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HTGR Safety Design Principles

Frederik Reitsma
Nuclear Power Technology Development Section
Department of Nuclear Energy

Joint IAEA-ICTP Workshop on the Physics and Technology of Innovative High Temperature Nuclear Energy Systems

Presentation Aim

Introduce you to the safety design principles of modular HTGRs

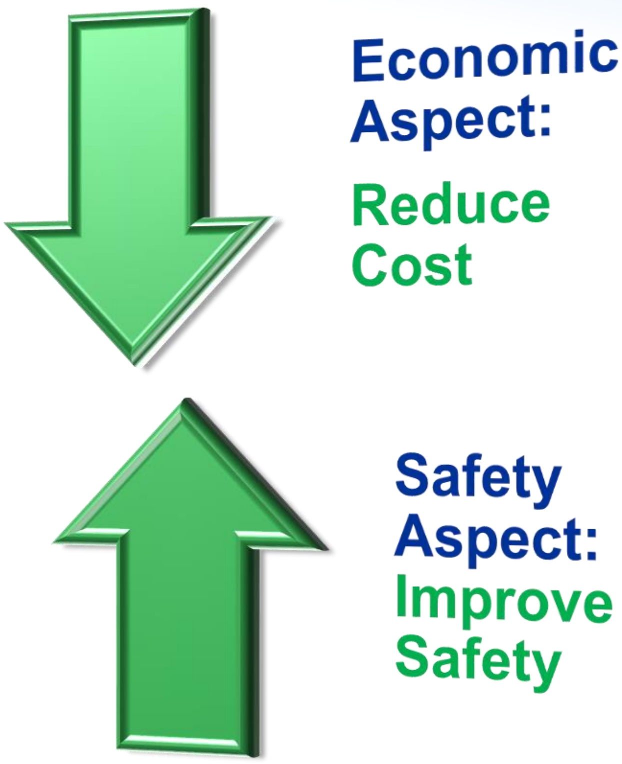
Presentation Objectives

By the end of this session, participants should be able to:

- Define what a modular HTGR is
- Be able to explain the main principles that must be adhered to by designers to ensure the safety claims of mHTGRs are not violated
- Explain the inherent safety characteristics and passive means that can be employed
- Understand some of the failure mechanism and severe accidents that have the potential to lead to some delayed releases and how these can be mitigated

Advanced Reactor Design Goals

- **Advanced** reactor designs include both evolutionary and innovative reactor technologies.
- **Evolutionary** designs (Generation III/III+) improve on existing designs through small or moderate modifications with a strong emphasis on maintaining proven design features to minimize technological risk.
- ***Innovative designs (Generation IV) incorporate radical changes in the use of materials and/or fuels, operating environment and conditions, and system configurations.***



SMR Development Objectives

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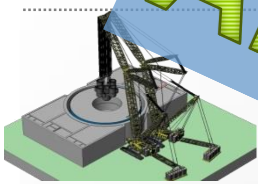
All mHTGRs are SMRs

Economic
- Lower upfront capital cost
- Economy of serial production

Better Affordability



Modernization
- Multi-module
- Modular construction

Shorter Construction Time

Flexible Application
- Remote regions
- Small grids

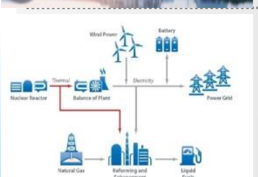
Wider Range of Users

Smaller Footprint
- Reduced emergency planning zone

Site Flexibility

Replacement for Aging Fossil-fired Plants
- Reduced greenhouse gas

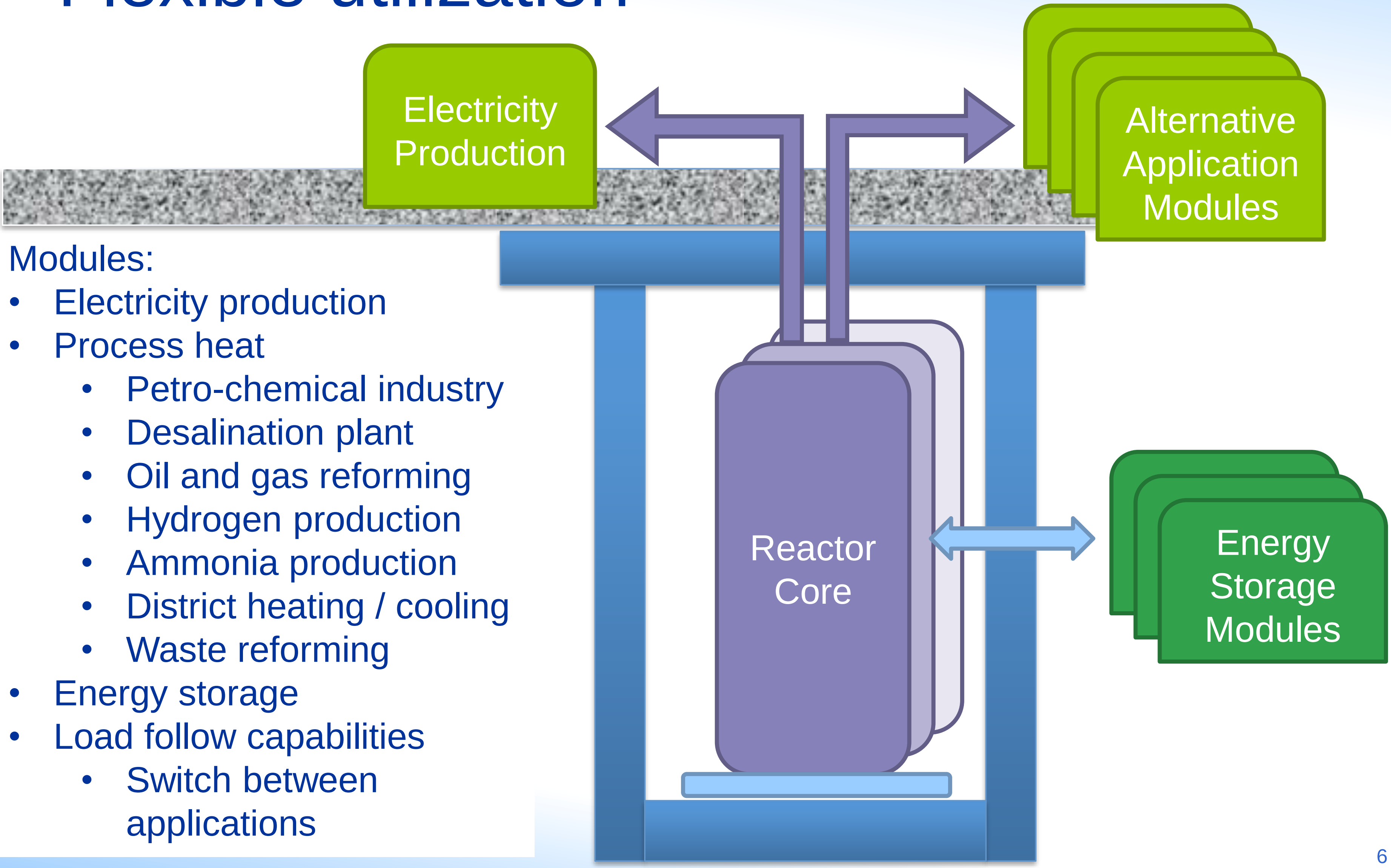
Reduced CO_2 Production



Potential Hybrid Energy System
- Optimized use of renewables

Integration with Renewables

What's new that SMRs can offer? Flexible utilization



Modules:

- Electricity production
- Process heat
  - Petro-chemical industry
  - Desalination plant
  - Oil and gas reforming
  - Hydrogen production
  - Ammonia production
  - District heating / cooling
  - Waste reforming
- Energy storage
- Load follow capabilities
  - Switch between applications

Non-electric Applications of SMRs at Different Coolant Output Temperature

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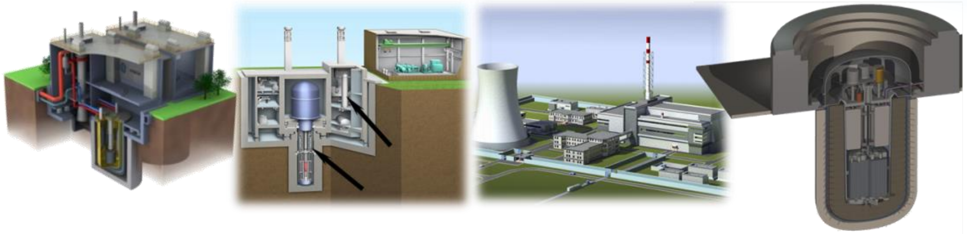
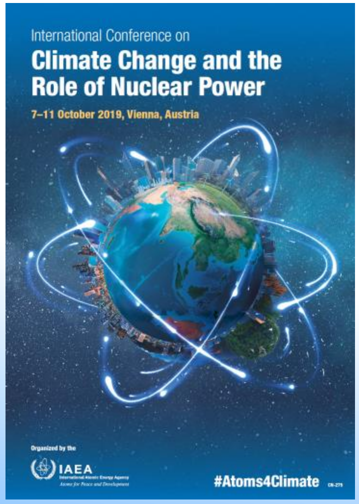
Reactor type
Very high temperature reactors
Gas-cooled fast reactors
Molten Salt reactors
Supercritical water-cooled reactors
Sodium-cooled fast reactors
Liquid metal cooled reactors
Water cooled reactors



100 200 300 400 500 600 700 800 900 1000 1100 1200

(ºC)

- District heating
- Seawater desalination
- Pulp & paper manufacture
- Methanol production
- Heavy oil desulfurization
- Petroleum refining
- Methane reforming hydrogen production
- Thermochemical hydrogen production
- Coal gasification
- Blast furnace steel making



High Temperature Gas Cooled SMRs (Examples)

HTR-PM

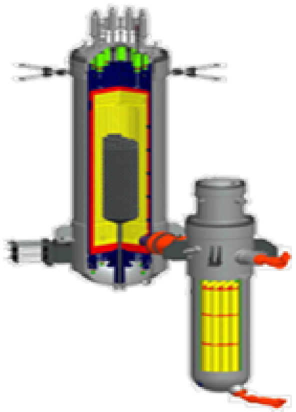


Image Courtesy of INET, China

Modular Pebble Bed High Temperature Gas Cooled Reactor

Helium/Graphite cooled

- 210 MW(e) / 500 MW(th)
- Core Outlet Temp: 750°C
- Fuel Enrichment: 8.5% UO_2 TRISO coated particle
- No. of fuel spheres: 420,000 /module
- Modules per plant: 2
- Advanced stage of construction-

Expected Commercial Operation in 2019

GTHTR300

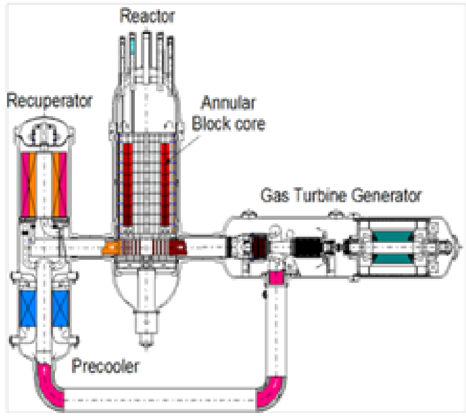


Image Courtesy of JAEA, Japan

Prismatic High Temperature Gas Cooled Reactor

Helium/Graphite cooled

- 100-300 MW(e) / 600 MW(th)
- Core Outlet Temp: 850-950°C
- Fuel Enrichment: 14 % UO_2 TRISO ceramic coated particle
- Fuel temperature limit: 1600°C
- Modules per plant: 4
- Inherent safety features
- Multi-purpose application: power generation, hydrogen production, process heat, steelmaking, desalination and district heating

HTMR100

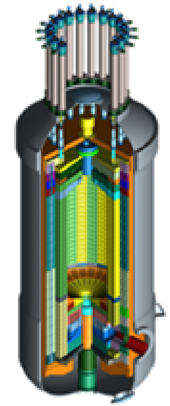


Image Courtesy of STL, South Africa

High temperature Gas Cooled Reactor

Helium cooled / graphite moderated

- 35 MW(e) / 100 MW(th) per module
- Core Outlet Temp: 750°C
- Fuel Enrichment: 15% Th/Pu, <10% U_{235} Th/LEU and Th/HEU
- Module per plant: (4-8) pack
- Number of Fuel units: ~150,000 pebbles
- Better load following capability and flexibility in multi-module configuration

EM^2

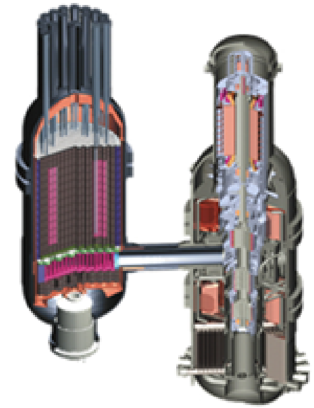


Image Courtesy of General Atomics, USA

High Temperature Gas Cooled Fast Reactor

Helium cooled

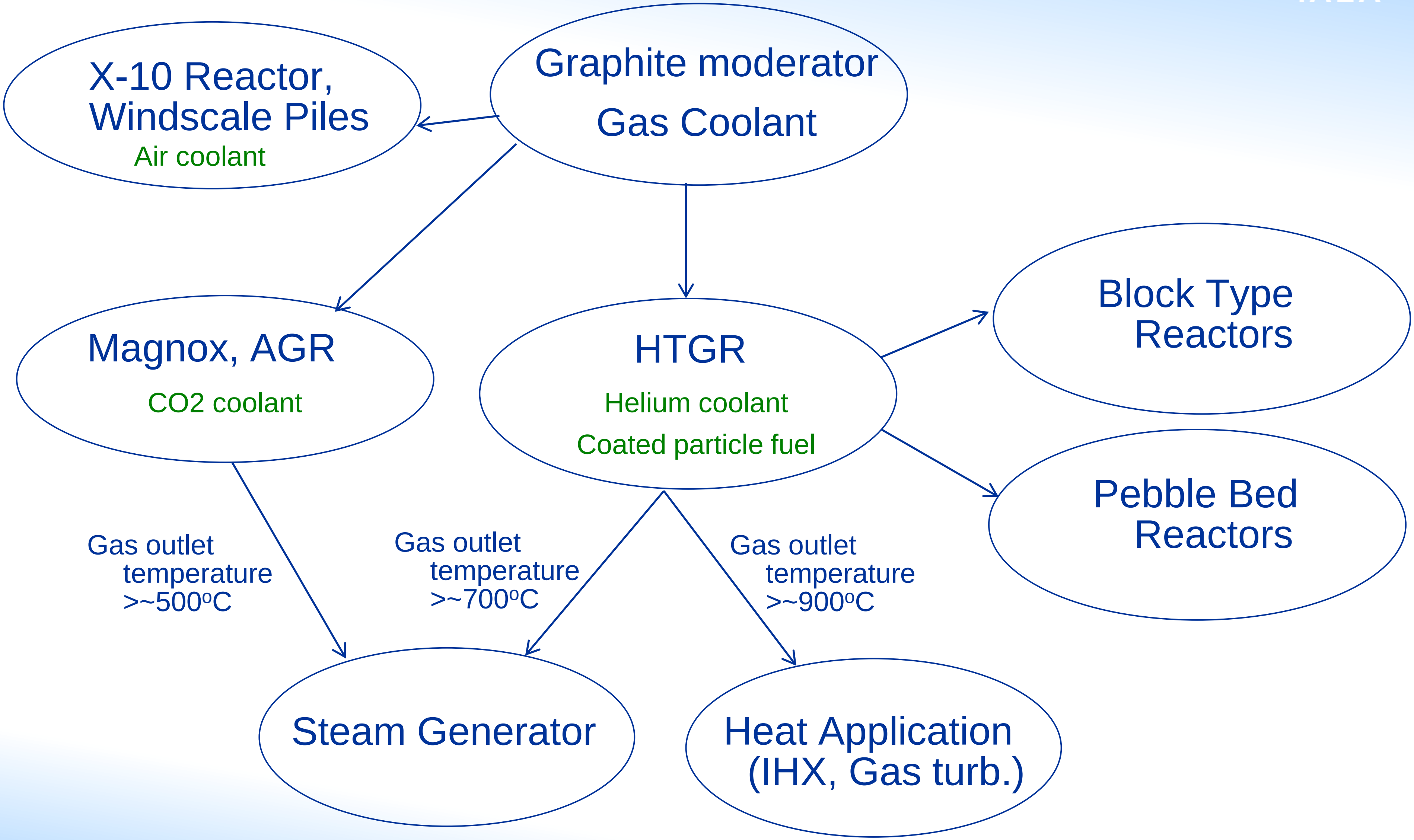
- 240 MW(e) and 500 MW(th)
- Refuelling cycle: 30 years
- Core Outlet Temp: 850°C
- Fuel enrichment: 1% U_{235} - 1% Pu, MA coated particle
- Efficiency: 48%
- Fully enclosed in an underground containment
- Utilization of spent fuel
- Simplified power conversion system and 30% reduction in material requirements than that of current NPPs

Contents

- What is HTGRs
- Why HTGRs
- Salient Safety Features of HTGRs
- A few key aspects

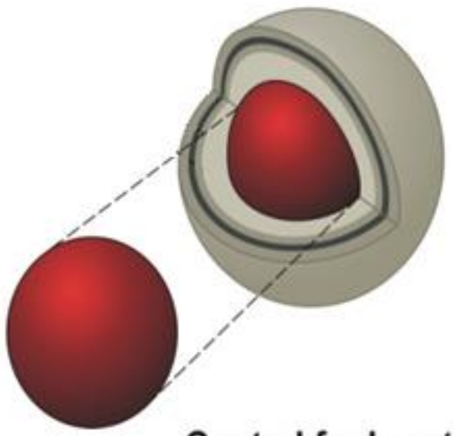
- HTGRs deployment for high temperature heat and cogeneration
- Concluding remarks

Graphite Moderated Gas Cooled Reactors



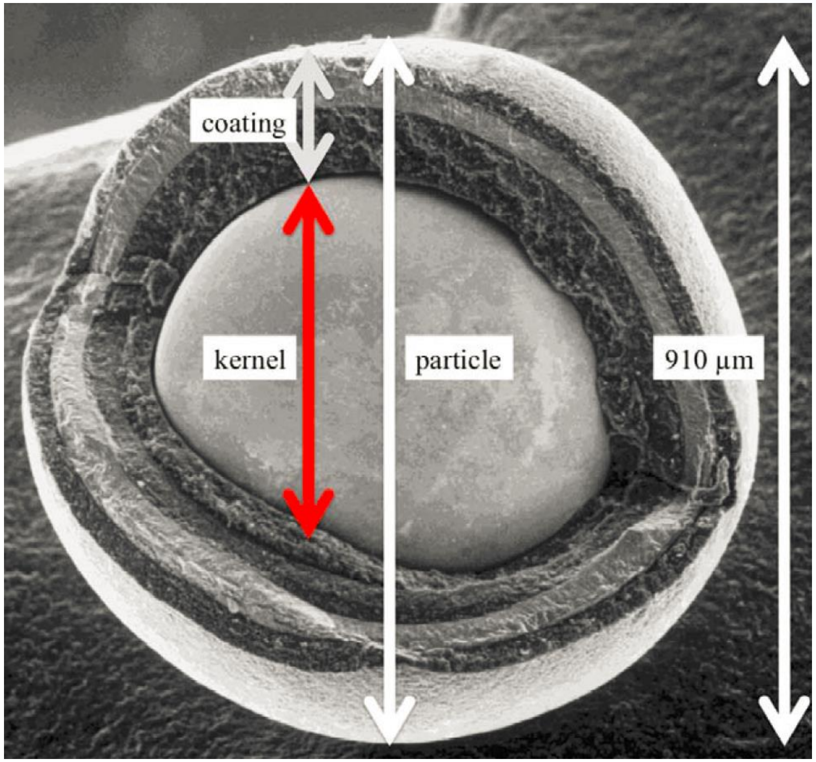
(V)HTGRs Characteristics

- High Temperature Gas Cooled Reactors is an advanced reactor system (part of GEN-IV) with the following main characteristics:
  - High output temperatures (750-1000ºC)
  - Use of coated particle fuel
  - Helium coolant
  - Graphite moderated
  - Small reactor units (~100 - 600 MWth)
  - To be deployed as multiple modules
  - Low power density (typically 3-6 W/cc compared to 60-100W/cc for LWRs)
  - Two basic design variations – Prismatic and pebble bed design

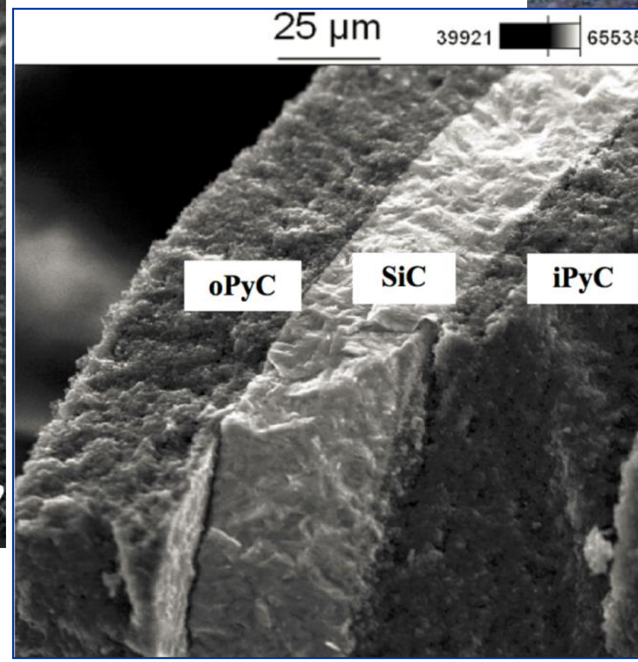


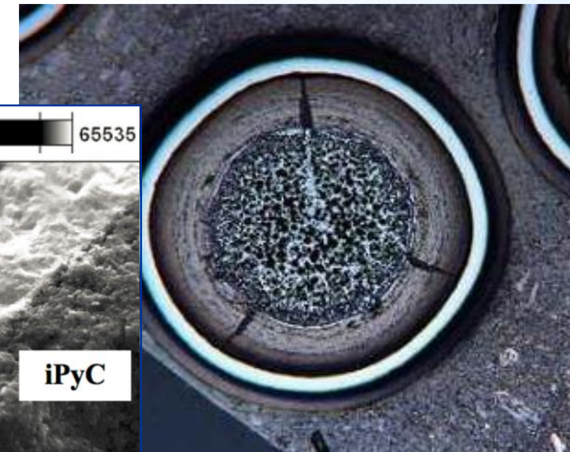
Coated fuel particle

TRISO Fuel: Coated Particle Design



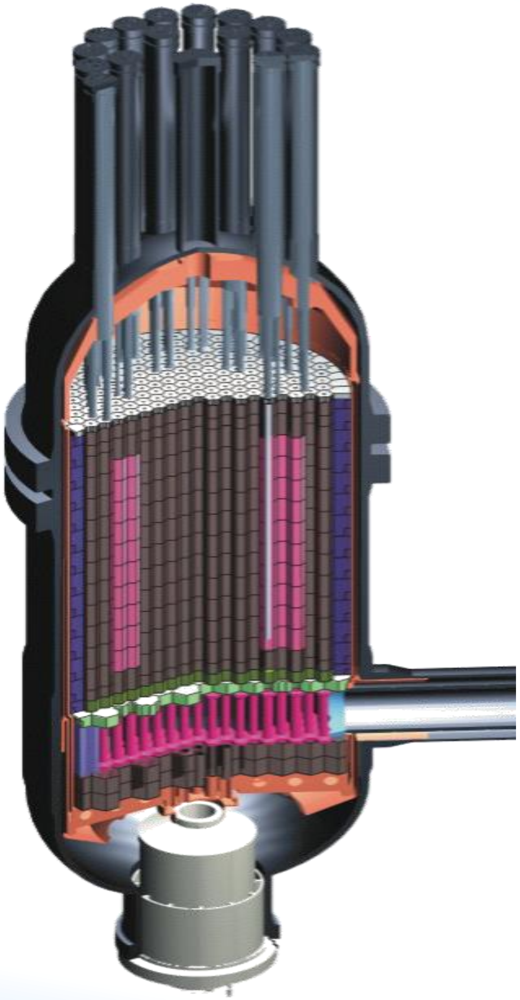
Triso fuel show no failures at extreme temperatures up to $>1800^{o}C$

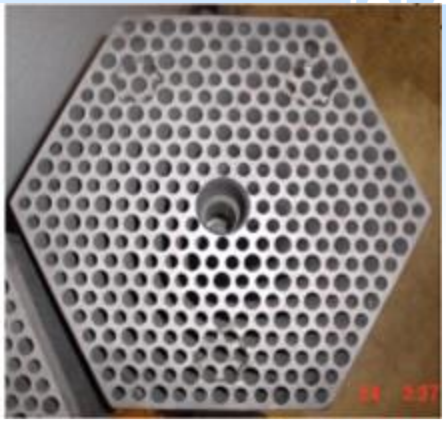


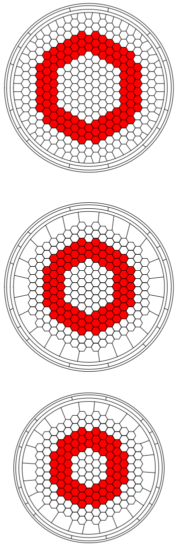


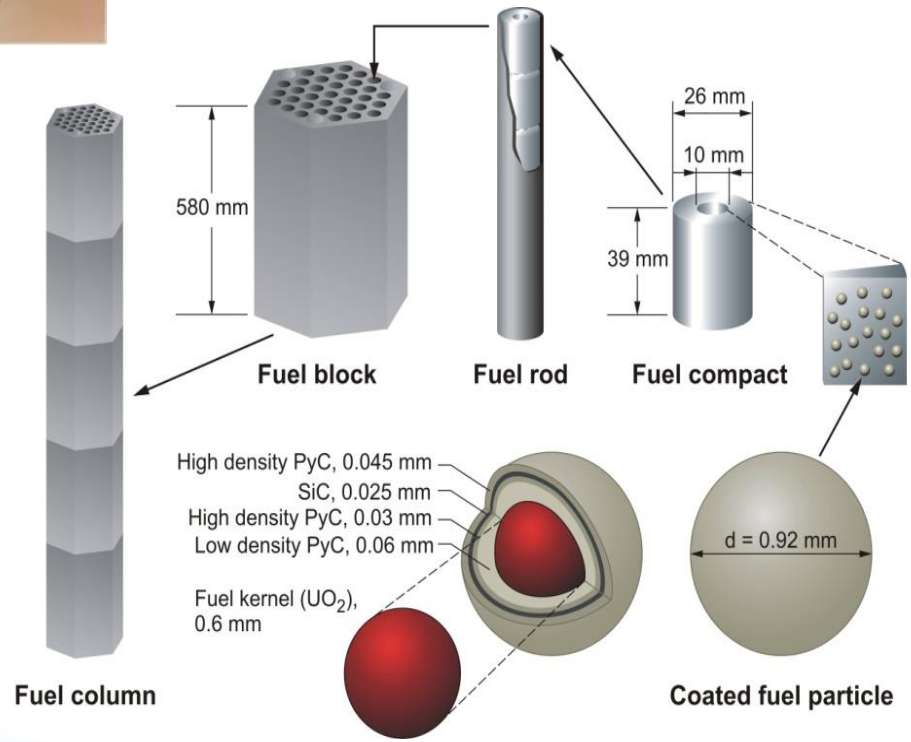
- The key safety feature:
  - Fission product retention capability of coated particle fuel
  - It contains the vast majority of all fission products even under the most severe postulated accidents

Prismatic (block-type) HTGRs

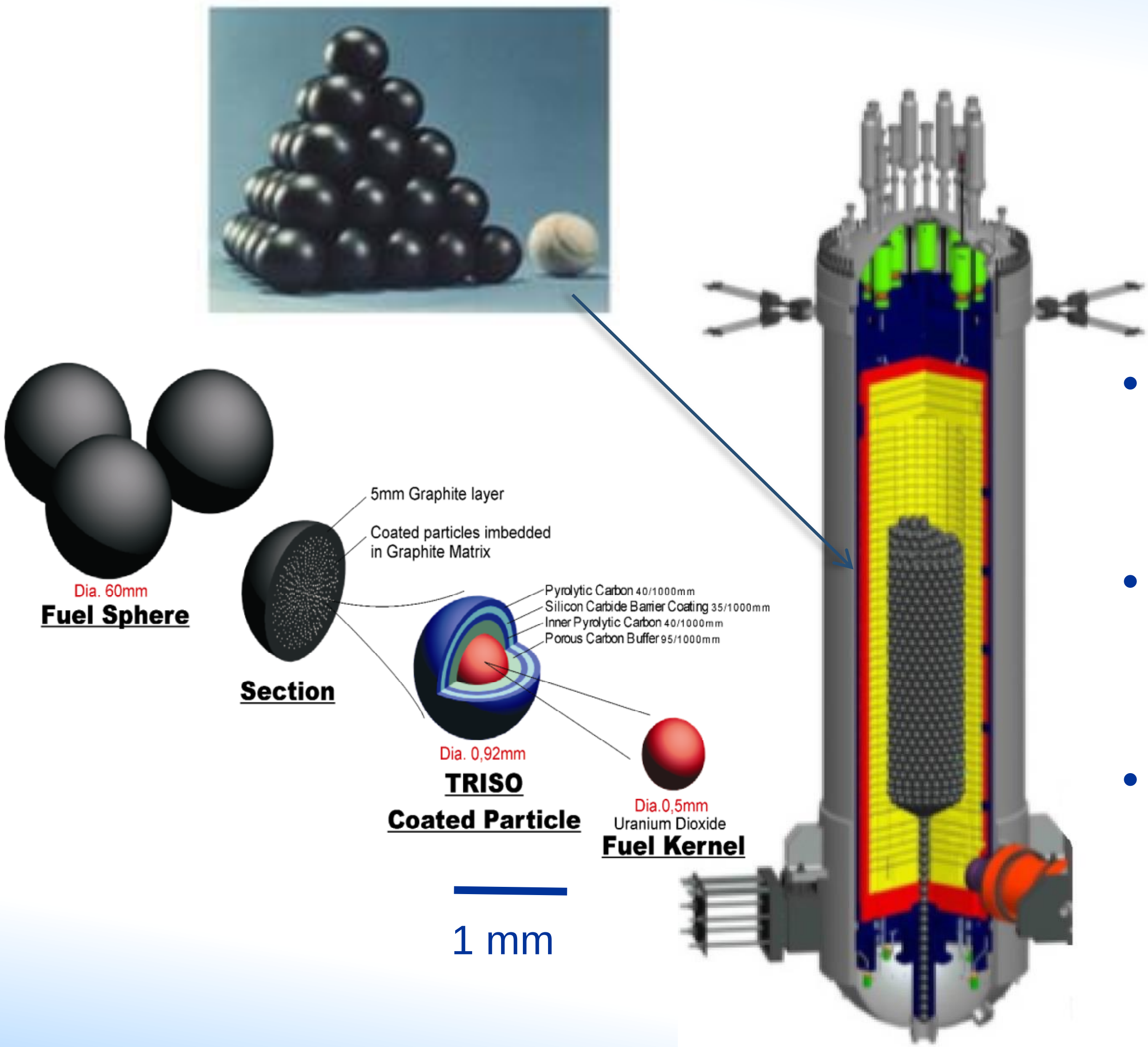






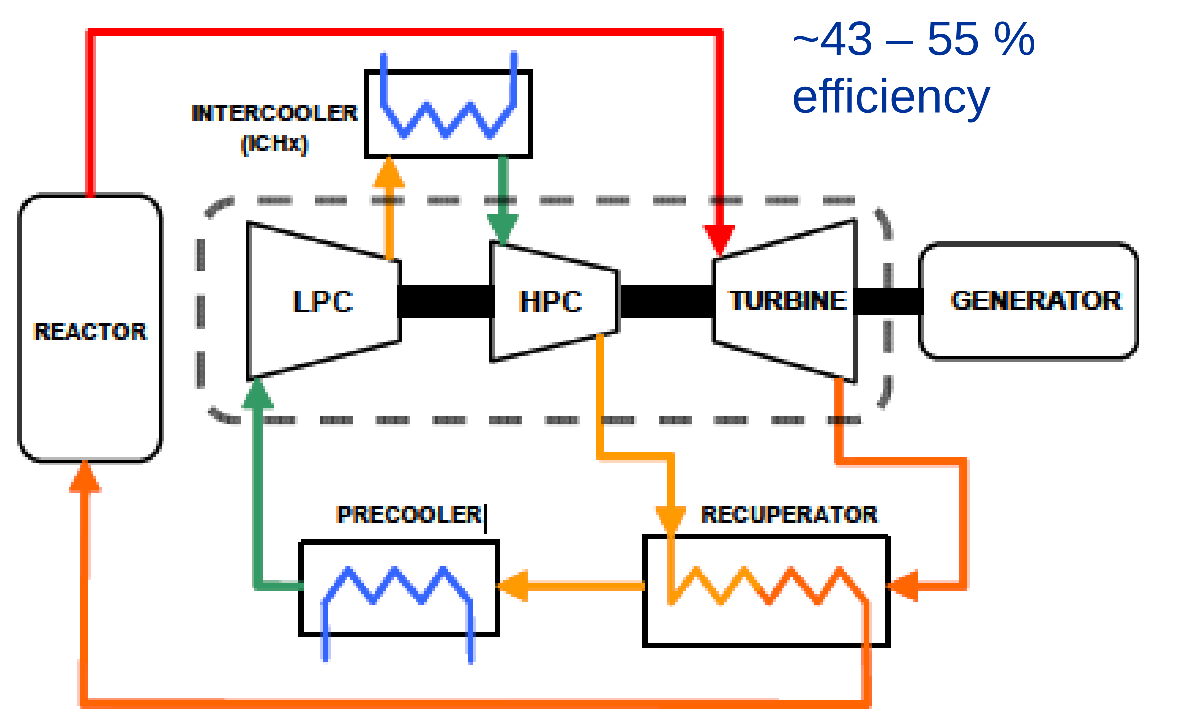


Pebble type HTGRs

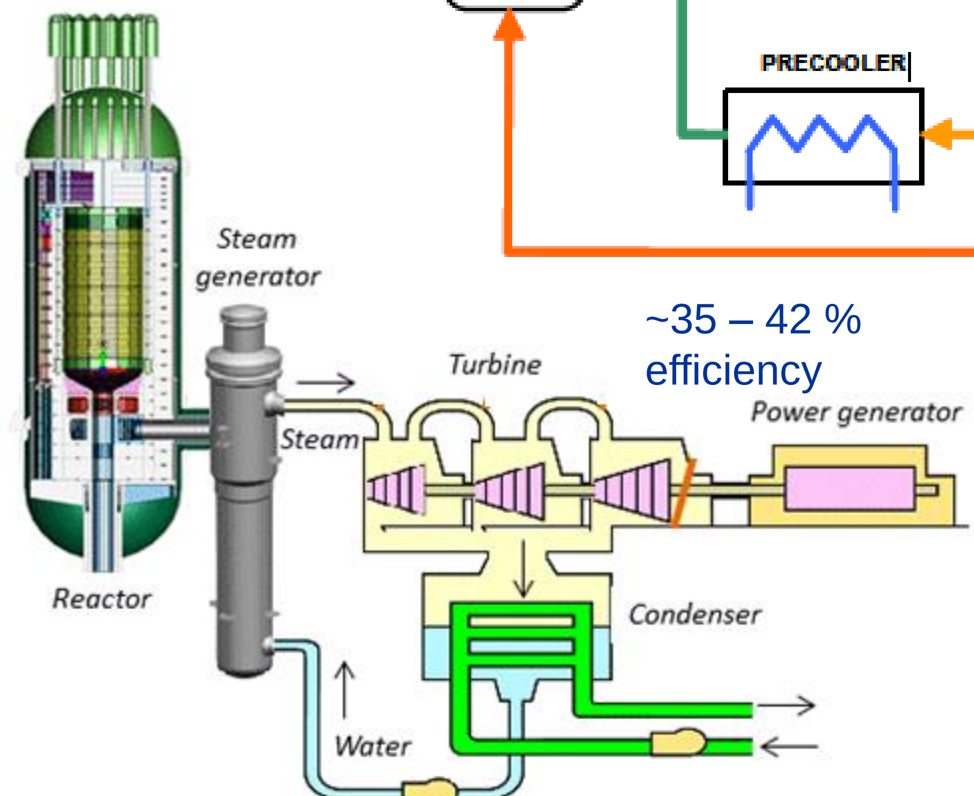


- Spherical graphite fuel element with coated particles fuel
- Fuel loaded in cavity formed by graphite to form a pebble bed
- On-line / continuous fuel loading and circulation

HTGRs - Power Conversion Cycles



~43 – 55 % efficiency



~35 – 42 % efficiency

Power generation:

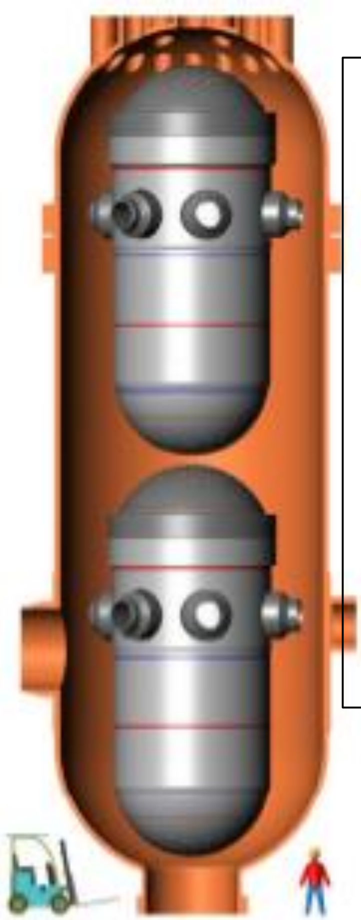
- Can make use of Brayton cycle / gas turbine for increased efficiencies
- Or use conventional Rankine cycle

HTGRs - Benefits

- Higher (↑20-50%) efficiency in electricity generation than conventional nuclear plants due to higher coolant outlet temperatures
- Potential to participate in the complete energy market with cogeneration and high temperature process heat application
  - Process steam for petro-chemical industry and future hydrogen production
  - Market potential substantial and larger than the electricity market
  - Allows flexibility of operation switching between electricity and process heat
- Significantly improved safety
  - Decay heat removal by natural means only, i.e. no meltdown
  - No large release - radioactivity contained in coated particle fuel
  - EPZ can be at the site boundary
- Position close to markets or heat users
  - Savings in transmission costs
- Can achieve higher fuel burnup (80-200 GWd/t)
  - Flexible fuel cycle and can burn plutonium very effectively

HTGRs Challenges

- The low power density leads to large reactor pressure vessels (but site requirements not larger)
  - Forging capability can also set limit on RPV diameter and power (e.g. ∅6.7 m → < 350 MWth in South Korea)
- Helium coolant has low density and thus requires high pressurization
- Helium coolant is non-condensable – so a traditional containment cannot be used
- Coated particle fuel costs are expected to be higher



600 MWt HTGR RPV
vs
PWR RPV

Development status - HTGRs

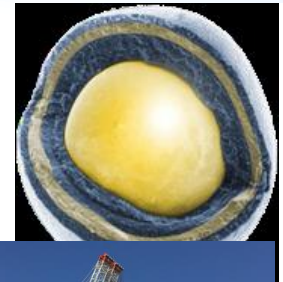
- HTR-PM construction of a commercial demonstration plant

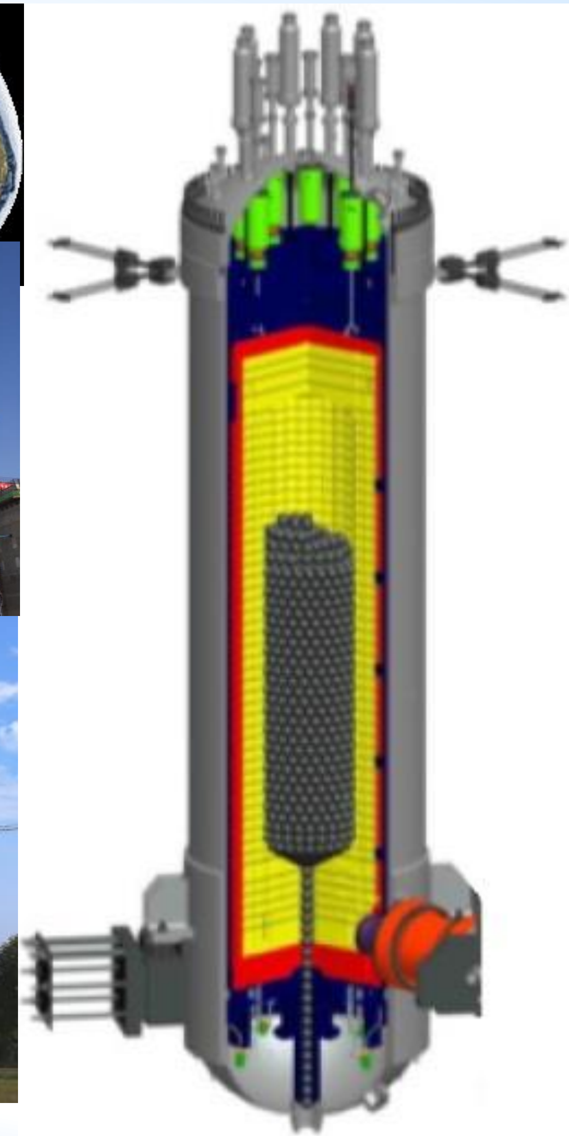
  modular 2 x 250MWth

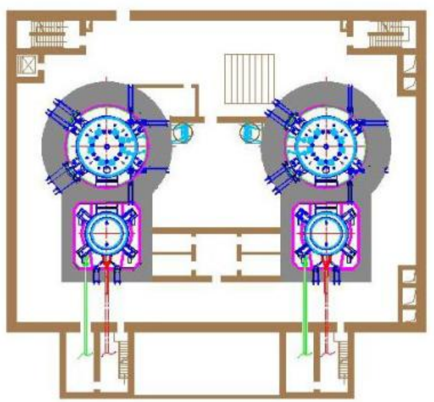
  operation in 2018

  Shidao Bay,

  Shandong province, China



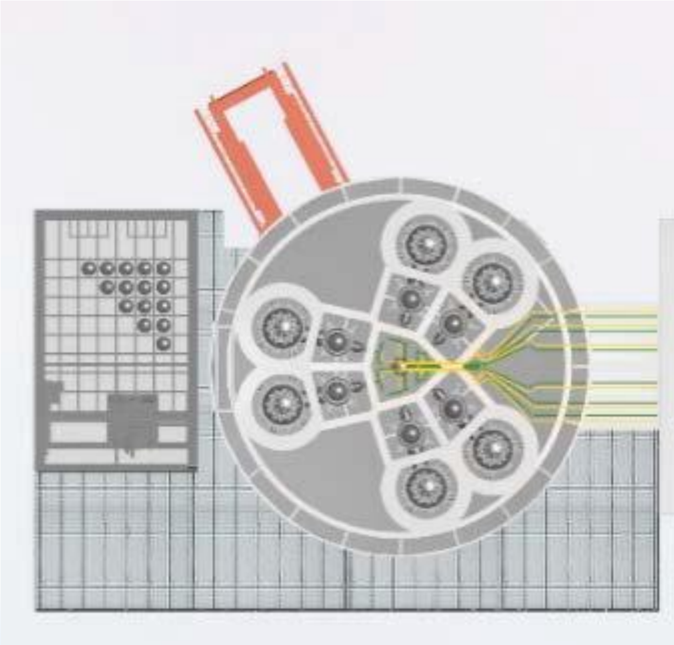




HTR-PM600

- Commercial 600MWe NPP under development
- 6 reactor modules connected to one steam turbine,
  - the same safety features,
  - the same major components,
  - the same parameters,

  comparing with HTR-PM demonstration plant;
- Market to replace existing coal power stations, process heat
- the same site footprint and the same reactor plant volume comparing with the same size PWRs.
- feasibility study for 5 possible sites (3 different owners) including for 2 NPPs at Ruijin city, Jiangxi province (inland NPP site)



HTGRs and Saudi Arabia

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Kingdom of Saudi Arabia and China cooperation

- Jan, 2016

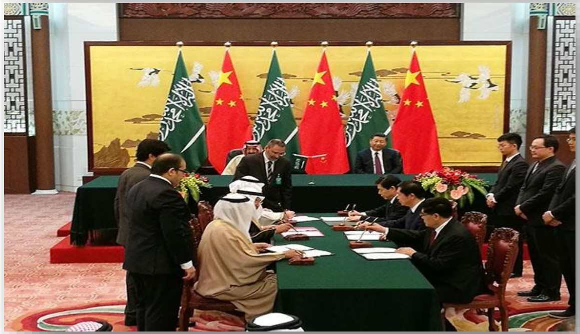
  "MEMORANDUM OF UNDERSTANDING FOR COOPERATION ON HIGH TEMPERATURE GAS COOLED REACTOR PROJECT IN SAUDI ARABIA"
- Mar, 2017

  "AGREEMENT TO CONDUCT A FEASIBILITY STUDY ON PEBBLE-BED MODULAR HIGH TEMPERATURE GAS-COOLED REACTOR IN SAUDI ARABIA"
- Nov. / Dec, 2017

  2017.11 Complete the Joint Feasibility Study report

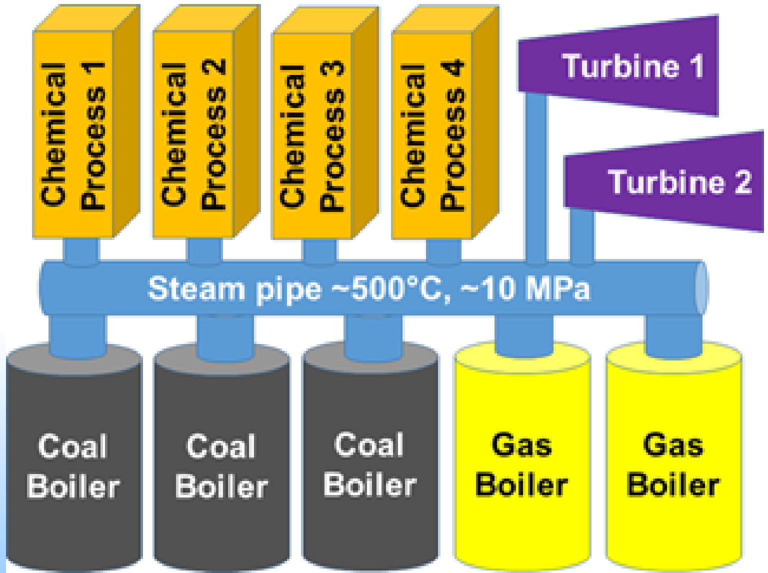
  2017.12 Feasibility Study final Meeting
- Aug, 2017

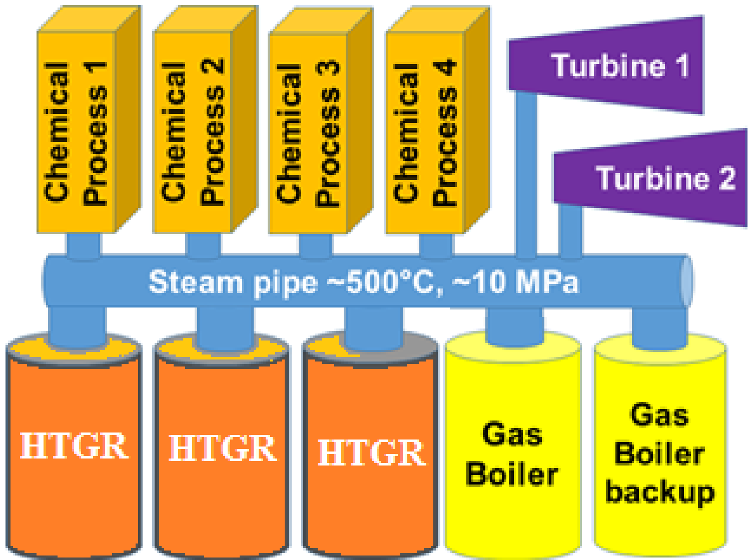
  "MEMORANDUM OF UNDERSTANDING FOR A JOINT VENTURE TO CO-DEVELOPING HTR-PM DESALINATION PROJECTS IN SAUDI ARABIA"



HTGRs and Poland

- Industrial Heat Market in Poland
  - 13 largest chemical plants need 6500 MW of heat at T=400-550°C
  - Construction of experimental reactor of ~10 MW_{th} in Swierk
  - Target to construct the first commercial reactor of 150-300 MW_{th} (165 MWth was determined to be optimum size for Poland)
  - Huge potential: Foresee 10, 100, 1000 reactors for Poland, Europe and the world …





Contents

How is the safety approach different…

- HTGRs have favorable inherent safety characteristics:
  - High quality ceramic coated particle fuel
  - Single phase helium as coolant
  - Strong negative reactivity coefficients
  - Slow transients due to large mass of graphite in the core
- modular HTGR designs that are based on design principles that ensure:
  - no significant radionuclide release are conceivable even if all coolant are lost / no active forced convection systems.
  - The residual heat removal is ensured solely through physical processes (thermal conduction, radiation, convection).
- To achieve this we typically need a design with:
  - Low power density
  - Long slender core and/or annular design
  - Reactor Cavity Cooling System external from the reactor to remove the decay heat

HTR-Modul principle

DIMENSIONS AND POWER ARE FIXED BY INHERENT PROPERTIES
[can not be chosen as usually]

Diameter: ‘given’ by shutdown from outside
D ~ 300 cm

Power density: ‘given’ by maximum fuel temperature [T = 1600 °C]
Q ~ 20 MW/m

Core height: ‘given’ by blower [dp~ 1.5 bar, Xenon]
H ~ 10 m

This yields a maximum power per Modul of:
P_{max} = 200 – 280 MW_{th}

Prof Lohnert, Centurion, Nov 10,2009

Helium coolant

- inert noble gas it does not undergo any phase change and has a very low chemical reactivity.
  - It is also invisible to neutrons, with basically no core reactivity effect.
  - Relative high heat transfer coefficient with no heat transfer limits.
- Unlike in the case of loss of coolant in WCRs, helium, when leaked out of the primary pressure boundary, does not condense.
  - In a sealed containment this will lead to a sustained elevated pressure that cannot be reduced by cooldown.

Core thermodynamic characteristics

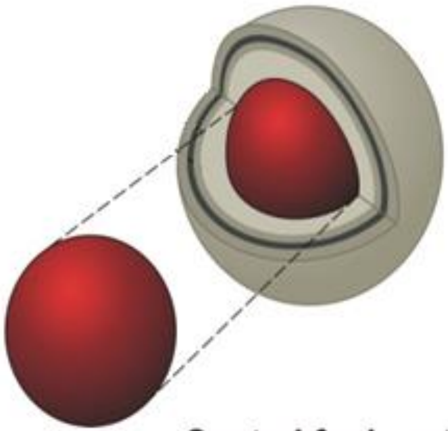
- Typical modular HTGR:
  - is quite low in power (typically 100-650MWth)
  - has large reactor vessels and low power density
  - has large graphite moderated cores and the thick graphite reflectors used.
- The large mass of graphite, with its high heat capacity, causes very slow core temperature changes and thus very slow transient response.
- Combined with the large temperature coefficient of reactivity this makes for benign behavior and enough time for the operators to respond.

Inherent Safety Characteristics

Ceramic coated particle fuel retains radioactive materials up to and above 1800˚C

Coated particle fuel

- contain almost all fission products for the expected operating and postulated accident temperatures in a modular HTGR.
- core design and operating parameters ensure large margins
- <u>No large early release of fission products</u> due to coated particle failure is therefore possible (no credible conditions).

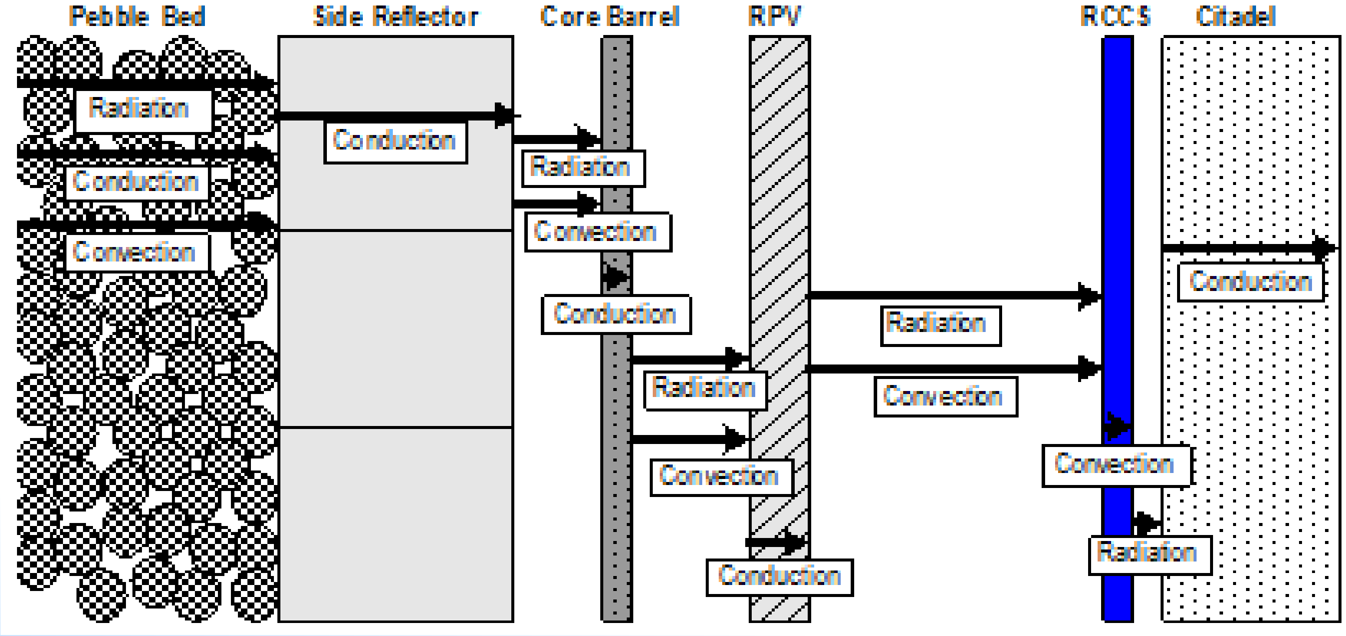


Coated fuel particle

- The failure mechanisms of CP fuel are decoupled and totally independent.
  - One coated particle failure cannot lead to the failure of a neighboring CP, as it is driven by the maximum fuel temperature.
  - A CP failure also has no effect on the cool-ability of the fuel as a failure will not change the heat removal path.
  - The amount of fission products that can potentially be release when a failure occurs is of course very small, and many CP will need to fail to be of any consequence.
  - In this respect it is very different from WCR fuel where one pin failure can inhibit the cooling of neighbors and cause significant additional failures or a partial core melt.

Residual heat removal

- Modular HTGRs rely on passive residual heat removal if none of the active systems are available.
  - independent if the helium coolant is still present or has been lost.
  - post shutdown decay heat removal is solely through physical processes
  - decay heat is dissipated from the core through the reactor structures to the uninsulated reactor vessel and then primarily by radiation to the reactor cavity cooling system (RCCS) on the outside.
  - (This does not mean that an active system may not be included in the designs but these are not needed in the safety argument).

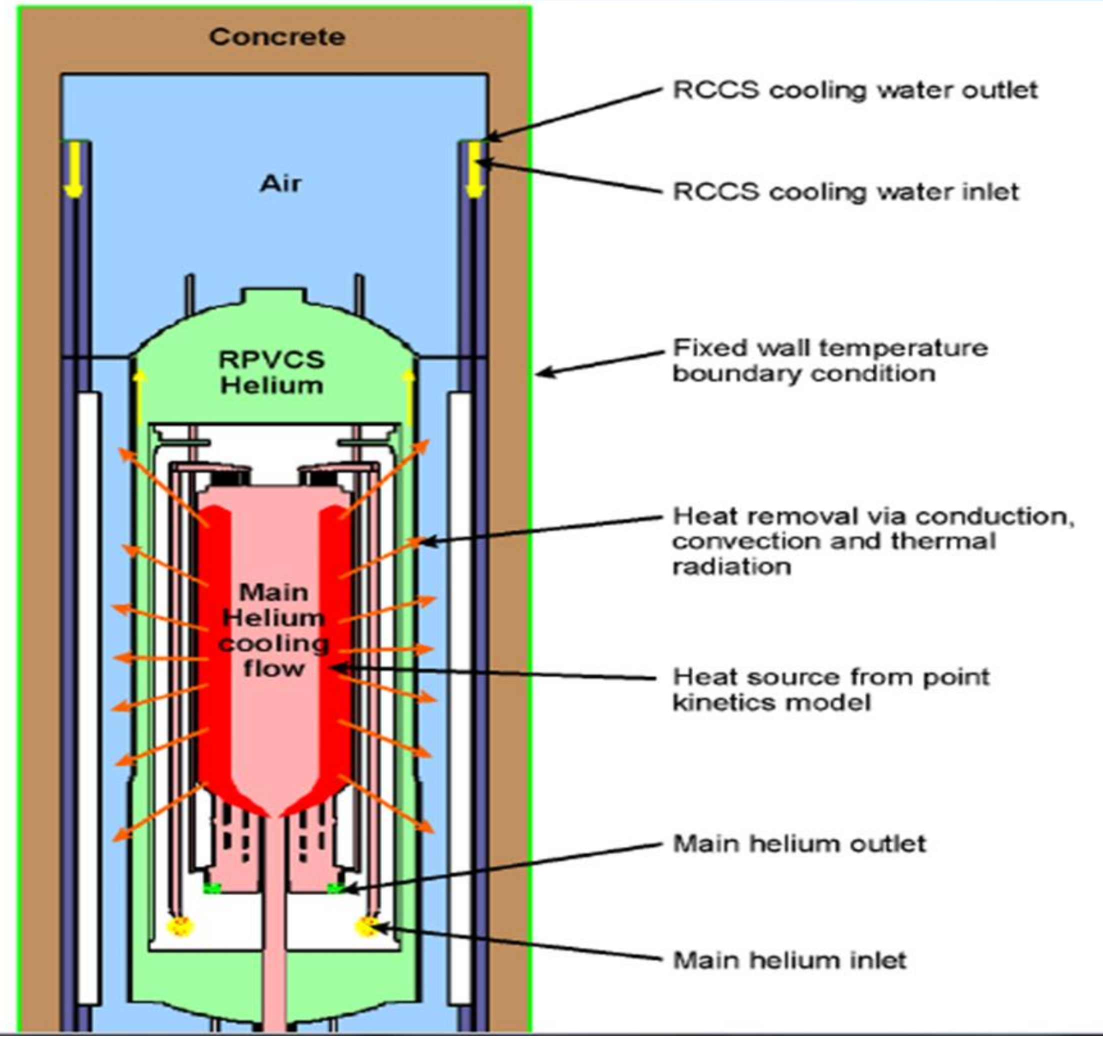


low core power density and slim core geometry

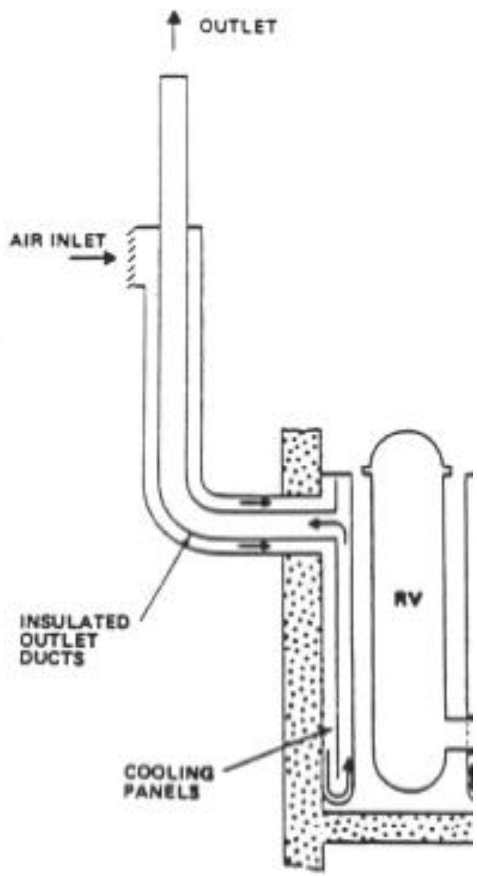
Principle of reactor cavity cooling design – HTR-Module

PRINCIPLE OF PASSIVE DECAY HEAT REMOVAL OF THE

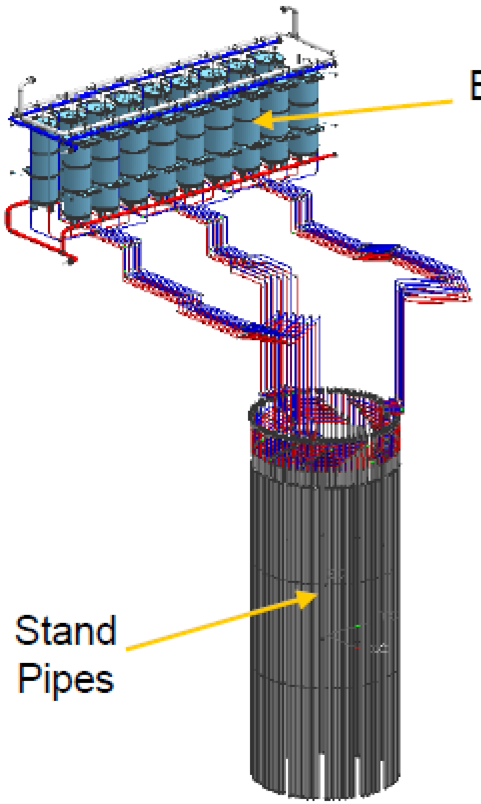
MODULAR HTR



Concepts to remove heat to the ultimate heat sink



Active, Passive, or combination
Water or Air cooled

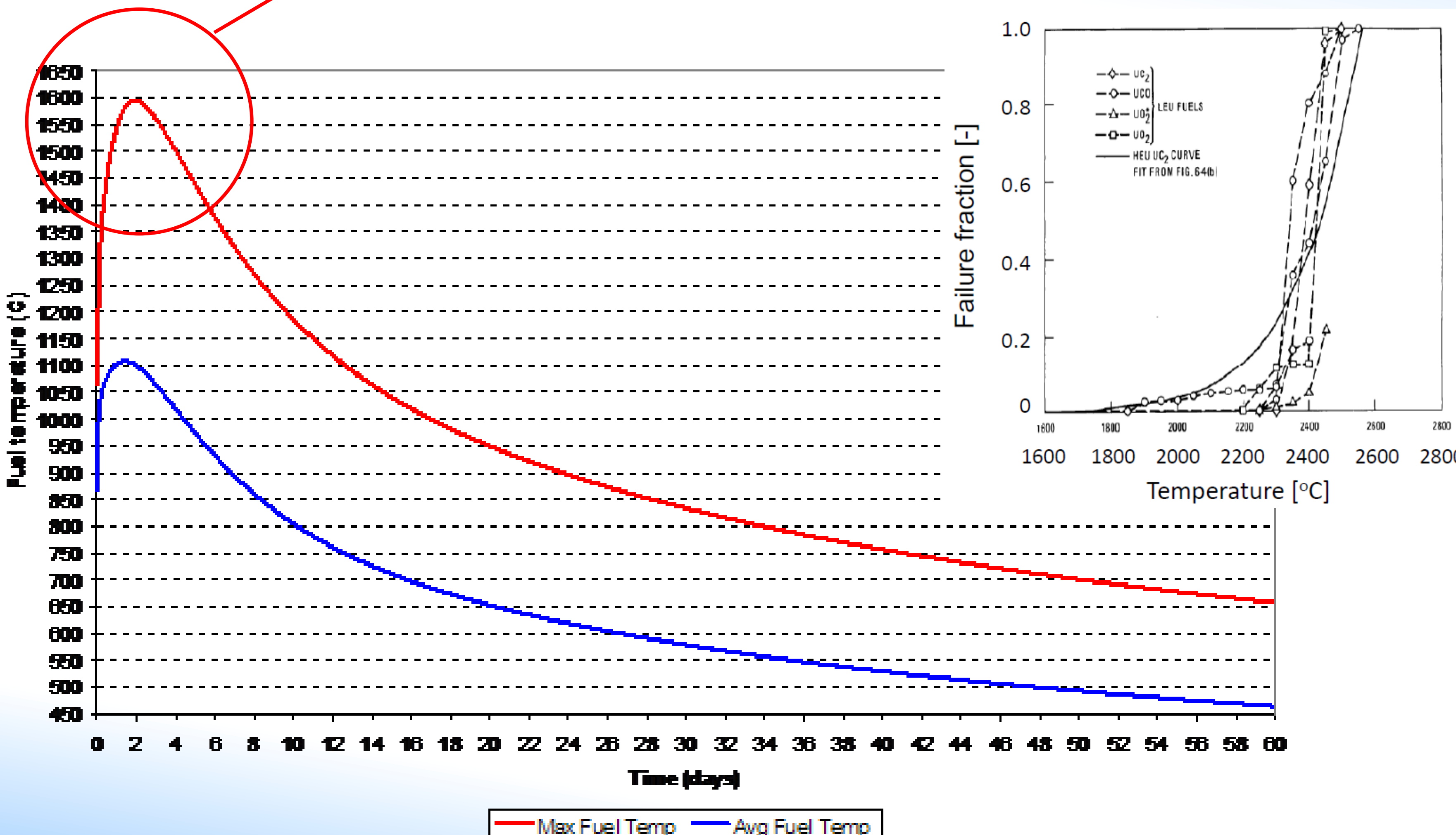


Safety class dependent on the design.
Often seen as investment Production
Release of radioactivity is similar with or without the system functioning….

Passive Heat Removal

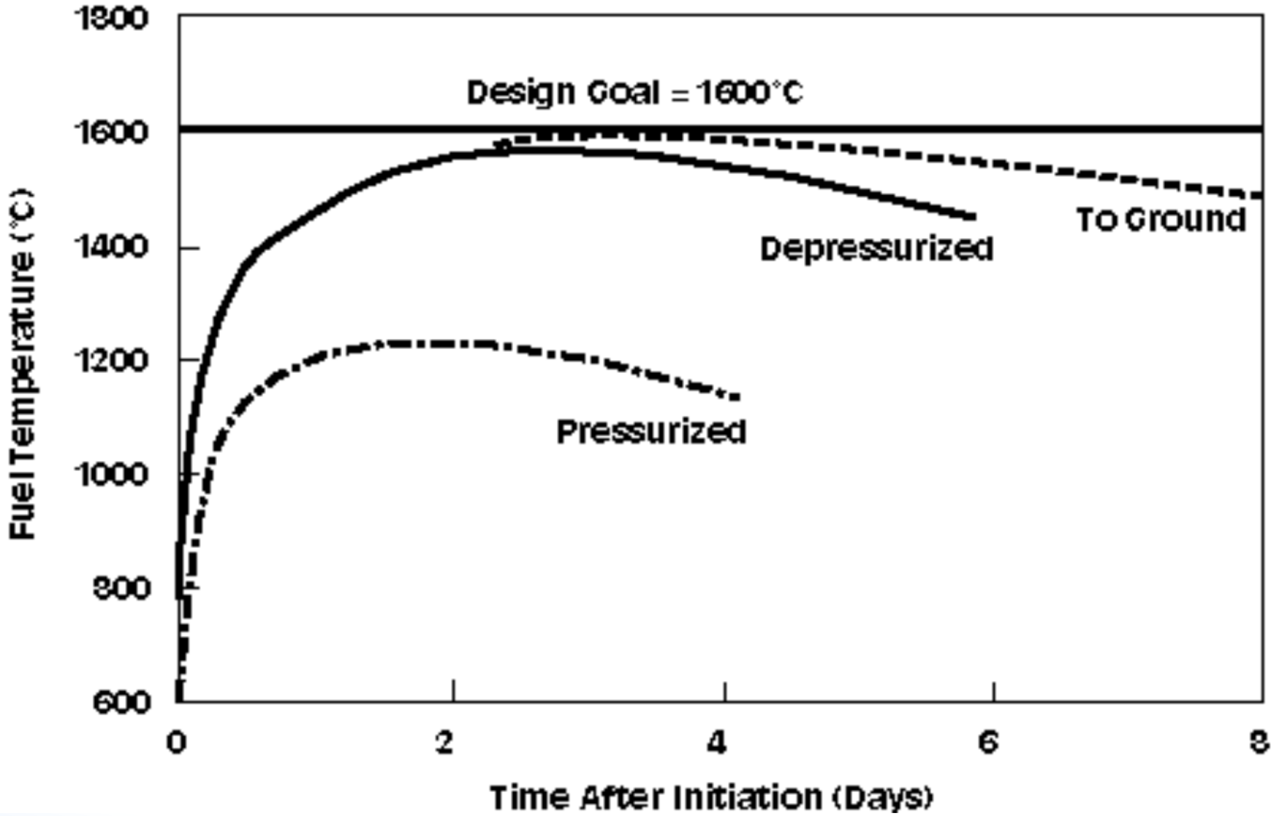
Example of Fuel Temperatures behavior for a DLOFC Event – over 60 days

If T is too high it will start some releases



Inherent Safety Characteristics

Fuel temperatures remain below design limits during loss-of-cooling events



Fuel temperatures are not significantly increased if the cavity cooling system fails

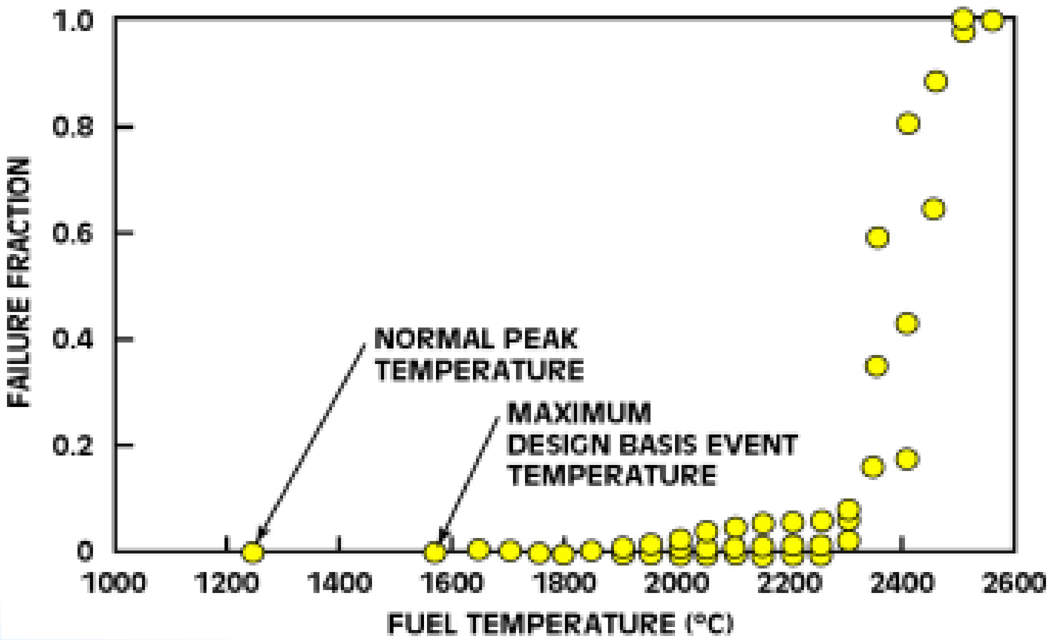
Fuel typical characteristics

Coated particle key safety features:

- Fission product retention capability of coated particle fuel:
  - Normal operation temperatures (now up to 1250°C proven)
  - Can sustain fast transients / power excursions
  - It contains the vast majority of all fission products even under the most severe postulated accidents with temperatures up to 1800°C
  - Some tolerance for water and air ingress (limits)
- A ceramic fuel – can not melt
- CP can achieve high burnup (80-200 GWd/te)

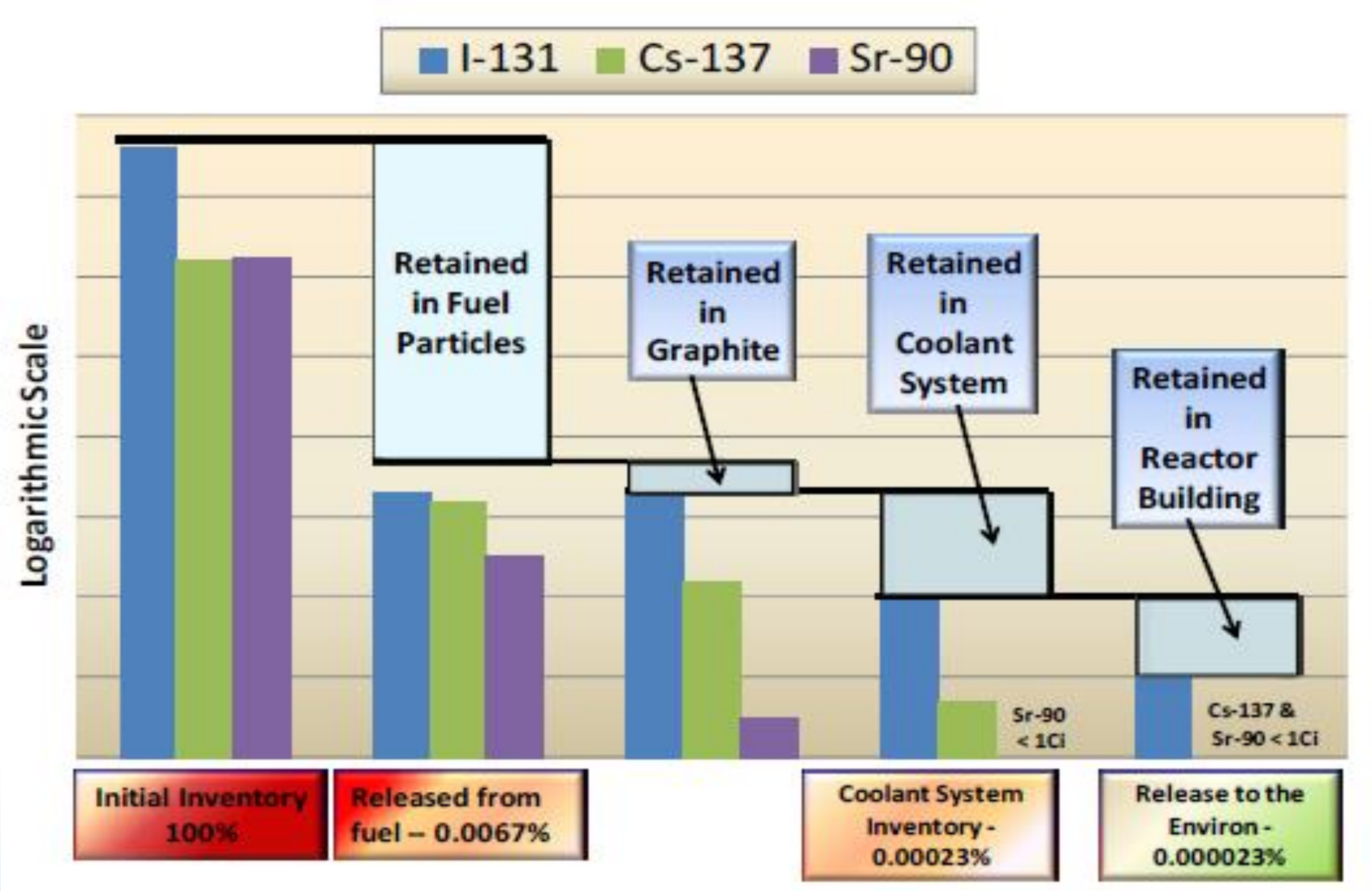
Residual heat removal

- Typically the maximum accident temperatures are kept well below temperatures at which point fission product retention of some coated particles may be challenged or coatings may start to fail.
- Coated particle failures only occur if these high temperatures are maintained for a long time (several 100 hours).
- More importantly only a very small fraction of the fuel (typically < 5%) will be at these high temperatures, while the rest of the fuel is substantially cooler.



The Safety Concept of Modular HTGRs

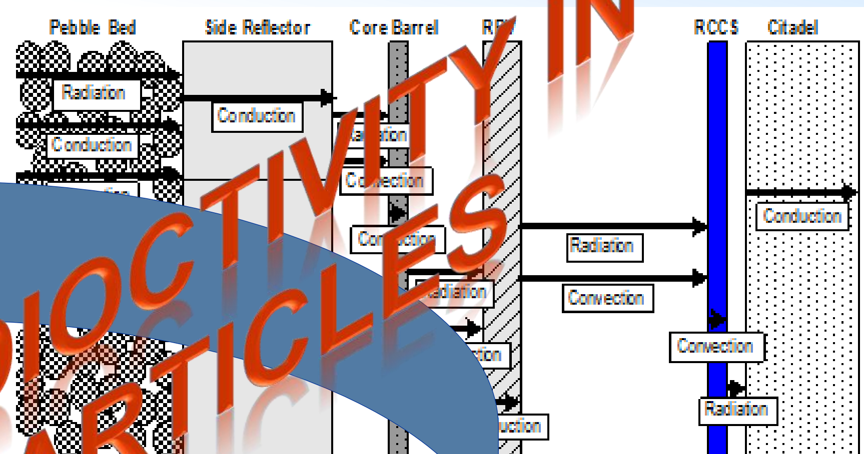
- Containment of Fission Products – Illustration at DLOFC conditions



Inherent Safety Characteristics

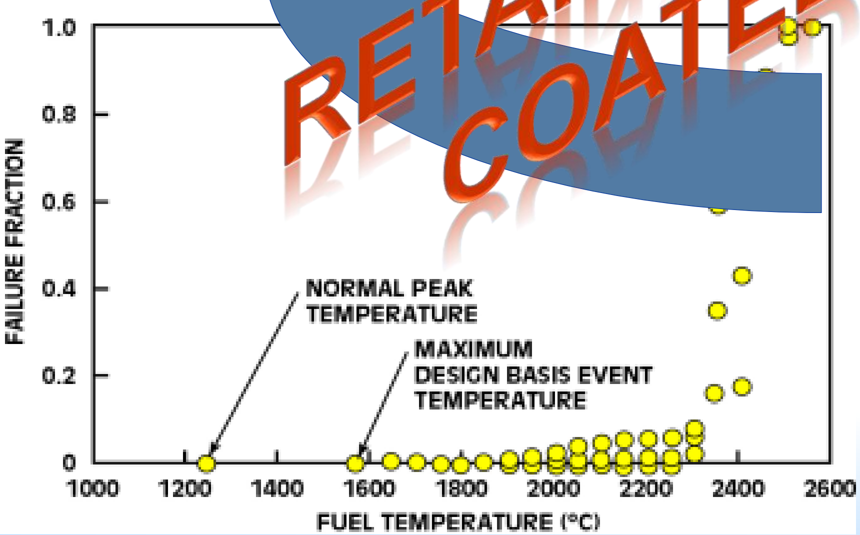
Ceramic fuel retains radioactive materials up to and above 1800˚C

Heat removed passively without primary coolant – all natural means

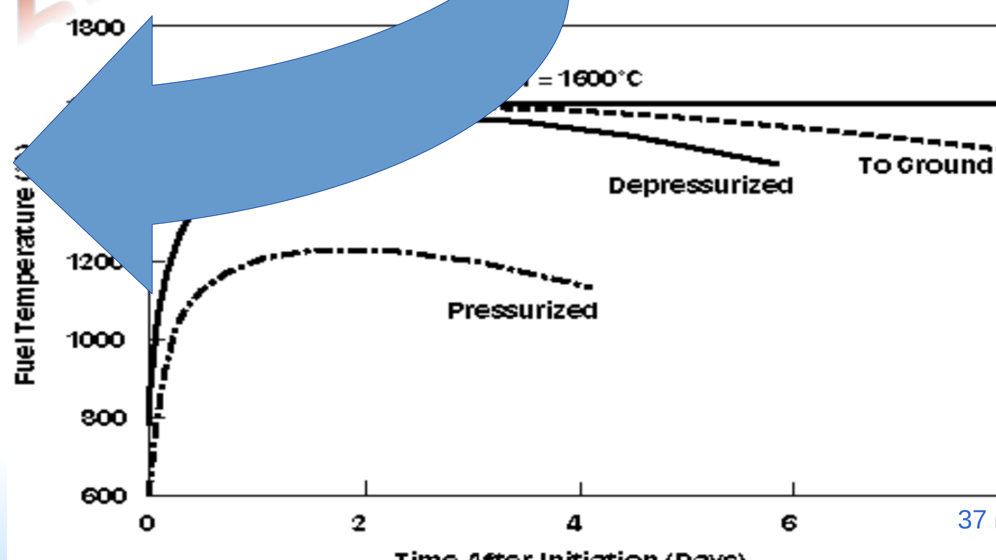


RETAINS RADIOCTIVITY IN COATED PARTICLES

Coated particles stable to beyond maximum accident temperatures



Fuel temperatures remain below design limits during loss-of cooling events



The safety features

- **Significantly improved safety characteristics**
  - **No core meltdown or core damage**
  - Can sustain full load rejection / station blackout conditions
  - No need for multiple layers / multiple trains of cooling capabilities
  - **Simplified designs and few safety related systems**
- **Passive safety characteristics is achieved through:**
  - **Low power density (~ 30 times lower than LWRs).**
  - Strong negative temperature coefficient means the reactor automatically shuts down without operator interaction.
- **Most transients are slow (develop over hours and days)**
  - Very large heat capacity (>800 tons of graphite)
  - Maximum fuel temperatures in DLOFC after 24-36 hours
- Coolant is decoupled from neutronics

Safety Conclusions

- The modular HTGR safety philosophy targets a catastrophe-free safety terrain without large releases. There should be:
  – No need for operator action
  – No need for offsite emergency response
- The safety design approach is top-down and based on passive and inherent safety features.
  – Emphasis is on prevention by protecting TRISO fuel particles
  – Cliff-edge effects are to be excluded even in extreme events
- the reactor designer must still assure a safe design – must stay true to the modular HTR safety philosophy

Impact on deployment

- What does that mean for deployment?
  - Improved public acceptance possible
  - Positioning NPP close to electricity and process heat user
  - No need for a large EPZ – could be at the site boundary
  - Can sustain full load rejection / station blackout conditions
  - No need for multiple layers / multiple trains of cooling capabilities
  - Simplified designs and fewer required safety related systems
  - This should contribute to a simplified nuclear power plant design and better economic competitiveness
  - But need safety design requirements and a regulator that understand this….

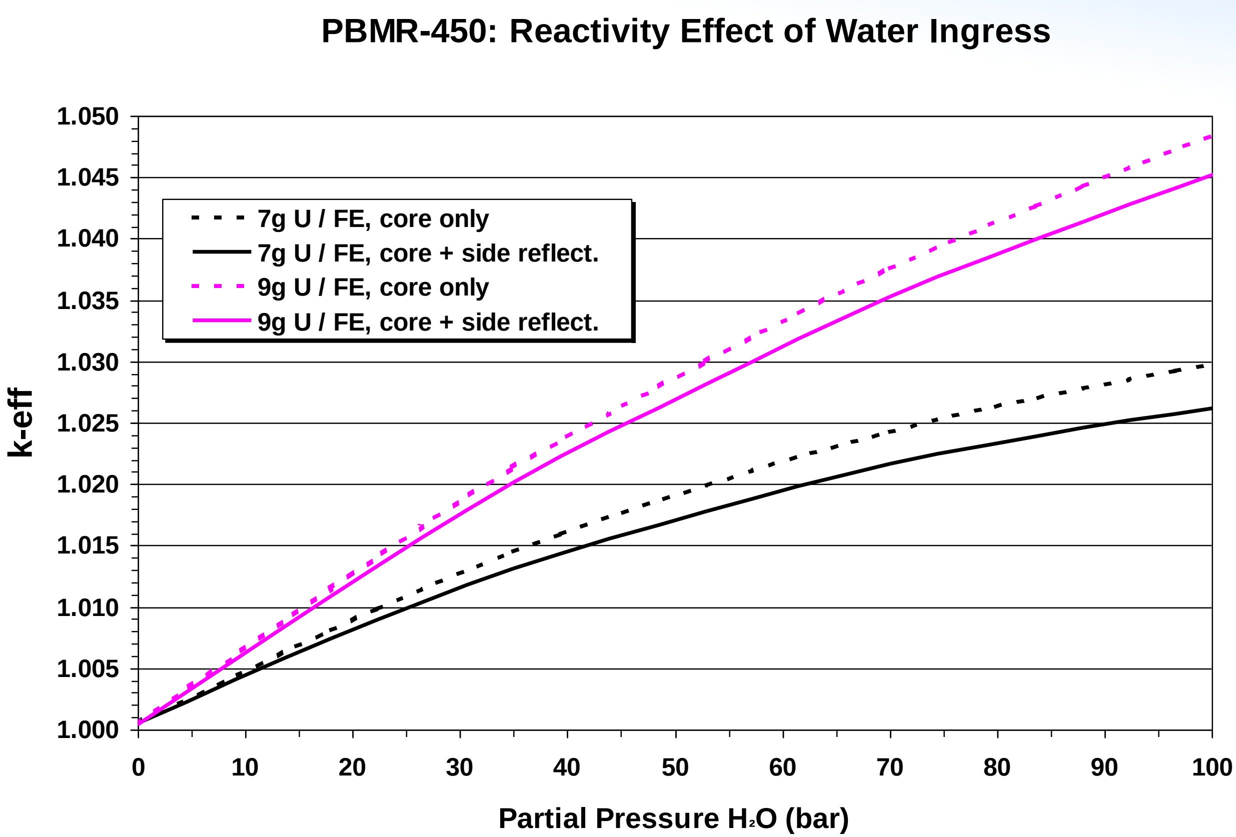
Remaining key safety aspects: Severe Accidents

- Water ingress
- Air Ingress
- Dust as radioactivity transport mechanism

Water ingress – limit the effect

- The typical pebble bed reactor core is under moderated
  - This means additional moderator being added (water) will increase the reactivity and lead to a power excursion if not controlled.
  - Reducing the HM loading will decrease the effect but also lead to lower burnup and increased fuel costs
  - A balance to be found while ensuring adherence to safety approach
- Example on how it can be addressed by typical safety requirements (for design basis accident):
  - The SG shall be designed such that the double guillotine rupture of a single SG tube with one SG dump train not available shall permit no more than 600kg water ingress into the primary side.
  - The heavy metal loading of the fuel should be optimised so that the expected additional reactivity can be countered by the fast acting shutdown system (assuming a single failure)
  - Moisture detection activate the reactor protection system, stop the blower, isolate and perform SG dump.
  - Limited amount of water may reach the core (and first get into contact with graphite reflector structures)

Typical behaviour – Water ingress



Mass equivalent of partial steam vapour pressures used in the simulations. Partial steam vapour pressure (bar) Amount of water added (kg)

	PBMR-400	**PBMR-200**
30	275	217
60	549	434
100	915	723
200	1831	1447
300	2746	2170
400	3661	-

- Can show that only small amounts of water vapor expected to entre the core
- Design features (side-by side RPV and SG)…

Water ingress accident

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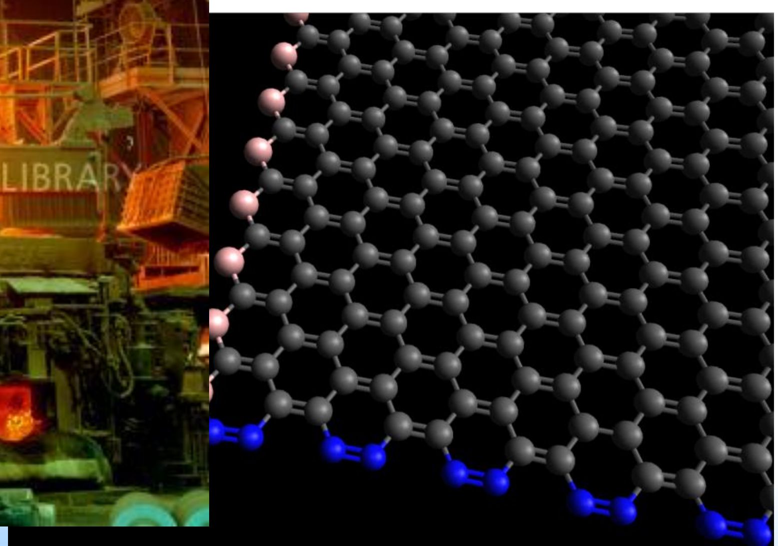
- Interaction of steam with defective cp
  (release of iodine and noble gases)
- Remobilization of plated-out activity
  (if in connection with depressurization, major part of fission products can leave primary system)
- Release from graphite corrosion
  (less significant, small release, longer-term effect)

Key safety aspects: Graphite Corrosion

- Water ingress
  - Can lead to graphite corrosion at high temperatures
  - Water amounts to be limited (direct cycle, water dump in Rankine cycle)
- Air ingress
  - Can lead to graphite corrosion at high temperatures
  - Eventually may lead to exposed coated particles and potentially additional release of FPs
  - Massive air ingress to be prevented
    - No chimney effect
    - Penetration at the bottom limited

Graphite oxidation

- Graphite is heat resistant
- Nuclear grade graphite cannot burn (INL report), just oxidize
- Graphite is used as electrodes…. (and that not even reactor grade)
- Very well studied… qualified graphite
- Miss-perceptions of graphite fires

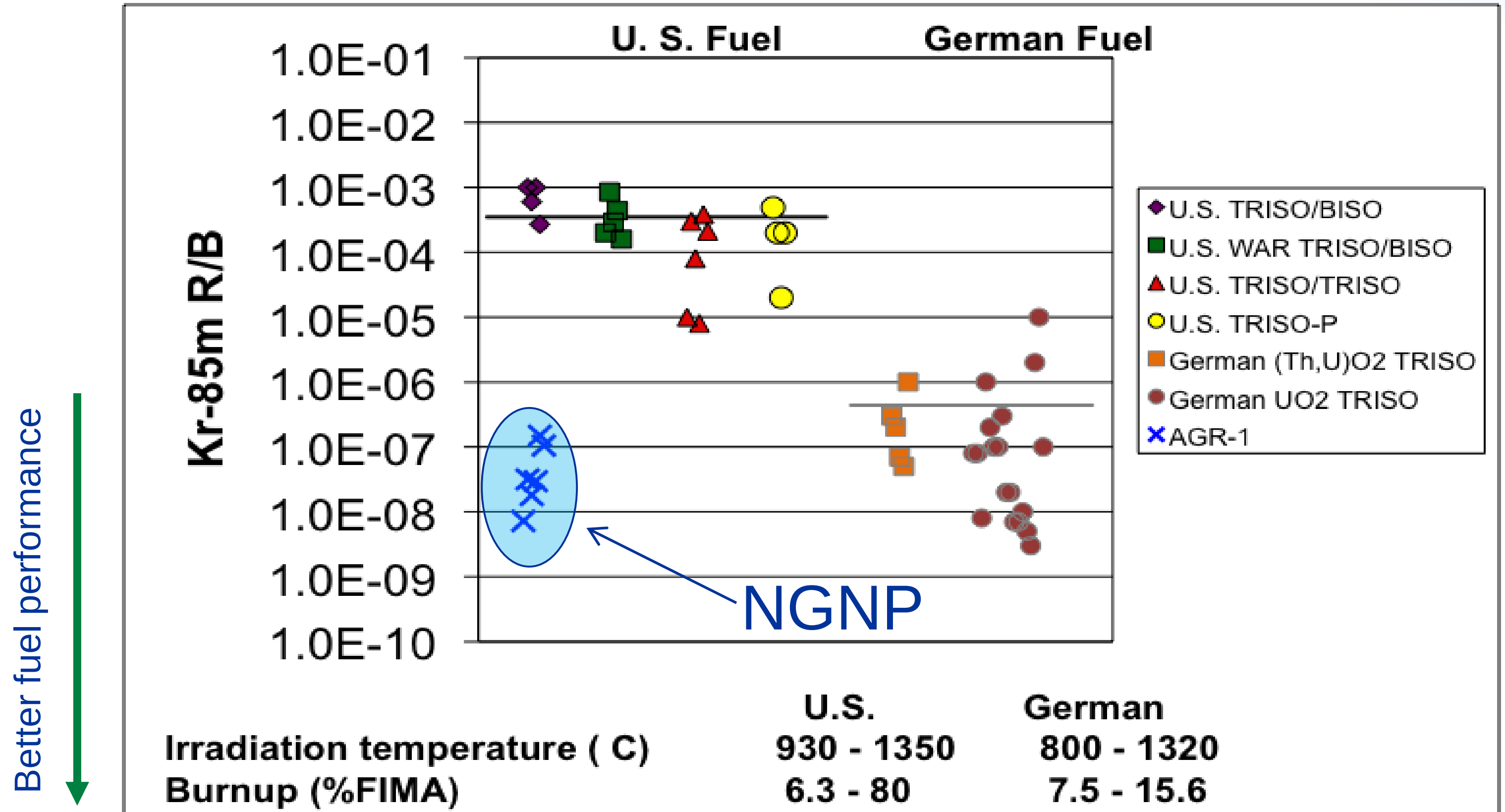


… graphite burning…????

- Graphite powder metal fire extinguishers can also be used on lithium fires, although unlike the copper powder, the graphite powder will not stick to a vertical surface. However, graphite powder can be used on metals that burn at very high temperatures, such as zirconium and titanium.
- Graphite powder can also be applied to burning metal powders, where even the gentle blast from a fire extinguisher could lift up the powder and cause a dust cloud explosion. Graphite powder has the added advantage of drawing heat away from the fire as well as smothering it.

A few Key aspects… FUEL ARE KEY

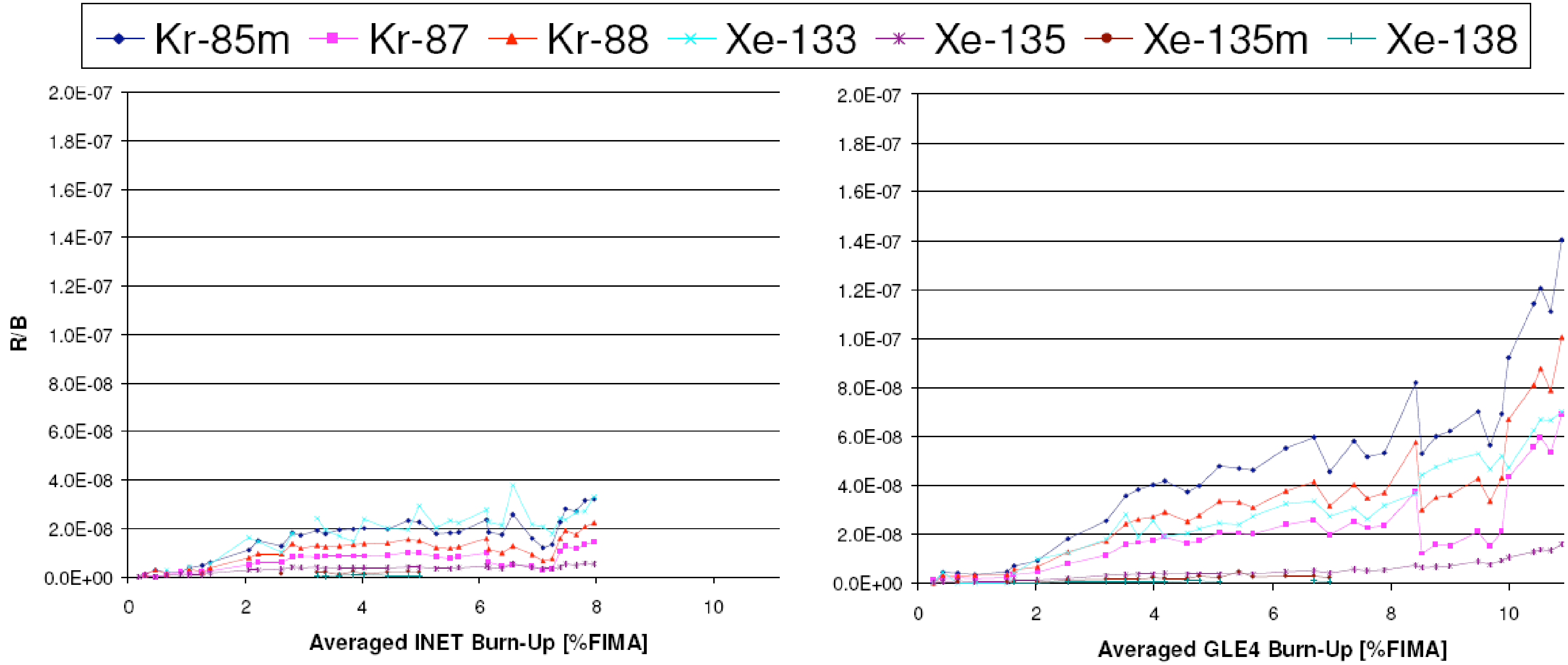
- Fuel
  - Good quality and mass production well established and now well understood



	U.S.	German
Irradiation temperature (C)	930 - 1350	800 - 1320
Burnup (%FIMA)	6.3 - 80	7.5 - 15.6
Fast fluence (10^{25} n/m^2)	2.0 - 10.2	0.1 - 8.5

Fission gas release from HFR-EU1

- Very low R/Bs in irradiation of Chinese (left) and German (right) spheres



JRC-IE, NRG, INET, FZJ

Excellent / complete FP retention and extremely clean graphite enable these results

Automatic power reduction

Reactivity Control

Safety demonstration at HTR-10 reactor during HTR conference in Beijing, September 2004

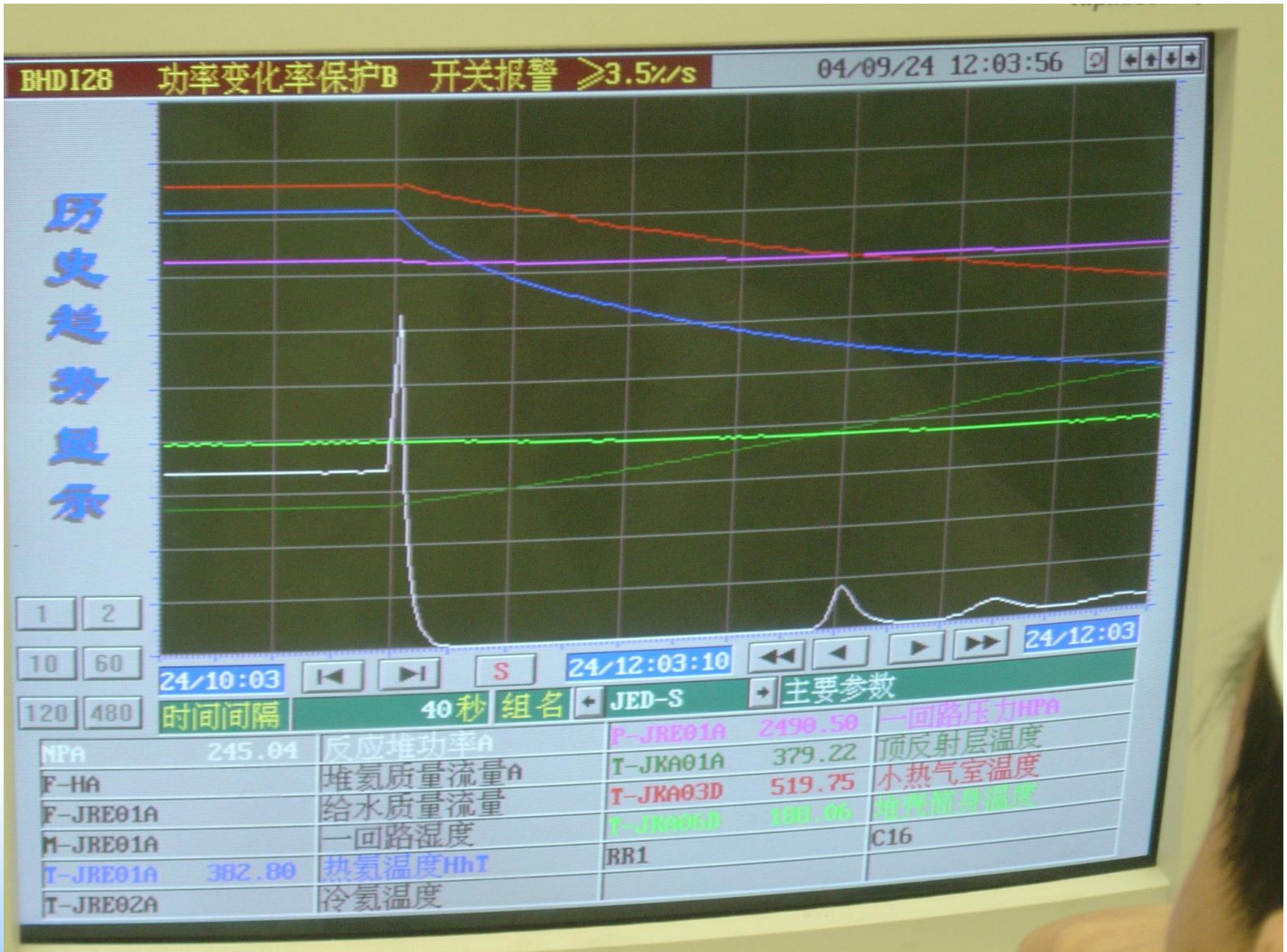
Events:

1. Single control rod withdrawn
2. Coolant circulation stopped
3. Power initially increases due to reactivity insertion but then decreases
4. Automatic shutdown due to reactivity feedback effects (increased temperatures)

Automatic power reduction

Reactivity Control

Safety demonstration at HTR-10 reactor during HTR conference in Beijing, September 2004



Pillars of MHTGR safety

- A quick reminder of the most important pillars of the safety case:
  - Coated particle fuel
  - Helium coolant
  - Reactivity and reactor shutdown
  - Core thermodynamic characteristics
  - Residual heat removal

“*Safety Terrain*” of LWRs vs Modular HTGRs

Light Water Reactors

The basic “*safety terrain*” (or safety landscape) of today’s LWRs is well known.

As seen at Fukushima Daiichi, it is a terrain that features **cascading “cliff edge” effects** in accidents only moderately beyond the design basis:

- **Fuel undercooling** → film boiling, fuel failure, core damage
  - ➔ **Core melting** → uncoolable geometry, Zr reaction, hydrogen
    - ➔ **Vessel failure** → core-concrete reaction, direct heating
      - ➔ **Containment breach** → high-pressure large release

"*Safety Terrain*" of LWRs vs Modular HTGRs

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Modular HTGRs

result in a **safety terrain that is fundamentally much gentler and more forgiving**:

- ➢ **Fuel failure mechanisms of CP fuel are decoupled and totally independent**

  ➔ **One coated particle failure cannot lead to the failure of a neighbouring CP**, as it is driven by the maximum fuel temperature.

  ➔ **Failure also has no effect on the cool-ability of the fuel** as a failure will not change the heat removal path**.**

  ➔ **CP failure will release miniscule amount of FPs -** many CP will need to fail to be of any consequence.

Based on inherent and passive safety features, there is no cliff-edge effects or large releases even in extremely rare events far beyond the design basis.

Presentation Objectives

By the end of this session, participants should be able to:

- Define what a modular HTGR is
- Be able to explain the main principles that must be adhered to by designers to ensure the safety claims of mHTGRs are not violated
- Explain the inherent safety characteristics and passive means that can be employed
- Understand some of the failure mechanism and severe accidents that have the potential to lead to some delayed releases and how these can be mitigated

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Thank you!