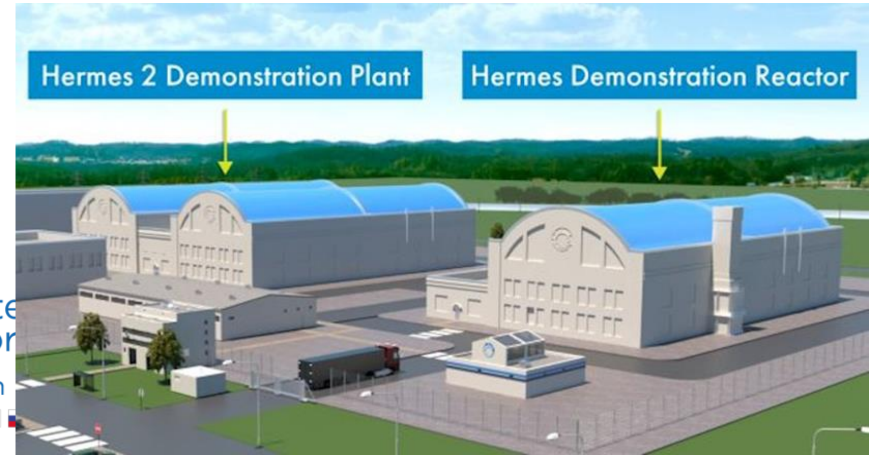
Source: GIF VHTR UK Member Dr Tim Abram (tim.abram@manchester.ac.uk)

HTGR Projects: USA



X-energy will site the first 4 XE-100 (200MWt) units at Dow Chemical's facility at Seadrift, TX. Planned operation by 2029.

Kairos Power starred construction on fluoride-cooled Hermes test reactor (35 MWt) at Oak Ridge, TN in July 2024. It is the first non-water-cooled reactor approved for construction in the US in more than 50 years. Two commercial units (Hermes 2) with intermediate liquid-sodium loops and a common power conversion unit will also follow at the same site.



Radiant and Westinghouse were awarded DOE funding for front-end engineering and experiment design of their respective TRISO-fueled microreactor designs.

Will be housed in repurposed EBR-II DOME testbed facility at INL.

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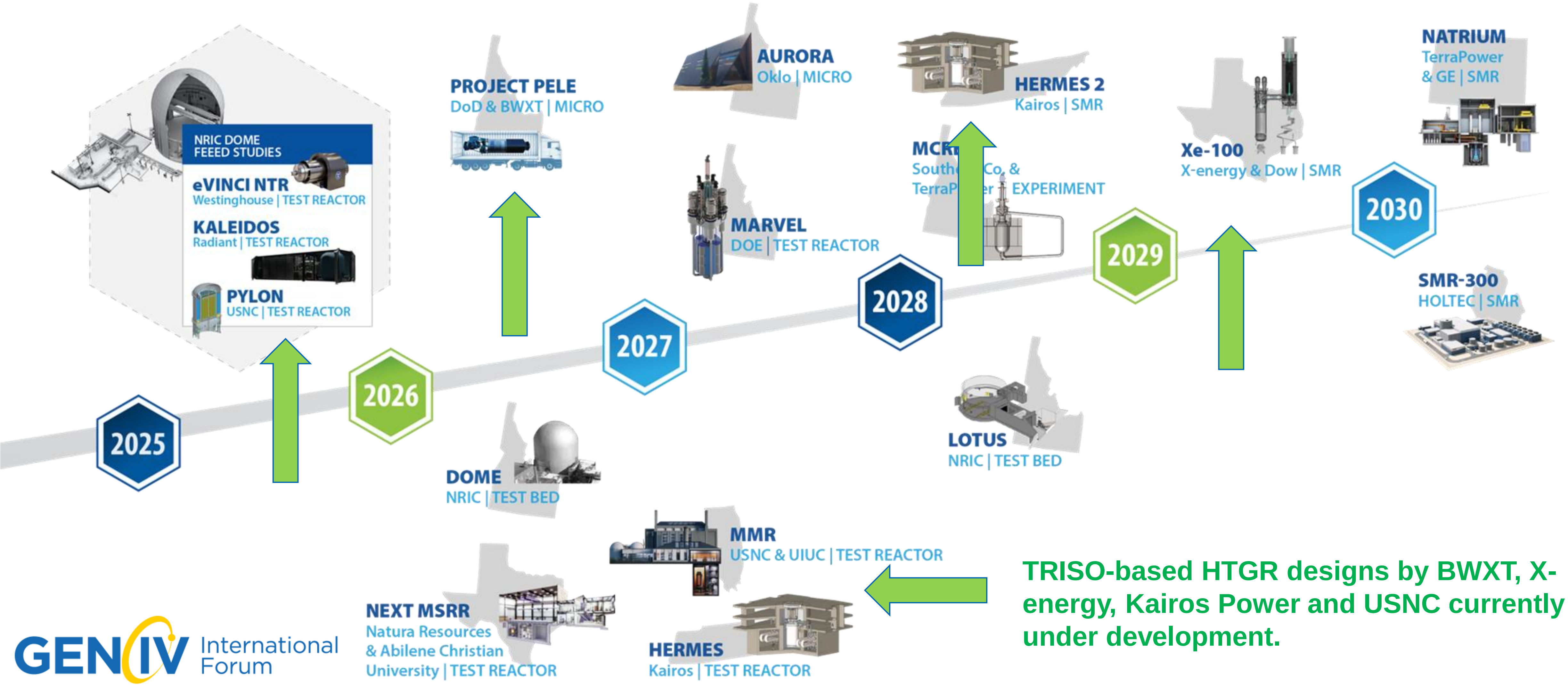
Source: GIF VHTR USA Member Dr Gerhard Strydom (Gerhard.Strydom@inl.gov)

HTGR Projects: USA



TRISO-based HTGR designs by BWXT, X-energy, Kairos Power and USNC currently under development.

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Source: GIF VHTR USA Member Dr Gerhard Strydom (Gerhard.Strydom@inl.gov)

Outline

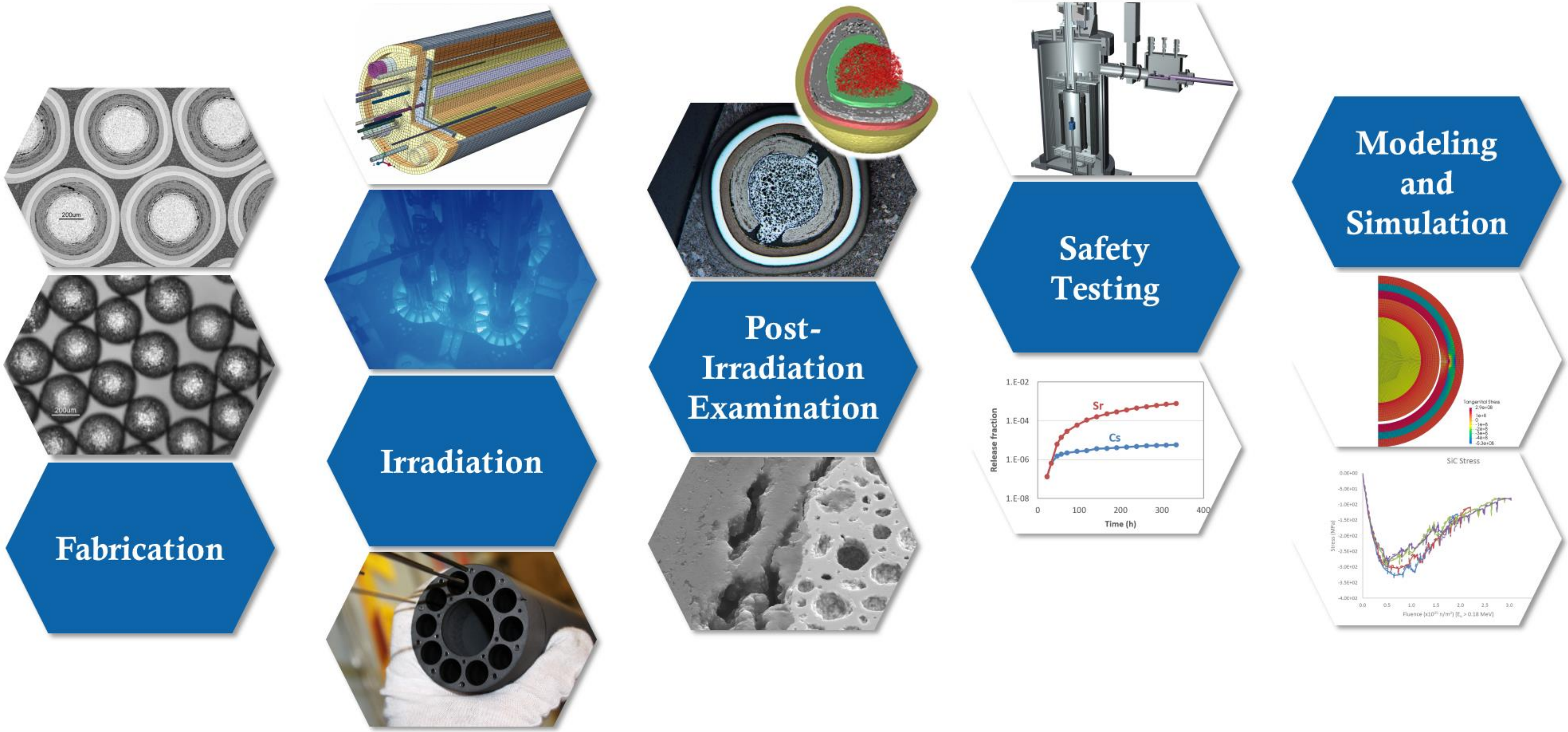
- (V)HT(G)R Basics: Family Members, History, and Main Technical Attributes
- Current International HTGR Deployment Landscape
- **Examples of HTGR R&D Activities and Collaborations within the GIF VHTR Framework**
- Questions and Discussion

GIF VHTR System and Project Arrangements

- 10 country signatories are currently part of GIF VHTR System Arrangement (SA)
- GIF VHTR R&D activities are defined within 4 Project Arrangements (PAs) – members shown below
  - Materials (MAT)
  - Fuel and Fuel Cycle (FFC)
  - Hydrogen Production (HP)
  - Computational Methods, Validation & Benchmarking (CMVB)
- Examples of current R&D activities within these PAs will be provided in the following slides

Agreement or Contract	Australia	Canada	Euratom	France	Japan	China	Korea	ZA	Russia	Switz.	UK	US
VHTR SA	S	S	S	S	S	S	S		O	S	S	S
HP PA		S	S	S	S	O	S				O	S
FFC PA		O	S	S	S	S	S				O	S
MAT PA	S	S	S	S	S	S	S			S	S	S
CMVB PA		O	S		S	S	S				O	S

Typical TRISO (and Graphite) Characterization Path: Make It, Irradiate it, Deconstruct and Stress Test It, Model It

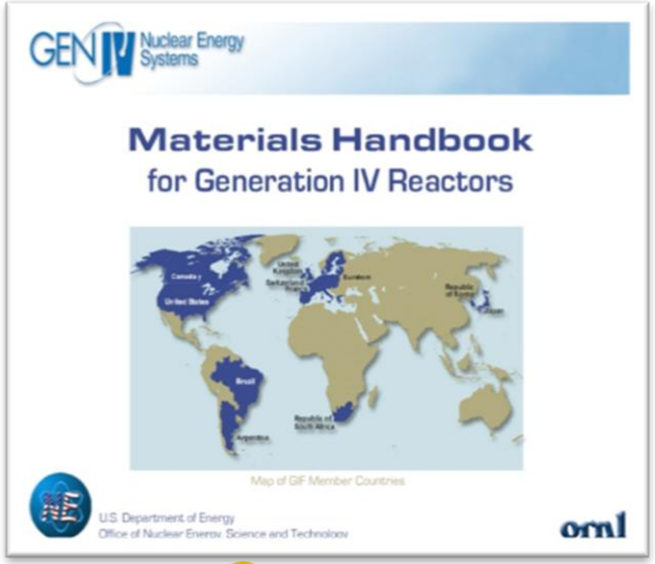


Source: GIF VHTR FFC Chair Dr Paul Demkowicz (paul.demkowicz@inl.gov)

GIF Technical R&D Projects: Materials (MAT)

VHTR Materials “Handbook” - a database for graphite, composites and metallic alloy data

- As of October 2024, the Handbook has collected 551 R&D reports from 11 Signatories.
- Access procedure detailed on website (next slide).



Country	As of April 2024		As of October 2024	
	Submitted	Uploading*	Submitted	Uploading*
Australia (+1)	19	1	19	2
Canada (+5)	16	1	16	6
China	6	2	6	2
EU	73	1	73	1
France (+14)	90	15	90	29
Japan	10	0	10	0
South Africa	27	0	27	0
South Korea	62	1	62	1
Switzerland	21	0	21	0
UK	8	0	8	0
US (+7)	149	0	149	7
VHTR (HLD†)	21	1	21	1
Sub-Totals	502	22	502	49
TOTAL	524		551	

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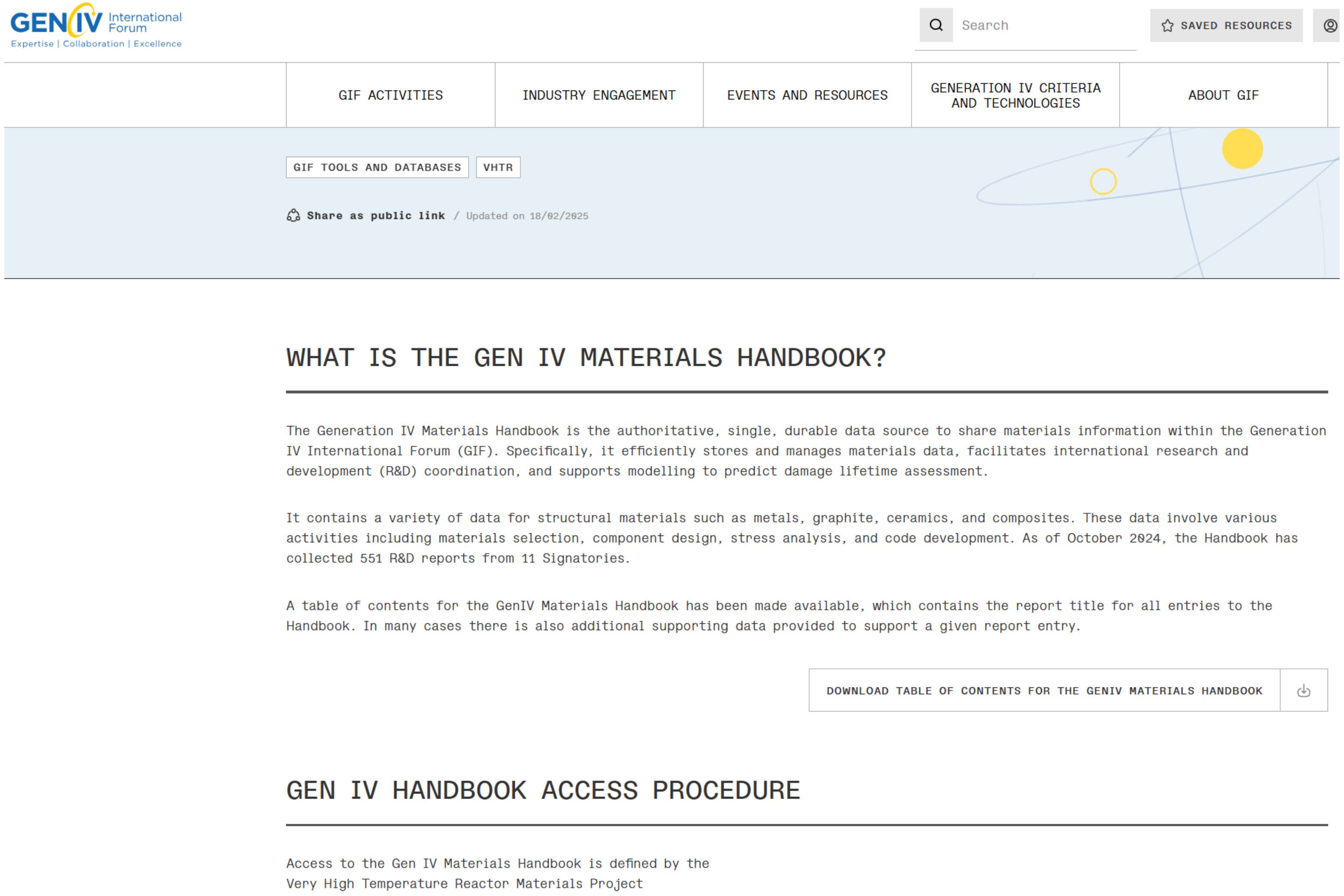
GIF Technical R&D Projects: Materials (MAT)

VHTR Materials Handbook Access



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WHAT IS THE GEN IV MATERIALS HANDBOOK?

The Generation IV Materials Handbook is the authoritative, single, durable data source to share materials information within the Generation IV International Forum (GIF). Specifically, it efficiently stores and manages materials data, facilitates international research and development (R&D) coordination, and supports modelling to predict damage lifetime assessment.

It contains a variety of data for structural materials such as metals, graphite, ceramics, and composites. These data involve various activities including materials selection, component design, stress analysis, and code development. As of October 2024, the Handbook has collected 551 R&D reports from 11 Signatories.

A table of contents for the GenIV Materials Handbook has been made available, which contains the report title for all entries to the Handbook. In many cases there is also additional supporting data provided to support a given report entry.

DOWNLOAD TABLE OF CONTENTS FOR THE GENIV MATERIALS HANDBOOK

GEN IV HANDBOOK ACCESS PROCEDURE

Access to the Gen IV Materials Handbook is defined by the Very High Temperature Reactor Materials Project

https://www.gen-4.org/resources/gif-tools-and-databases/generation-iv-materials-handbook

Handbook POC: Courtney Otani (INL) – Courtney.Otani@inl.gov

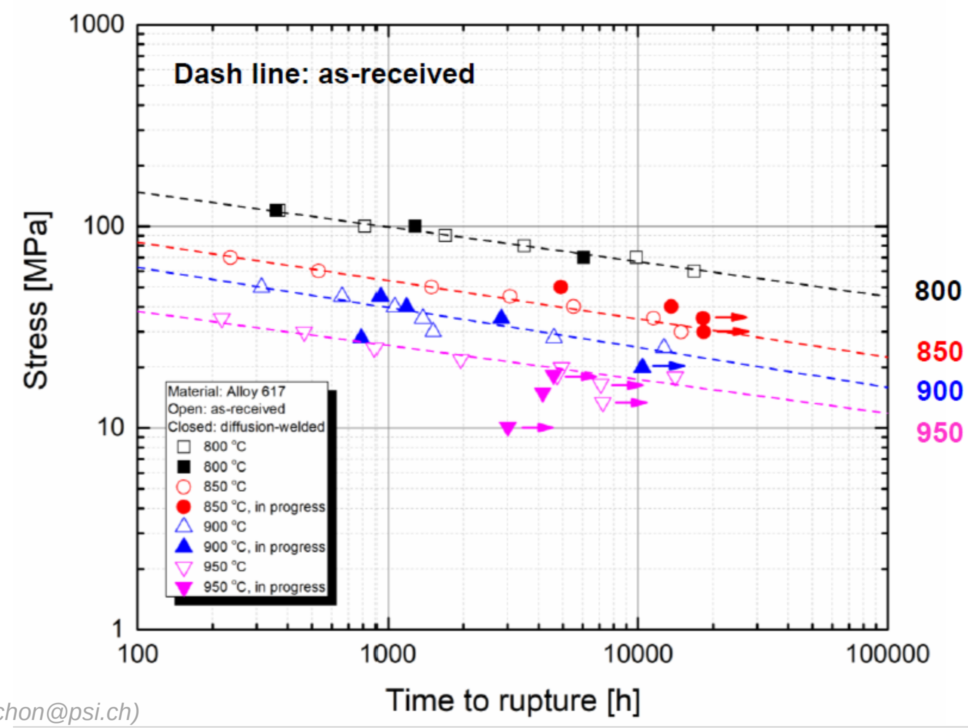
Example of Current R&D Contributions: Materials (MAT)

Korea: Metals and Design Methods

한국원자력연구원
KAERI
Korea Atomic Energy Research Institute

Task 6.2 (Testing)

- Diffusion-welded Alloy 617: creep-rupture
  - Temperature: 800, 850, 900, 950 °C
  - Comparison of time-to-rupture of the diffusion weldment to that of the as-received alloy



800 °C => completed
850 °C => completed
900 °C => running
950 °C => running

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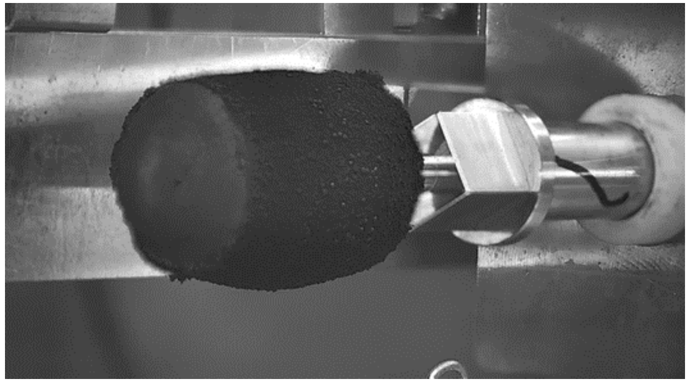
Source: GIF VHTR MAT PMB Chair Dr. Manuel Pouchon (manuel.pouchon@psi.ch)

Example of Current R&D Contributions: Fuel and Fuel Cycle (FFC)

China

- Deconsolidation and burnup analysis of HTR-10 spheres.
- High-temperature annealing of SiC coating to examine microstructure.
- ZrC coating layer deposition and annealing tests (to 2200 °C).
- HTR-PM:
  - 1,190,000 pebbles made for HTR-PM
  - First load fuel (4.2% ^{235}U) completed; started 8.5% ^{235}U fabrication



France

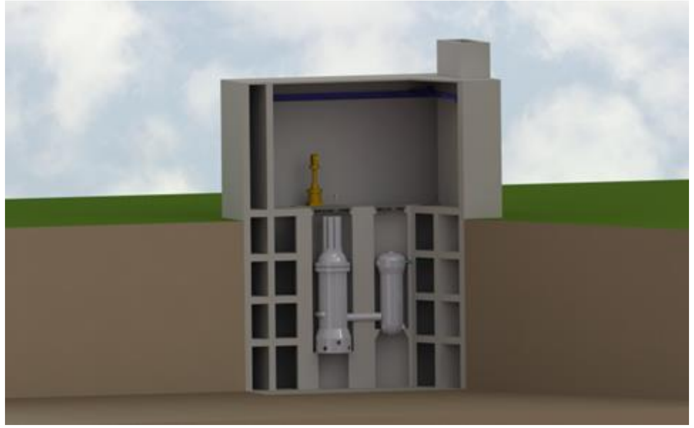
- Along with CEA support for startups, there are more interest in TRISO fuel activities.
- Planning fuel modeling activities as part of next work package with the ATLAS code.

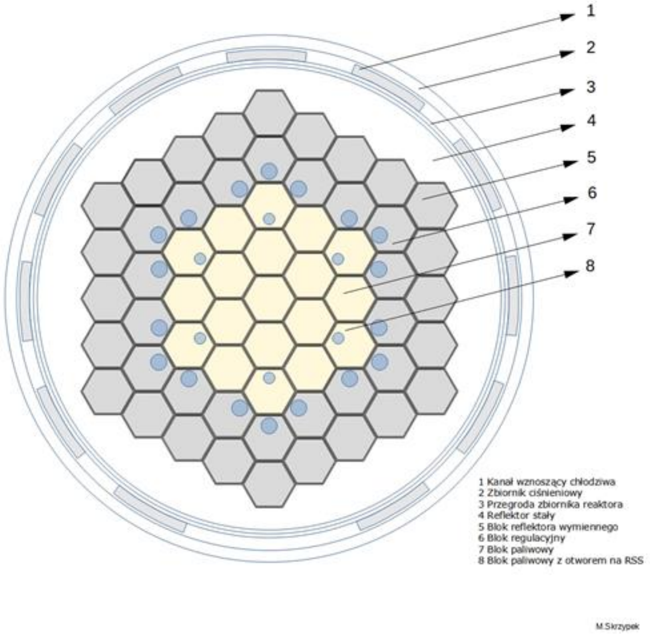
Source: GIF VHTR FFC Chair Dr Paul Demkowicz (paul.demkowicz@inl.gov)

Example of Current R&D Contributions: Fuel and Fuel Cycle (FFC)

EU/Poland

- HTGR-POLA project plan to develop an advanced TRISO laboratory with capacity to manufacture 2-3 kg a day. Laboratory Mission includes fuel development and fabrication, characterization, irradiation and PIE.





US

- AGR-5/6/7 irradiation experiment PIE and high-temperature safety testing in progress
  - 15 compacts have been deconsolidated; 17 safety tests performed.

  AGR-3/4 fission product transport experiment
  - PIE experiment reporting and data analysis to support fission product transport parameter refinement

  Development of air/moisture testing capability for irradiated fuel; will start operations in 2025

Source: GIF VHTR FFC Chair Dr Paul Demkowicz (paul.demkowicz@inl.gov)

Example of Current R&D Contributions: Hydrogen Production (HP)

Canada

- CNL is making significant progress in the development of co-electrolysis demonstration at a cement production facility.

St Marys Cement

Existing cement plant operated by St. Marys Cement (Ontario)

EU & France

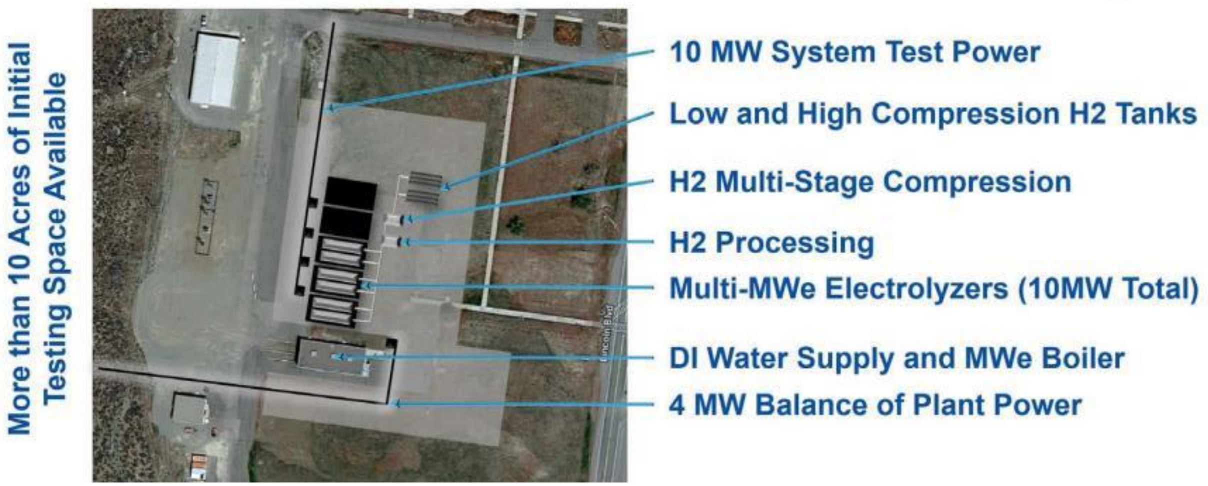
- EU: R&D progress on hybrid sulfur cycle includes demonstration projects scaling up to 500-700 kW, in collaboration with industrial partners such as Grillo (Germany), a key player in sulfuric acid manufacturing and recycling.
- France: Largest HTSE electrolyser installed in an industrial environment ready to start : ~ 2.6 MWe, ≥ 60 kg H2/h

Source: GIF VHTR HP PMB Chair Dr. Pierre Serre-Combe (pierre.serre-combe@cea.fr)

Example of Current R&D Contributions: Hydrogen Production (HP)

UK

- UK's contributions to the VHTR HP PMB focus on High Temperature Steam Electrolysis (HTSE) modelling work, coupling technologies, and industrial engagement to understand end-user needs.
- The UK is also working on creating a supportive regulatory environment for hydrogen, including the development of the Low Carbon Hydrogen Standard and the Hydrogen Regulators Forum.



US

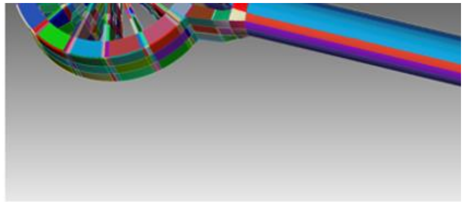
- U.S. is advancing HTSE technology through the H2NEW program, focusing on improving cell performance and durability, optimizing operating conditions, and reducing hydrogen production costs.
- Also working on scaling up hydrogen production and post processing technologies at the Idaho National Laboratory's Energy Technology Proving Ground, which aims to demonstrate industrial scale hydrogen and synfuels production by the late 2020s.

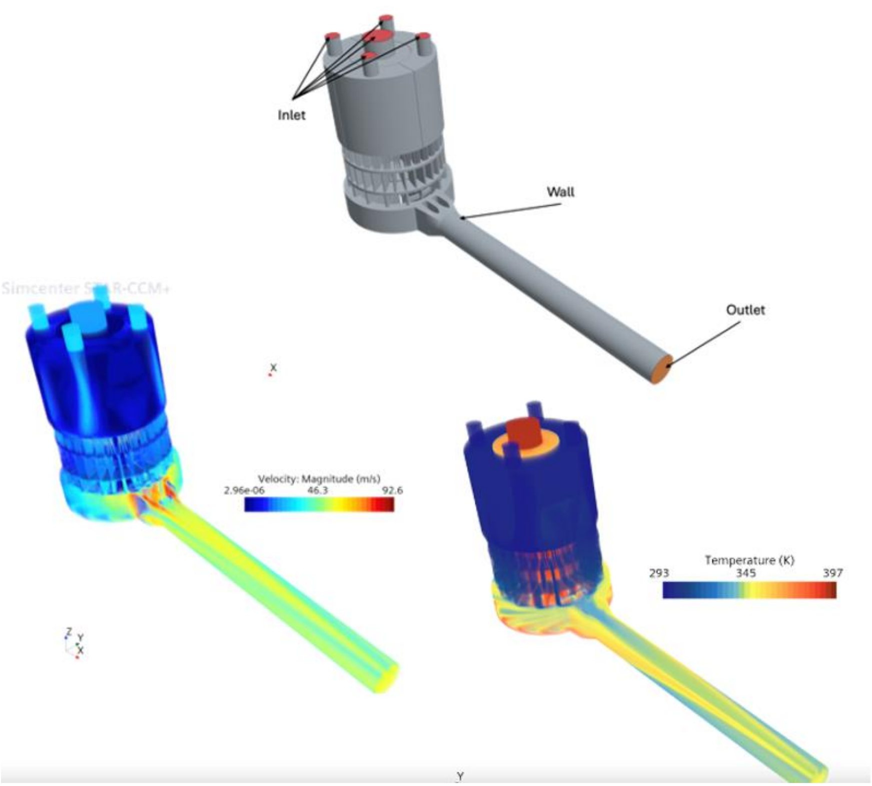
Source: GIF VHTR HP PMB Chair Dr. Pierre Serre-Combe (pierre.serre-combe@cea.fr)

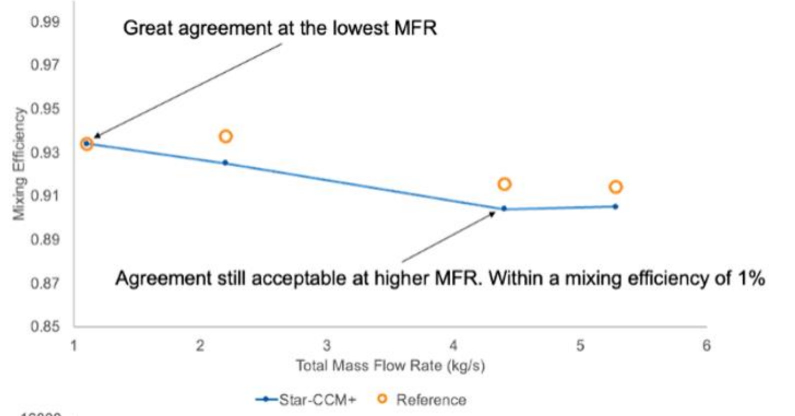
Example of Current R&D Contributions: Computational Methods, Validation & Benchmarking (CMVB)

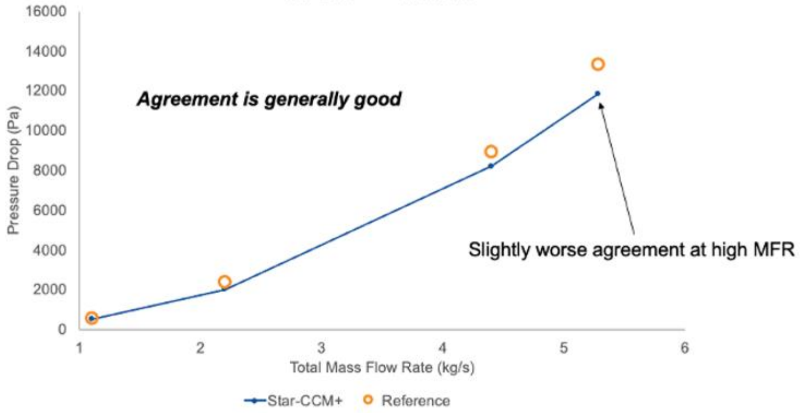
US

• Task2.2 Lower Plenum Mixing Facility Progress Update









- Work is currently being performed to create an all-hexahedral mesh for LES simulation with the NekRS code. This includes sensitivity tc geometric simplifications that will aid in the mesh generation.
- Data between LES and RANS simulation will be compared to determine the efficacy of RANS models for lower plenum mixing
- Simulation data for both the LES and RANS simulations will be compared with experimental data once it is received.

Source: GIF VHTR CMVB PMB Chair Dr. Paolo Balestra (Gerhard.Strydom@inl.gov)

Example of Current R&D Contributions: Computational Methods, Validation & Benchmarking (CMVB)

Canada

- PIRTs for GCRs is ongoing and progress was presented at the G4SR-5 conference at Ottawa held in October 2024.
- Stand-alone and coupled code predictions for the lower plenum configuration representative of OSU HTTF PG-28 test (OECD/NEAT TH BM) was presented at the NUTHOS-14 conference in Vancouver, held in August 2024.
- CNL coupled STAR-CCM+ with its system TH code: ARIANT and benchmarked it against OSU HTTF experiments (segregated domain coupling approach).
- License for INLs GRIFFIN code was procured and the self-directed user training is ongoing.

Japan

Modelling of ATR

Comparison between the OECD/NEA Benchmark model and our model

✓ The geometry and the material composition are set to the same as the OECD/NEA Benchmark model.

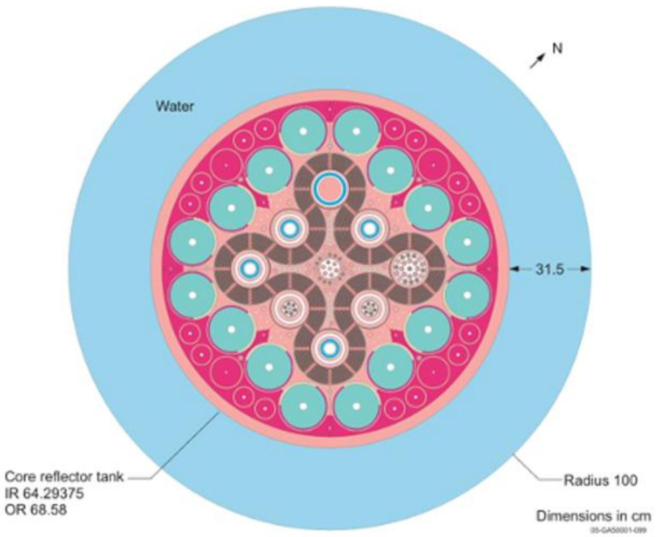


Fig. Schematic view of the OECD/NEA Benchmark model[1]

[1] NEA, NEA/NSC/DOC/(95)03/II, HEU-MET-THERM-022 (2019)

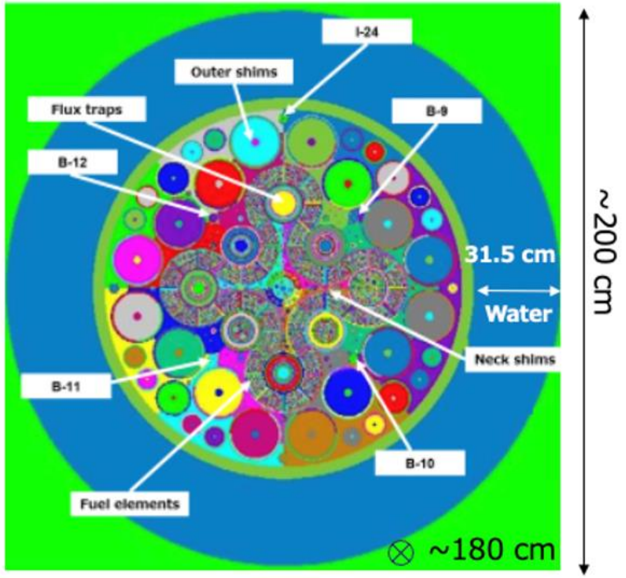


Fig. Output data of ATR full core model with MVP-3 code

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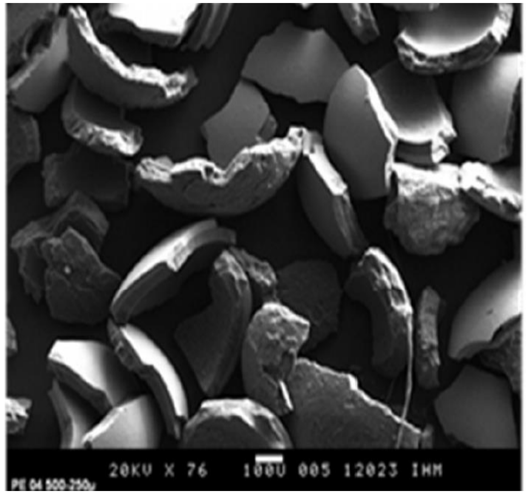
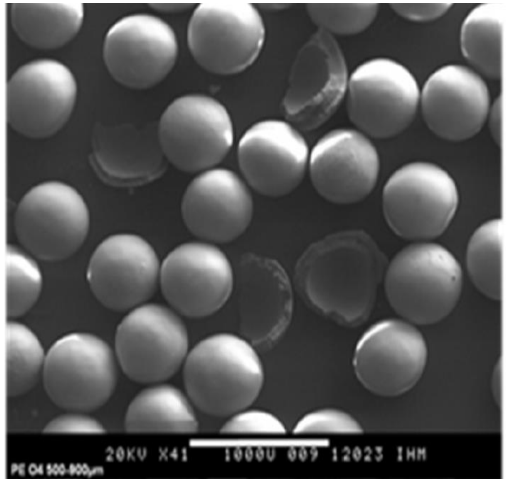
Source: GIF VHTR CMVB PMB Chair Dr. Paolo Balestra (Gerhard.Strydom@inl.gov)

GIF VHTR Activities: External Interfaces

- We interface with several IAEA activities and groups focused on HTGRs: Technical Working Groups on HTGR, NPLCES*, NEXSHARE **, IAEA Consultancy Meetings etc.
- VHTR SSC was instrumental at the origin of work on energy system integration, performed today in the GIF Non-Electric and Cogeneration Applications of Nuclear Energy (NECA) WG [&].
- VHTR SSC and RSWG worked collaborated on HTGR System Design Criteria [#], a joint white paper on non-proliferation and safety, and a new project on "3S By Design" with PRPPWG [##].
- HTGR waste (TRISO fuel and graphite, mainly)
  - Back-end is included in the FFC PMB scope, but with limited activities so far.
  - Euratom is performing work on this in the CARBOWASTE project and produced an HTR 2024 paper (reference below). A full report on GEMINI 4.0 waste options will be available by end of February.



Separated coating shells



Fuel kernels separated from coatings

Source: D. Hittner, et al. "Fuel and graphite waste management strategies for the HTGR reactor GEMINI+ ", Proc. Of HTR2024.

** Technical Working Group on Nuclear Power in Low-Carbon Energy Systems (https://www.iaea.org/topics/small-modular-reactors/technical-working-group-on-nuclear-power-in-low-carbon-energy-systems-twg-nplces)*

*** Network for Experiment and Code Validation Sharing (https://nucleus.iaea.org/sites/connect/NEXPublic/SitePages/Home.aspx)*

https://www.gen-4.org/gif-activities/working-groups/gif-proliferation-resistance-and-physical-protection-working-group

& https://www.gen-4.org/gif-activities/working-groups/non-electric-and-cogeneration-applications-nuclear-energy-working

 # https://www.gen-4.org/resources/reports/safety-design-criteria-generation-iv-very-high-temperature-reactor-system-2023

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A Few More Resources

- Gen-IV VHTR: https://www.gen-4.org/generation-iv-criteria-and-technologies/very-high-temperature-reactor-vhtr
- IAEA: https://www.iaea.org/topics/gas-cooled-reactors
- OECD/NEA: https://www.oecd-nea.org/jcms/pl_20497/high-temperature-gas-cooled-reactors
- US HTGR program: https://art.inl.gov/SitePages/ART%20Program.aspx

- MiNEA (2022), High-temperature Gas-cooled Reactors and Industrial Heat Applications, OECD Publishing, Paris, https://www.oecd-nea.org/upload/docs/application/pdf/2022-06/7629_htgr.pdf
- Fütterer, M., et al. 2020. The High Temperature Gas-Cooled Reactor. Encyclopedia of Nuclear Energy https://doi.org/10.1016/B978-0-12-409548-9.12205-5.
- Gougar, H. et al., “The US Department of Energy’s high temperature reactor research and development program – Progress as of 2019”, https://doi.org/10.1016/j.nucengdes.2019.110397
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- Windes, W. et al, “Discussion of Nuclear-Grade Graphite Oxidation in Modular High Temperature Gas-Cooled Reactors”, 2017.
- Kugeler, K. et al. 2017. The High Temperature Gas-cooled Reactor - Safety considerations of the (V)HTR-Modul. EUR 28712 EN, Joint Research Center.
- IAEA, Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to the PBMR-400, PBMM, GT-MHR, HTR-10 and the ASTRA Critical Facility, IAEA-TECDOC-1694, IAEA, Vienna (2013).
- IAEA, Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to Initial Testing of the HTTR and HTR-10, IAEA-TECDOC-1382, IAEA, Vienna (2003).
- IAEA 2001. Current Status and Future Development of Modular High Temperature Gas Cooled Reactor Technology. IAEA-TECDOC-1198.

Overview and Update of the GIF VHTR Activities

Questions and Discussion

Upcoming Webinars

Date	Title	Presenter
27 March 2025	Nuclear power: electricity and beyond the grid. Data-driven insights from IAEA's Power Reactor Information System (PRIS).	Marta Gospodarczyk, IAEA
15 April 2025	Advanced manufacturing supporting Gen IV reactor systems.	Isabella Van Rooyen, PNNL, USA
14 May 2025	Advanced Nuclear Technologies for Maritime Application.	Hussam Khartabil, IAEA Nadezhda Salnikova, OKBM, Russia Kirk Sorensen, Flibe Energy, USA Andreas Vigand Schofield, Seaborg Technologies

2025 Pitch your Gen IV Research Competition

- Are you a PhD student, post-doctoral fellow, or junior engineer with a PhD working on Generation IV nuclear energy systems? *(Completion of the PhD must be after Jan 1, 2023)*

- The GIF Education and Training Working Group (ETWG) invites you to participate in the 2025 edition of the "Pitch Your Generation IV Research" competition (PYG4RC).

- This competition provides a platform for you to showcase your research and gain recognition within the nuclear energy community.

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https://www.gen-4.org/resources/events/pitch-your-generation-iv-research-competition-2025