V4G4/GFR - NC2I/HTR meeting

26 May 2017, Budapest, Hungary

HTR activities around the world

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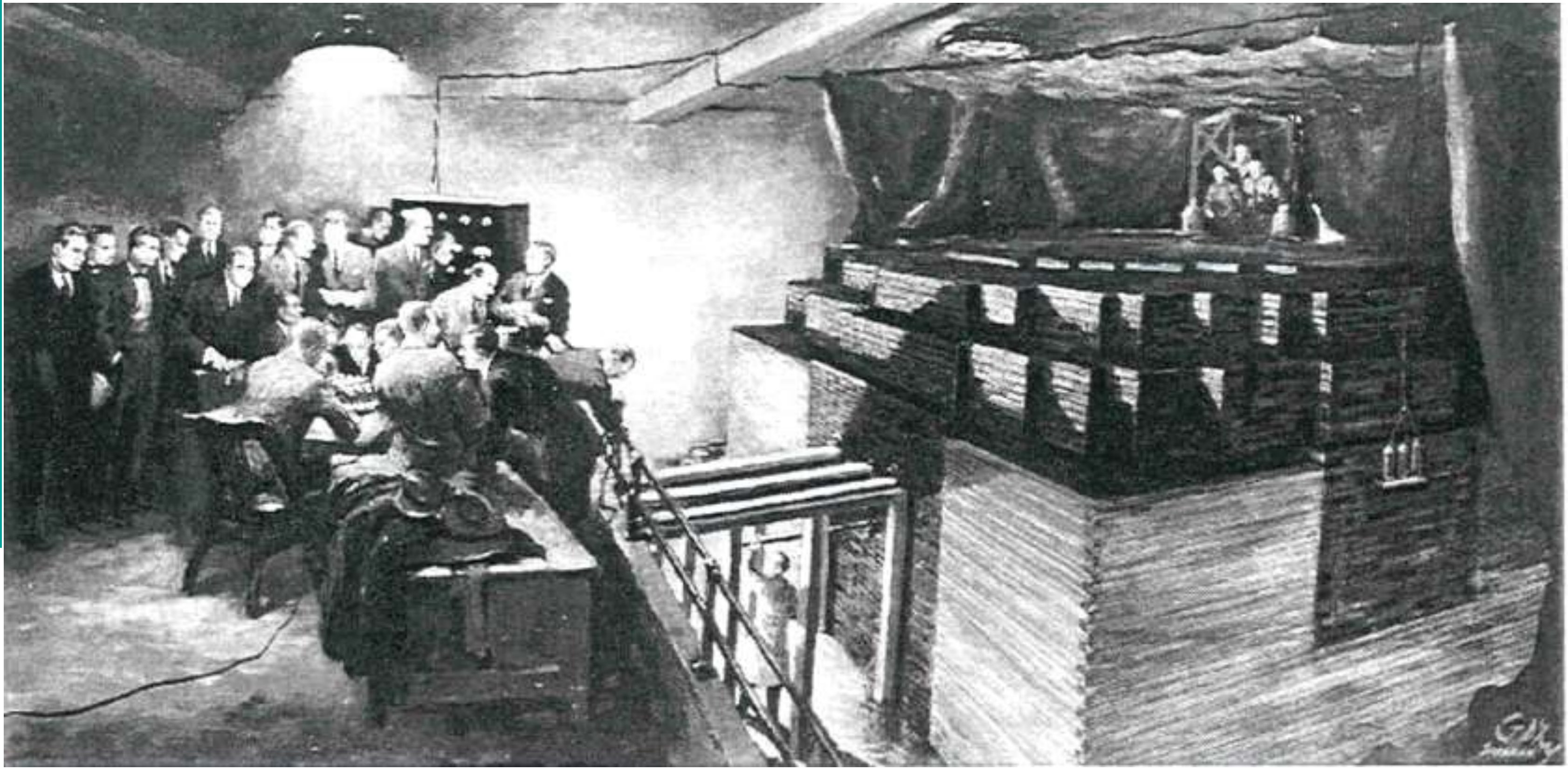
NC2I is one of SNETP's strategic technological pillars, mandated to coordinate the demonstration of high temperature nuclear cogeneration.

What is a HTR?

Nuclear Cogeneration Industrial Initiative

Evolution of graphite-moderated GCR



Chicago Pile 1 - 2 December 1942
Birth of the Atomic Age, Painting by Gary Sheahan

Historical Milestones

NC2I Nuclear Cogeneration Industrial Initiative

1938	Discovery of Nuclear Fission by Hahn / Strassmann
1942	First self-sustained chain reaction (E. Fermi)
1943	3.5 MW graphite-moderated Pu production reactor (ORNL)
1947	Graphite-moderated GCR at Brookhaven
1947-90	Graphite Low-Energy Exp. Pile (UK): first reactor in Europe
1948	36 MW_{th} British Experimental Pile Operation (BEPO)
1950	160 MW_{th} Windscale Pu Production Reactors
1951-53	UK studies on CO_2-cooled MAGNOX Reactors
1956-59	Commissioning of 4 Calder-Hall Reactors (240 MW_{el} total)
1956-68	Air-cooled 1.7 MW_{el} G-1 at Marcoule, France
1957	First Commercial GCR in France: 70 MW_{el} Chinon A1
1963	30 MW_{el} Advanced GCR (AGR) in Windscale (400°C → 650°C)
1976	First Commercial AGR at Hinkley Point B (625 MW_{el} / 41.5 %)

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NC2I
Nuclear Cogeneration Industrial Initiative

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1947-9 … pe

1948

1950

1951-5

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1963 30 MW_{el} Advanced GCR (AGR) in Windscale (400°C → 650°C)

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Mostly Air or CO_2 cooled reactors
→ Temperature limitations due to:
- oxidation/carburization
- CO_2 dissociation

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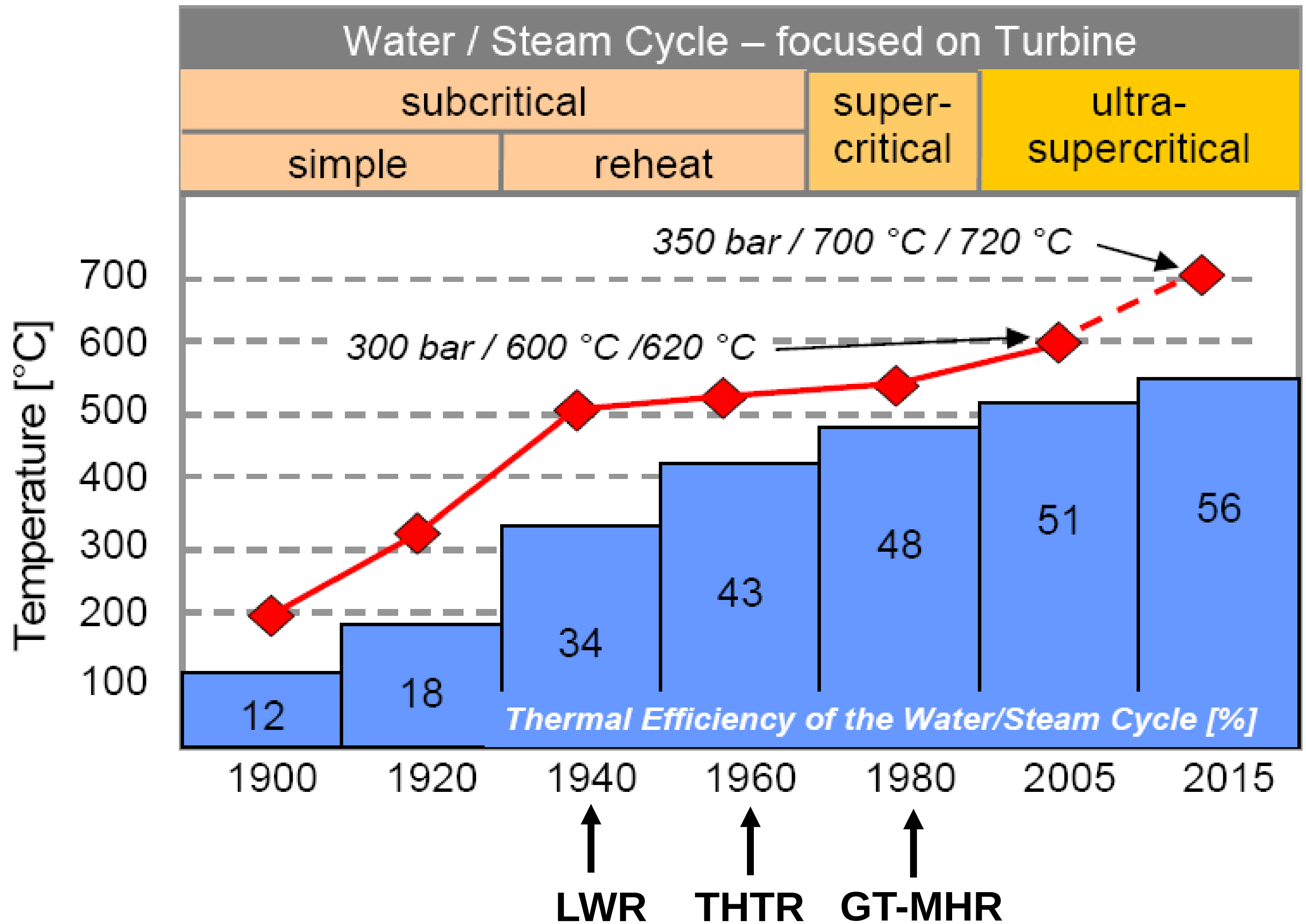
The quest for higher efficiency

Supercritical Steam:

>217.5 bar; >374.2°C



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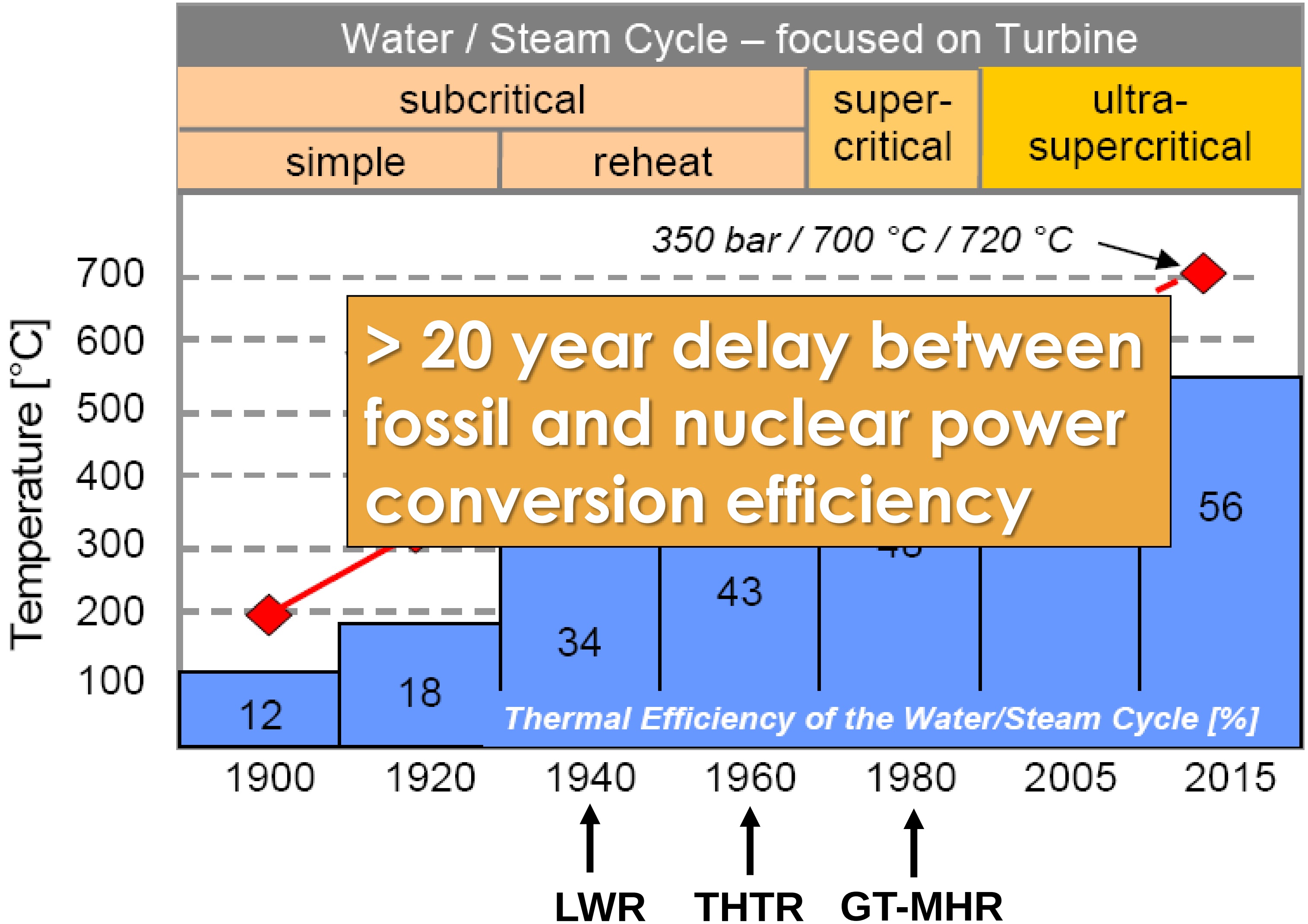

> 20 year delay between fossil and nuclear power conversion efficiency

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Historical Milestones He-cooled HTRs

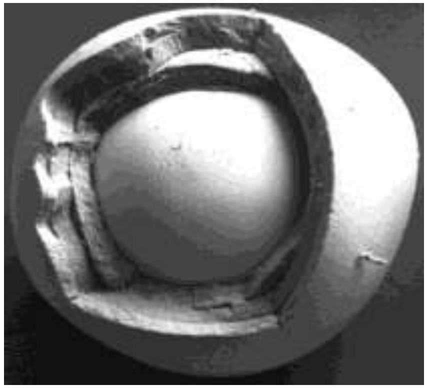
Nuclear Cogeneration Industrial Initiative

Prismatic block core	Pebble bed core

1966 – 1975	DRAGON OECD project: 20 MWth 350-750°C
1966 - 1974	Peach Bottom first electricity production: 40 MWe, 37% efficiency
1967 – 1988	AVR 15 MWe up to 950°C
1985 - 1989	THTR 300 MWe
1979 - 1989	Fort Saint Vrain 330 MWe
2002 - 2010	GT-MHR (design only)
1999 →	HTTR: 30 MWth 850-950°C
2000 →	HTR-10: 10 MWth
→ 2010	PBMR: 165 MWe (cancelled)
2018 →	HTR-PM (2 x 105 MWe) 750°C

Technical characteristics

Nuclear Cogeneration Industrial Initiative



- Fully ceramic core
- High-purity graphite as moderator/reflector → high thermal inertia
- Low power density → slow transients
- High fuel burn-up capability
- Chemically and neutronically inert helium gas as primary coolant
- High operating temperatures for high efficiency, CHP capability
- High conversion ratios (good neutron economy, possible use of thorium)
- Can be built with passive safety features
- Self-stabilization of transients (negative temperature coefficient)
- Low source terms (fission product retention in fuel and structures)

High Performance – Benign Safety

Technical characteristics

Coated Particle Fuel: The Key to HTR Safety

Initially:
UO_2 or UC in ceramic clad: poor fission product retention
Invention of Coated Particle in 1957-61
by UKAEA and Battelle, no patent granted
- Kernels made by precipitation from uranyl nitrate in ammonia
- Coatings via pyrolysis of hydrocarbons in fluidized-bed

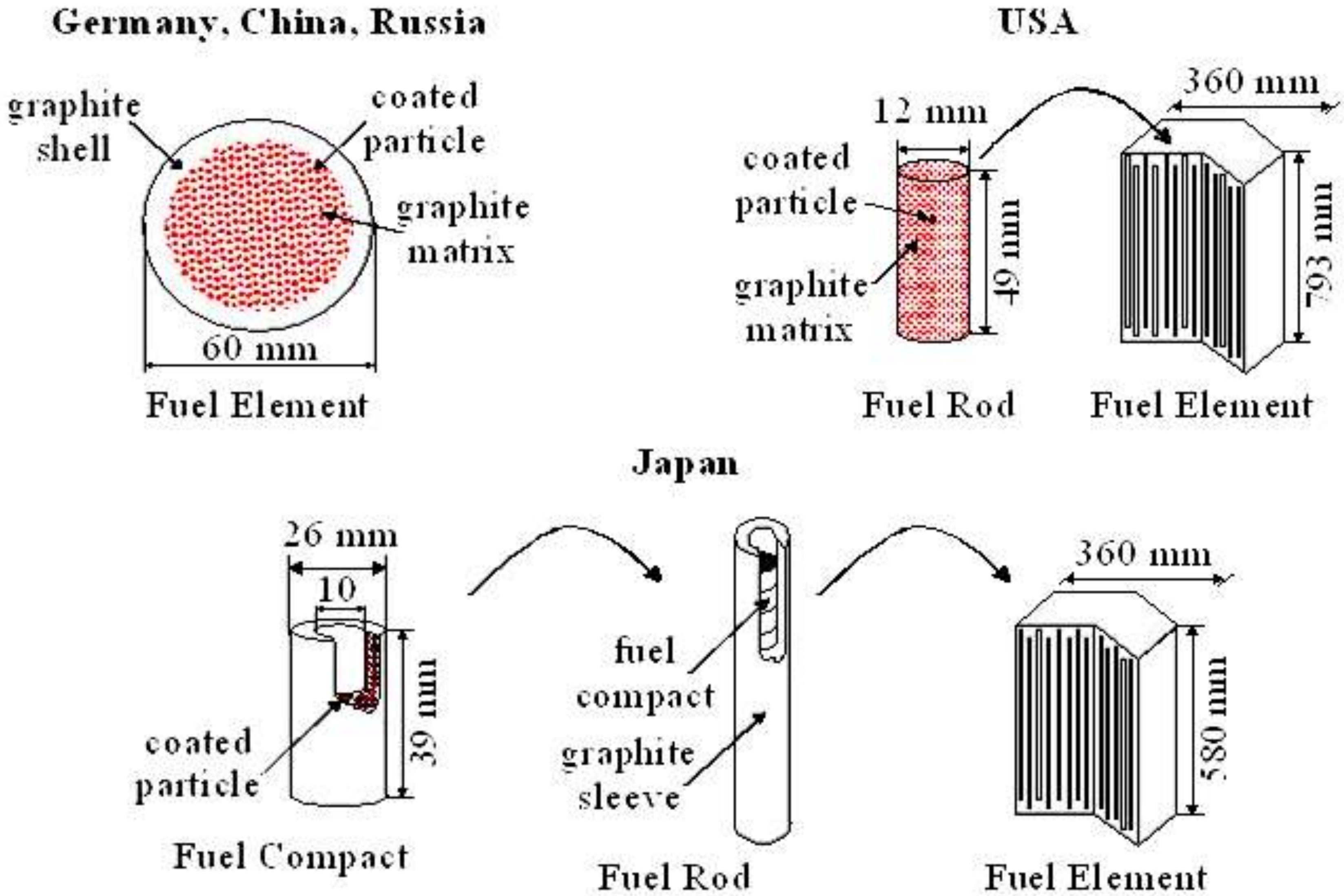
Next Step:
Early BISO particles comprise buffer & 2 PyC layers

Now:
TRISO particles have additional SiC diffusion barrier
→ fission product retention up to 1600°C or higher
(US): UCO kernel increases acceptable burnup and T_{max}

TRISO particles used in all modern HTR designs
Several manufacturers are active.

Technical characteristics

Pebble and Block Fuel



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Prismatic Block Fuel

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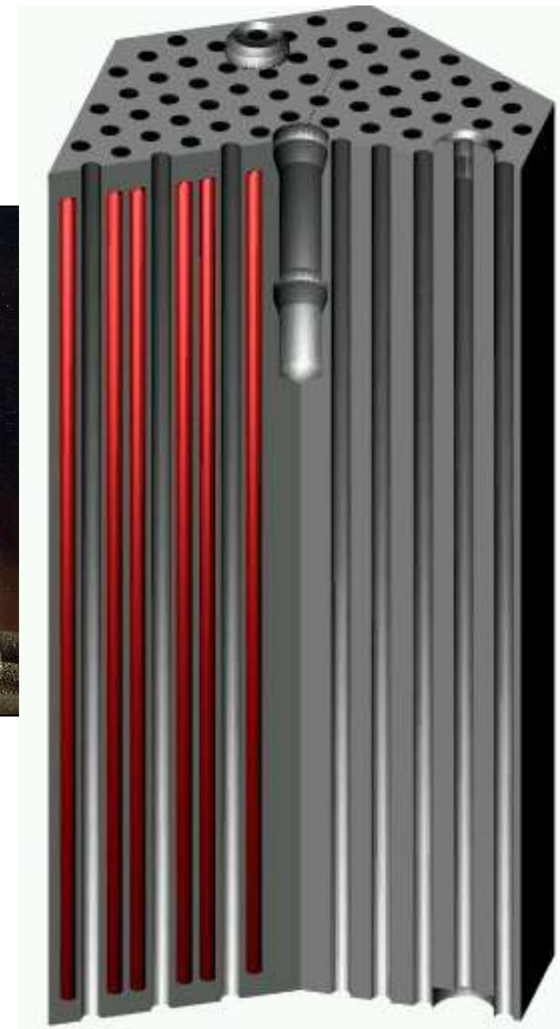
Particles → Compacts → Graphite Blocks → Core



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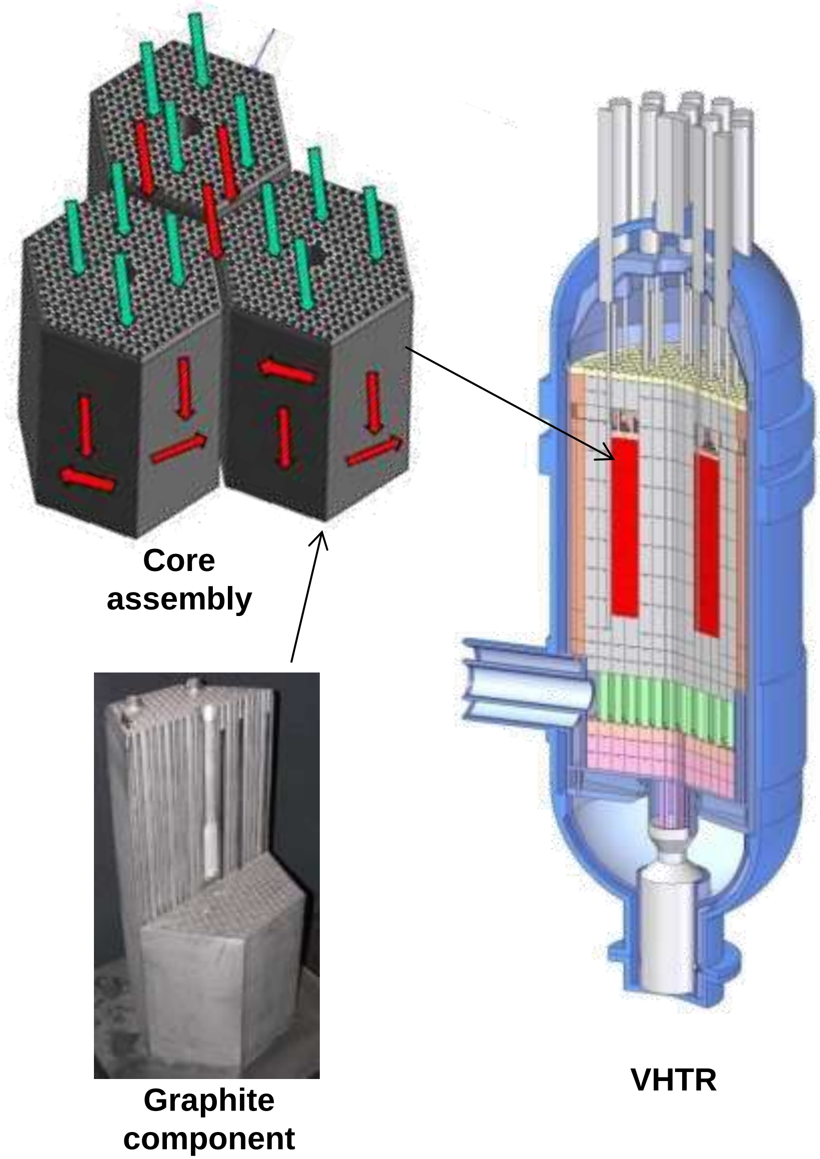
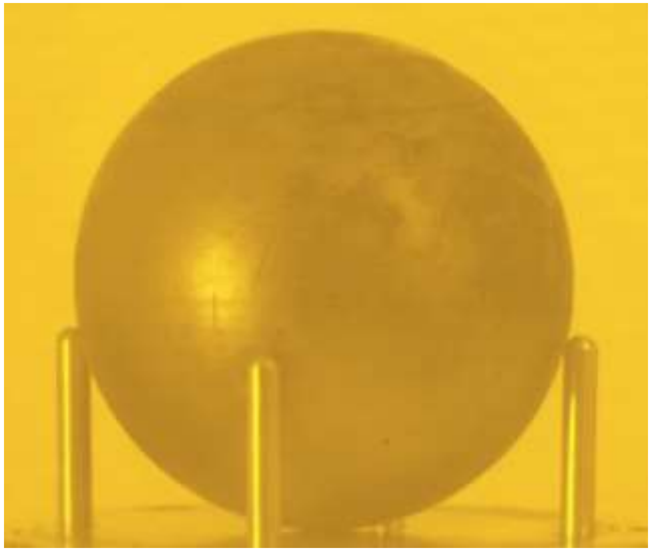
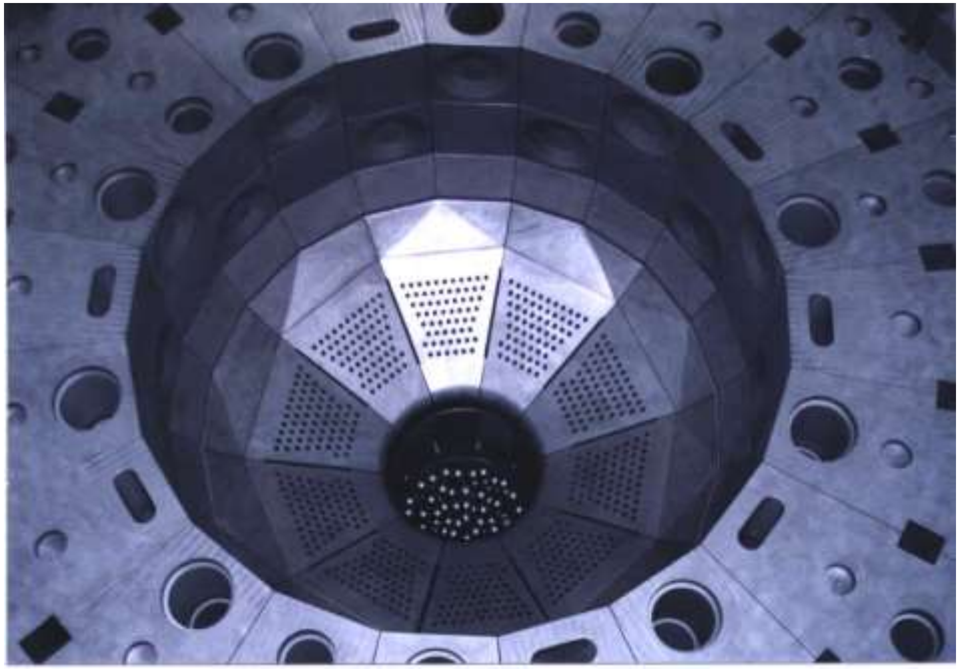
Prismatic Block Fuel



Pebble Fuel

Particles → Spheres → Pebble Bed → Core





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Possible Plant Layout

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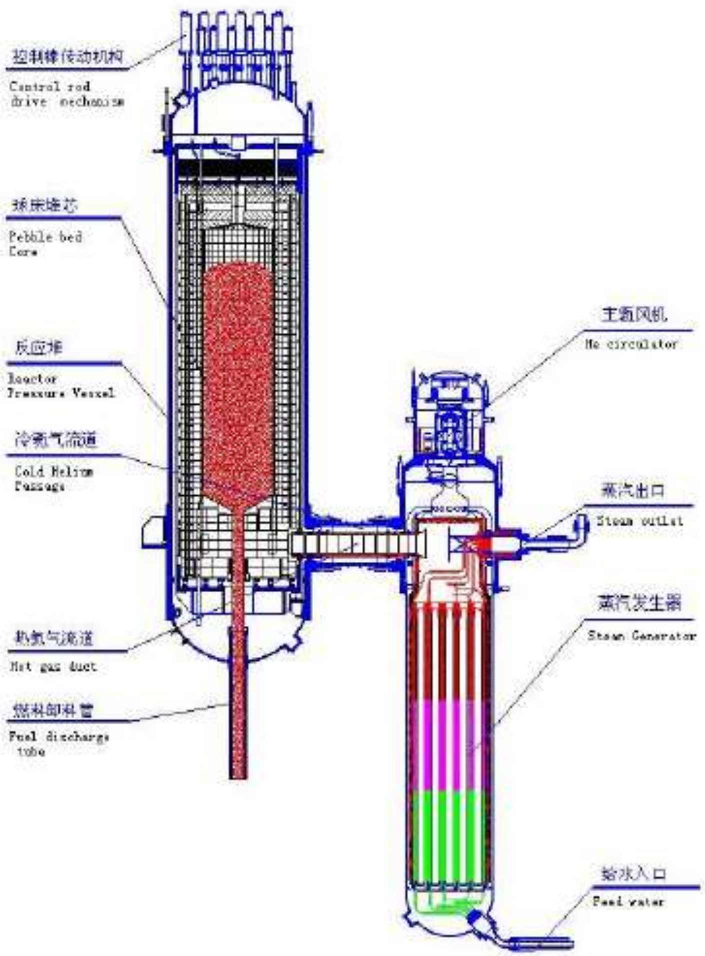
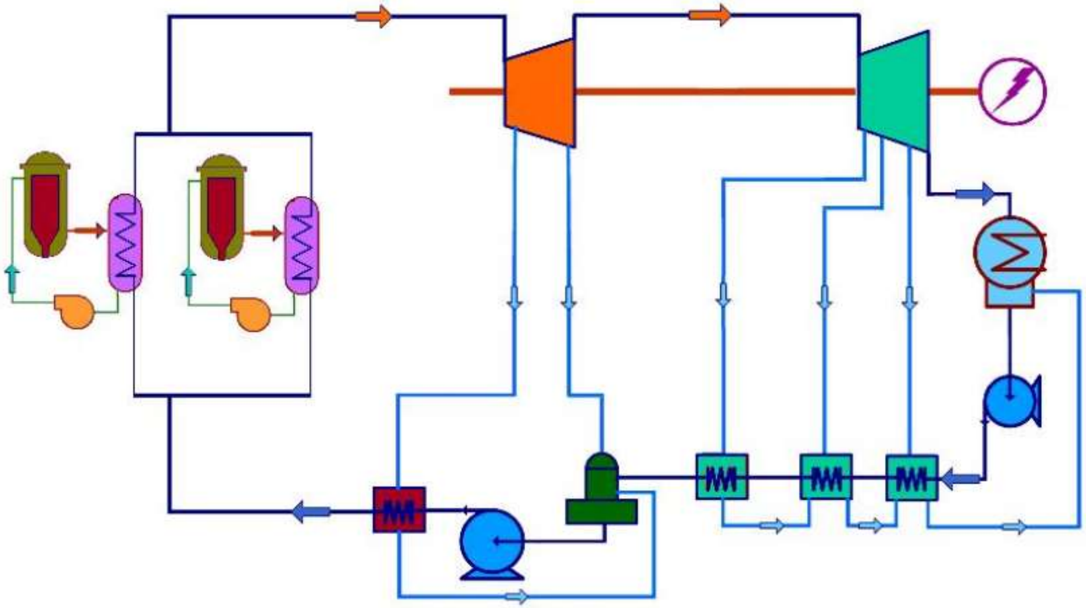
HTR-PM (European Technology under construction in China)
Full-scale pebble bed demonstration project



- Similar design as German HTR Modul (pebble bed)
- Max power density 6.6 MW/m^3
- He primary circuit
  7 MPa 250-750°C
- 2 x 250 MWth → 210 MWe

HTR-PM



Twin modules coupled to a common steam turbine 570°C

Under construction in Shidao China

Criticality expected end-2018

HTR: Ideal for CHP

Nuclear Cogeneration Industrial Initiative

In EU, the big near-term market for process steam < 600°C requires typically:

- **Reactor outlet temperature 750°C**
- **Reactor power 50-200 MWth**
- **Best availability**
- **Best safety**
- **Previous experience (de-risk)**
- **Competitive with fossil firing**

➔ HTR were soon identified as ideally suited.

➔ Competitive at Natural Gas price > 8 US$/MBtu

➔ Large development and demonstration programs in UK, US, Germany, Japan, China, South Korea, some with test reactors and prototypes;

European activities

NC2I – Nuclear Cogeneration Industrial Initiative

HTR-TN – High Temperature Reactor Technology Network

- 2000: 24 companies across EU create HTR-TN for technology recovery/revival;
- Precursor to NC2I as part of SNETP;
- Proposal and coordination of ~70 M€ technology projects, coordination and support actions incl. EUROPAIRS and NC2I-R (cf. presentation by T. Jackowski)
- Cooperation with US, Japan, China, South Africa, then with Gen IV International Forum, IAEA and OECD/NEA on selected topics such as fuel, materials, graphite, reactor safety, codes for design and licensing, process heat applications, economic analysis etc., initially with focus on R&D
- 2014: NC2I (EU) and NGNP (US) start the GEMINI-PRIME initiative on demonstration

European Projects

2001-2005: MICANET: Competitiveness and sustainability of nuclear energy in the European Union (Gen IV reactors, WP4 "non-electric applications") **+ 8 Technology Development Projects**

2005-2015: RAPHAEL, ARCHER, PUMA, CARBOWASTE: various HTR Technology projects

2009-2011: EUROPAIRS: Viability of nuclear cogeneration for industrial processes, initiate a partnership of nuclear organisations and end-user industries,

2013-2015: NC2I-R: Structure EU R&D for a nuclear cogeneration demonstrator fully meeting the market needs, in support of NC2I.

+ several national projects, e.g. in D, PL, CZ

H_2 production: ADEL, SOPHIA

2017-2019: GEMINI+: *cf. presentation by D. Hittner*

Poland and UK

Specific talk on HTR program in Poland

UK plans to become a SMR vendor on top of 18 GWe LWR program

→ UK SMR Techno-Economic Assesment (10/2015)

- NGNP submitted 350 MW_{th} prismatic HTR on behalf of NGNP+NC2I
- Urenco: U-Battery 10 MW_{th} prismatic HTR
- X-Energy: Xe-100 100 MW_{th} pebble bed HTR

UK SMR Competition for 250 M£ (3/2016)

NC2I submitted 350 MW_{th} prismatic HTR design on behalf of NGNP + NC2I

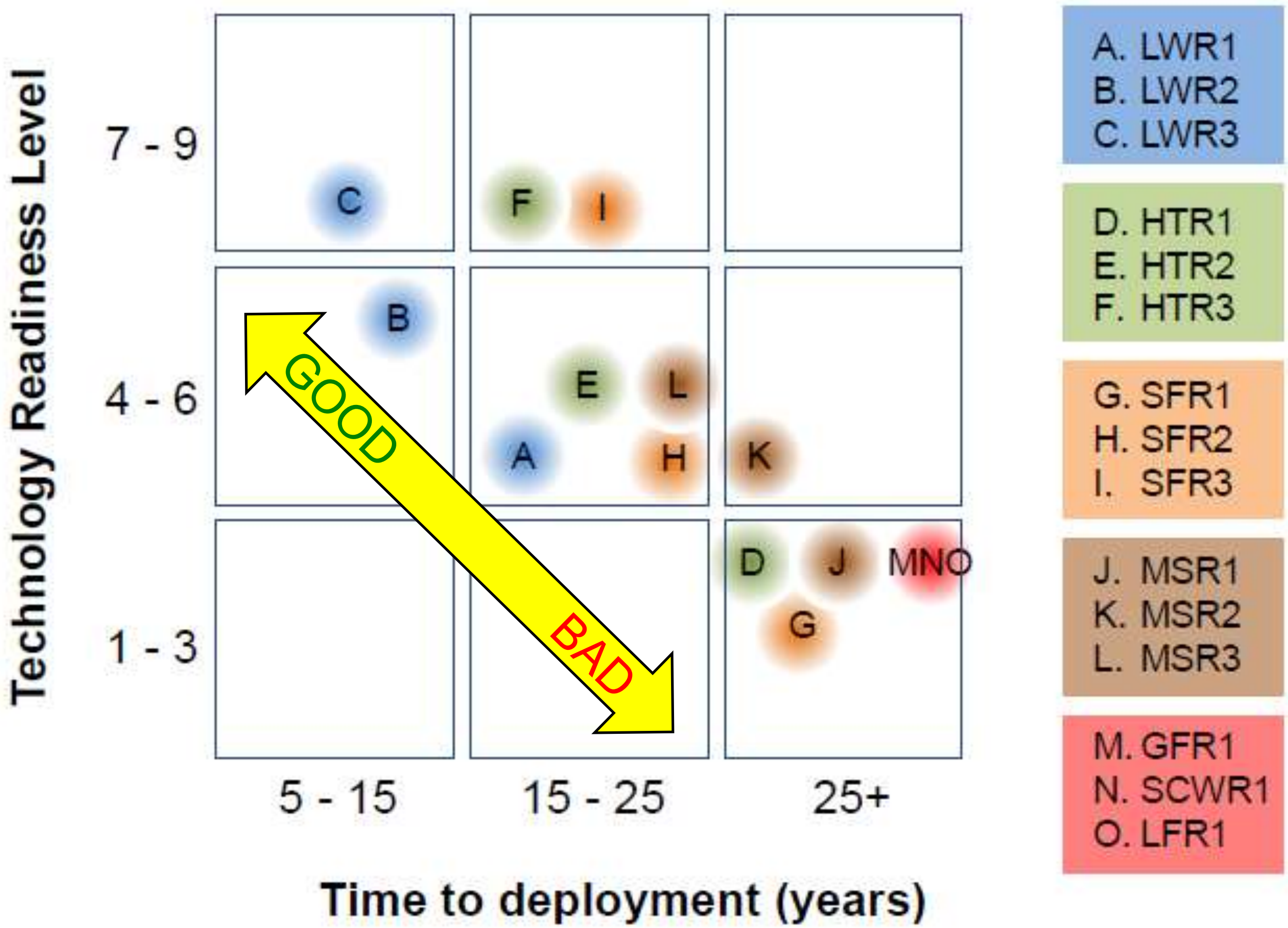
+ several other HTR proposals demonstrated high interest in the technology

Emerging Technologies and Effective Public Engagement in SMR Deployment

Prof. Andrew H. Sherry FREng
Chief Scientist, NNL

Small Modular Reactor Summit UK
Waldorf Hilton, London, 18 – 19 October 2016

SMRs… many TRLs



Activities Overseas

China: HTR-PM

- Start expected in 2018, electricity generation, later CHP, plans first 600 MWe inland NPP

Japan: JAEA

- Restart HTTR after post-Fukushima update, concept of a particularly safe design, clean fuel burner, commercial design, cooperation with Kazakhstan

USA: NGNP, X-energy

- process heat, CHP and isolated applications

Europe:

- Large legacy experience, technology projects; interest in UK and PL, cooperation with US, JA, KR (GEMINI/PRIME)

South Korea: NHDD

- hydrogen production for steel industry

Canada: Starcore Nuclear

- process heat and CHP

South Africa: PBMR (terminated in 2010)

- electricity generation (to be revived as AHTR by ESKOM)

Indonesia: BATAN

- Small 10 MWth test reactor, phase 2 depending on financing (Russia)

Saudi Arabia

CHP, water desalination, district cooling, recent agreement with China

Summary

- HTR has a high Technology Readiness Level
- A range of design options is available for reactor, power conversion and heat transfer systems depending on end user application
- Room for international collaboration and competition
- HTR can be built with very attractive passive safety features which make them compatible with end-user sites (e.g. chemical plants)
- Most of the supply chain for materials and components is alive or can be revived quickly
- Visible investor interest in a number of countries
- Large market potential for a multitude of applications

Summary

Nuclear Cogeneration Industrial Initiative

- High impact potential for EU policy goals (decarbonization, energy security, re-industrialization, jobs…)
- Large-scale long-term strategic infrastructure investment to provide energy alternatives to EU industry
- Natural gas prices in EU and Asia are at or above break-even level
- Remuneration of external benefits would be an advantage (energy security, climate change, re-industrialization…)
- Various technology options available to deliver CHP with grid services and to team up with variable renewables

NC2I supports the demonstration of nuclear cogeneration technology in Europe