Pebble Bed Modular Reactor:
Technology & Project Overview

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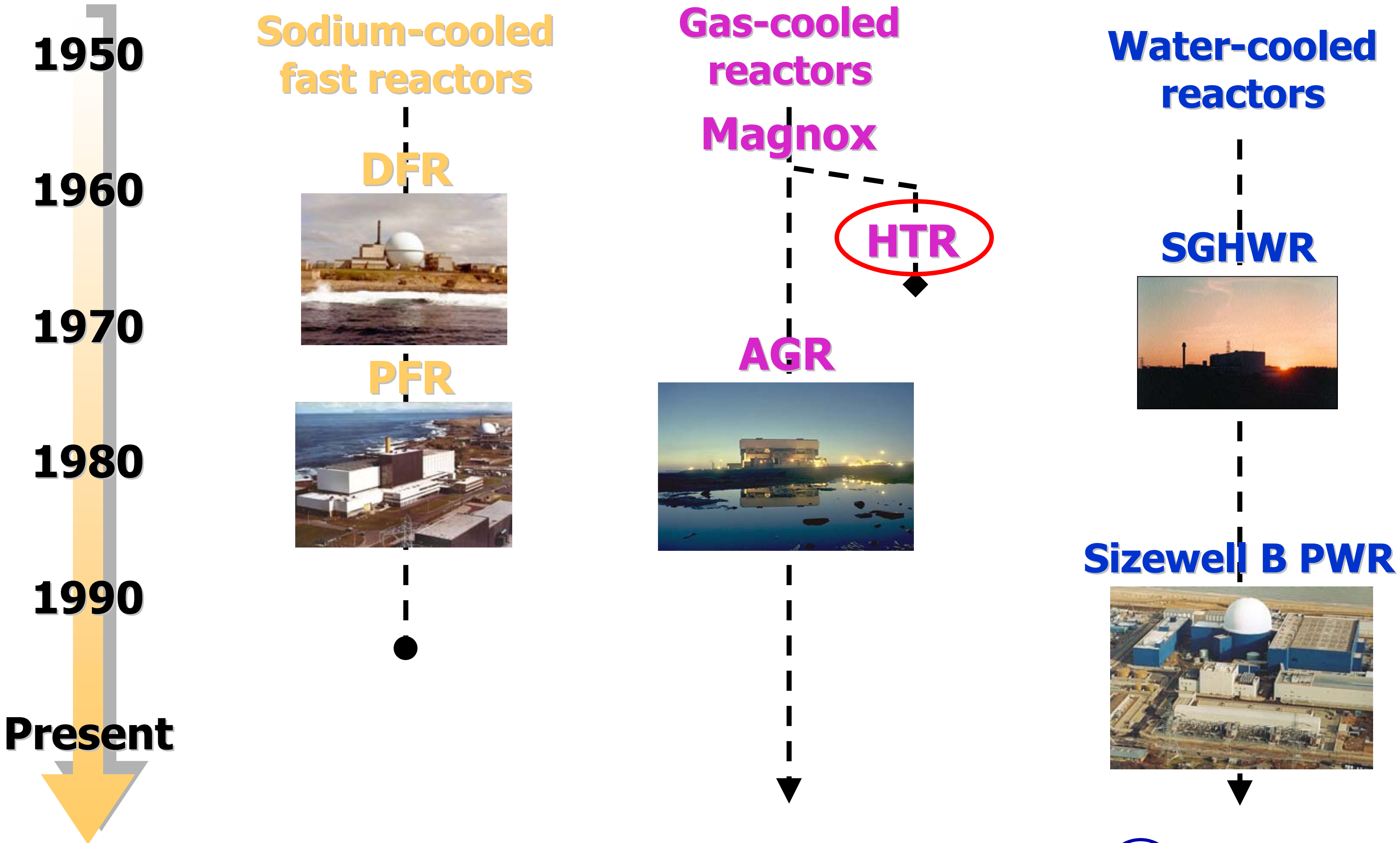
Contents

- **Background to High Temperature Reactors**
  - Basic technology
  - Early prototypes
- **South African Interest**
- **The PBMR Project**
  - Overview of PBMR design and technology
  - Commercial and economic issues
  - Applications for HTRs
  - Future prospects

Different types of reactors: UK experience



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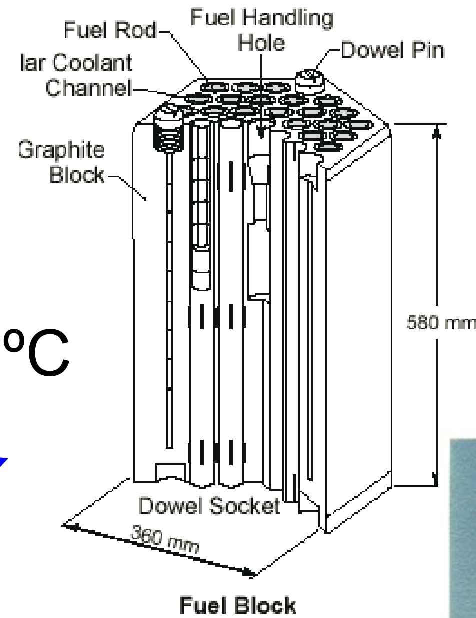
What are High Temperature Reactors?

First proposed by UKAEA's Harwell Laboratory in early 1950s

Typical characteristics:

- Graphite moderated
- Helium cooled
- Refractory fuel and core materials
- High gas outlet temperatures: ≥ 700ºC

Two major design variants:



Prismatic (or 'block') core

Pebble-bed core

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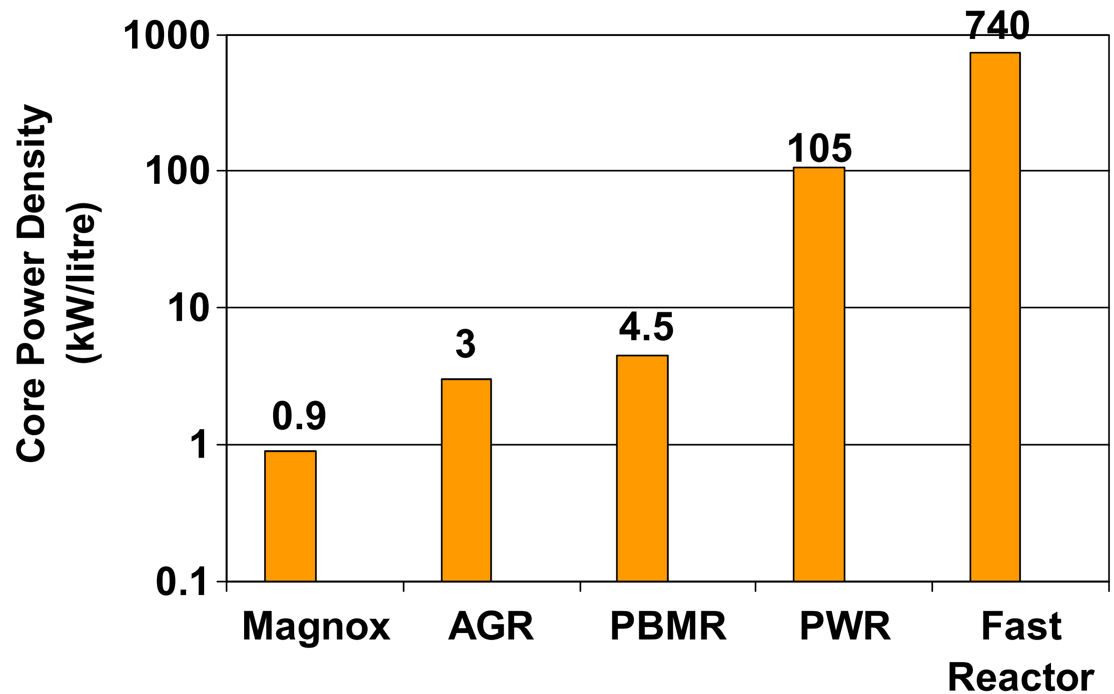
Why are HTRs of interest?

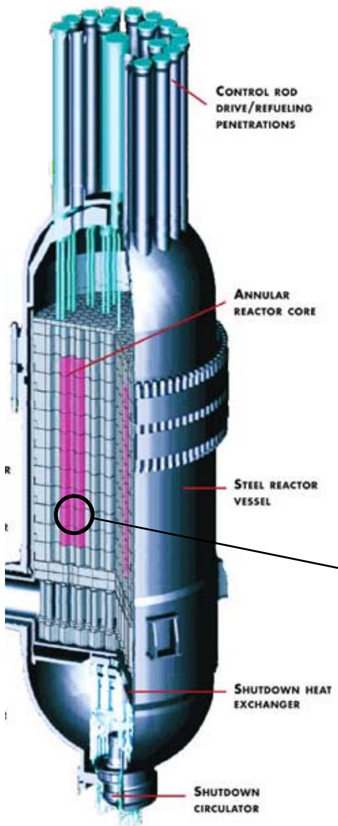
- Low core power density, inert single-phase coolant, highly self-limiting nuclear feedback characteristics: very high levels of safety

- High gas temperatures provide good thermal efficiency and allow use of direct-cycle gas turbines

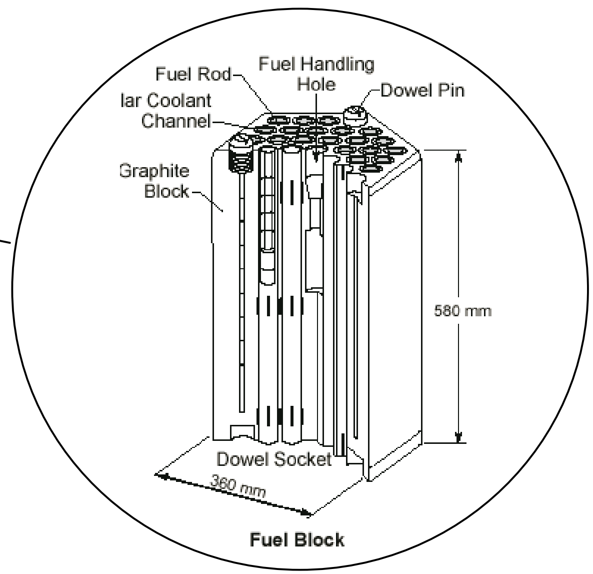


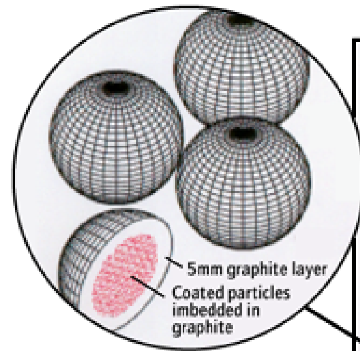
- High temperatures offer several alternative (non-electricity) applications, e.g. manufacture of hydrogen.

Blocks versus Pebbles

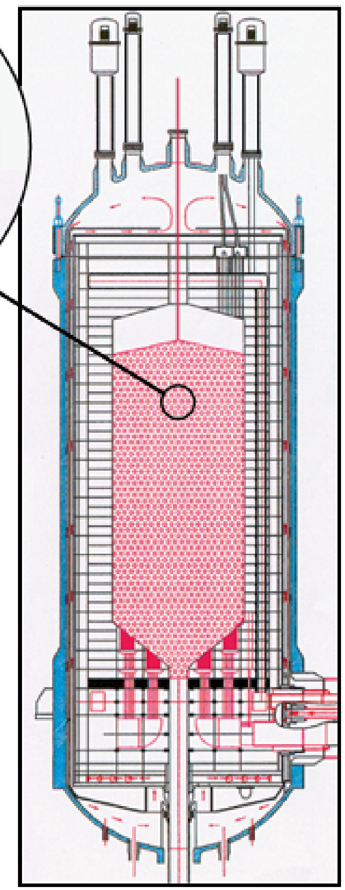


Prismatic (block) core





Pebble-bed core



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Pebble bed vs. Prismatic cores

Pebble-Bed	Prismatic
On-line refuelling	Batch refuelling
No large excess reactivity	Burnable absorbers required
Fuel can be drained from core	No uncertainty in fuel position
No kernel migration	Individual identification of fuel
Good geometric stability	Fuel is load-bearing and may distort
Rapid discharge of defective fuel	Reduced possibility of handling damage
Control rods in reflector	In-core control rods

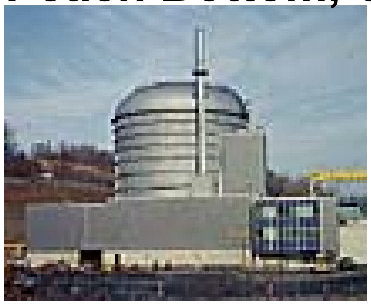
Experimental HTRs

- First operational HTR was the DRAGON
  - OECD DRAGON project began in 1959
  - 20 MWt reactor operated at Winfrith from 1966-1976
  - prismatic core design (block fuel)
  - 750°C helium outlet temperature
  - coated particle concept developed at Harwell / RAeE
- Dragon was followed by Peach Bottom, USA (67-74)
- AVR at Jülich, Germany ('68-'89) - the first pebble-bed design

⇨ **All experimental reactors showed remarkably good performance (AVR ran for 21 years!)**

DRAGON, UK

Peach Bottom, USA



AVR, Germany

Early commercial prototypes

Fort St Vrain (Colorado, USA)

- 330 MWe station designed by General Atomics
- prismatic core (block fuel) with secondary steam-circuit
- operated intermittently from 1979 - 1989
- many technical difficulties (leakage from water-lubricated bearings, high helium bypass flows...)

THTR (Uentrop-Schmehausen, Germany)

- 300 MWe HTR designed by HRB (ABB-Reaktor)
- pebble-bed design, with secondary steam-circuit
- operated from 1985-89
- some operating problems
- closed for political and economic reasons (post-Chernobyl era, dominance of light-water reactors)

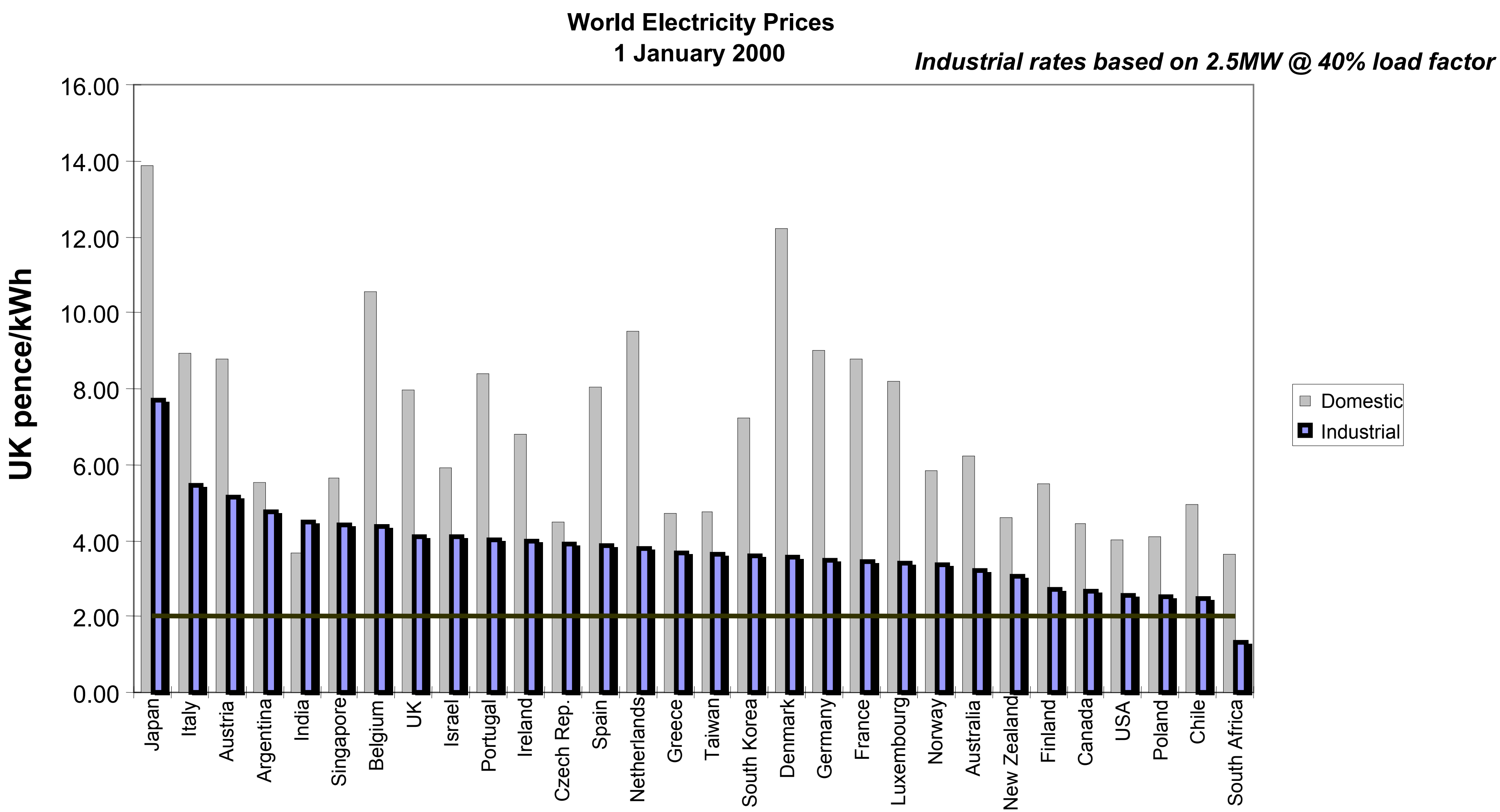
Why did the early HTRs not succeed?

Experimental reactors worked exceptionally well, but ...

- Prototype systems suffered from technical difficulties (especially Fort St Vrain)
- Large core structures required costly on-site construction
- No single dominant design
- Dominant position of Light Water Reactors based on US designs
- Adverse public opinion in Germany post-Chernobyl

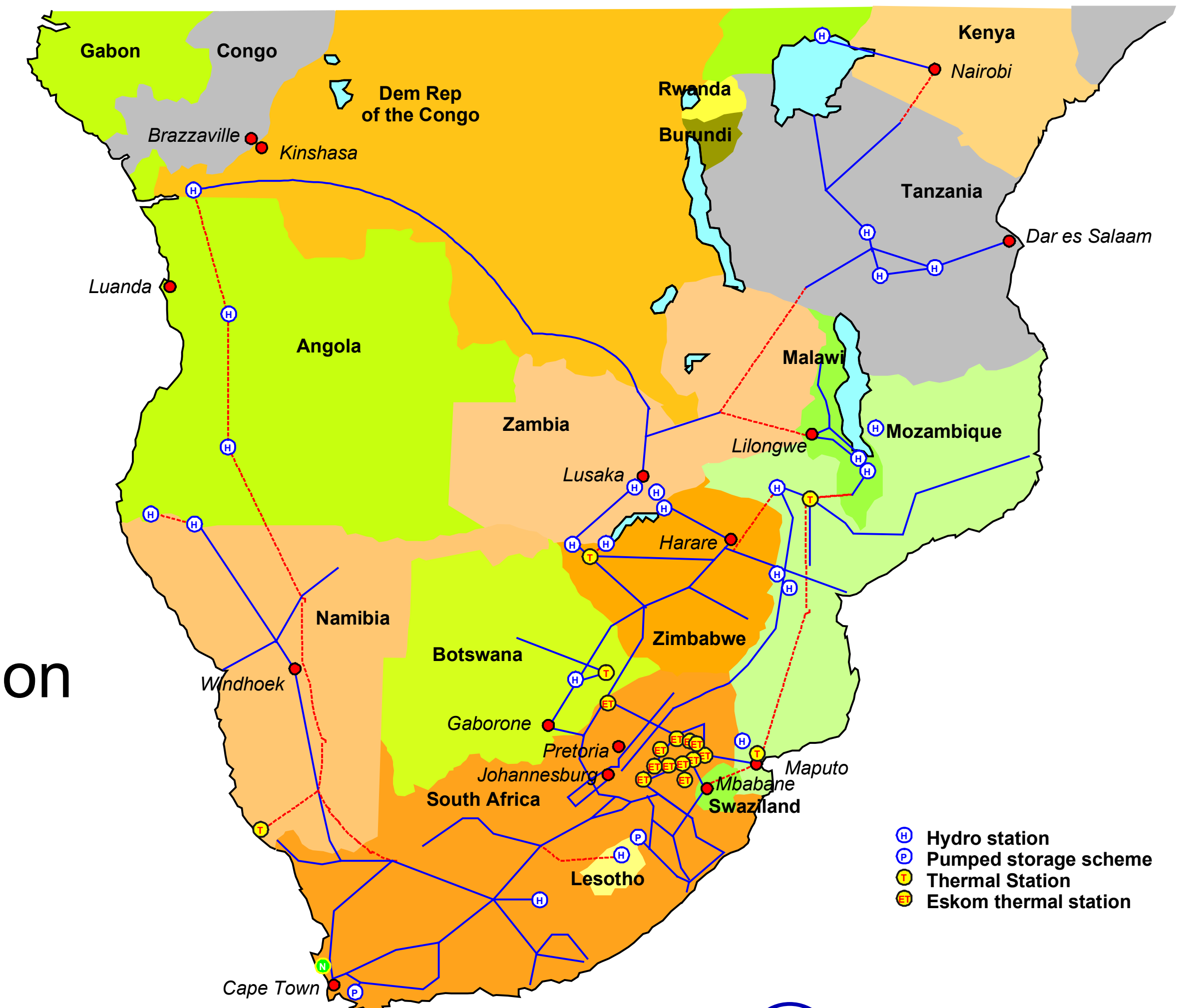
South African interest in HTRs ….

World electricity prices



Distribution of current capacity in southern Africa

- Capacity dominated by large coal-fired stations close to pit heads
- Poor quality coal
- High costs of coal transportation
- Limited transmission system / high transmission losses
- Need to serve remote communities



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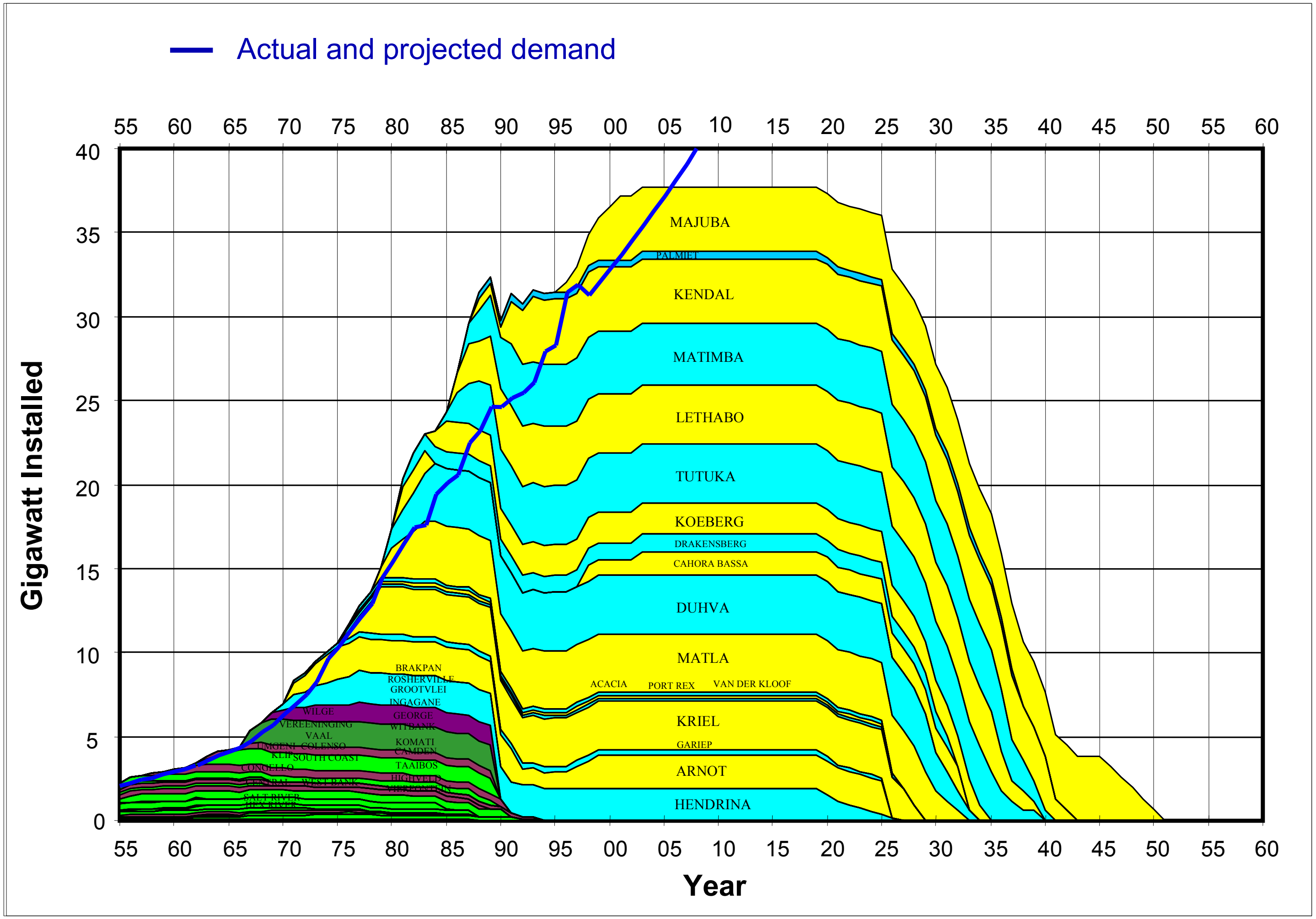
ESKOM installed capacity vs. demand



ESKOM requirements for new capacity

Comprehensive review of options conducted in early 1990s

- Competitive Economics (with Eskom coal stations)
- Distributed Generation (away from coal fields - small units)
- Short Lead Times (reduce risk / capacity mismatch)
- Load/Frequency Following (increased domestic loads)
- Reduced Environmental Impact (low/no emissions)

Review parameters favoured nuclear plant, but required:

- Economic performance
- Demonstrated Technology
- “Walk Away” Safety

ESKOM targets for new nuclear capacity

• Sent-out power	150-200 MWe per module
• Continuous stable power range	15-100%
• Ramp rate (0-100%)	10%/min
• Load Rejection w/o trip	100%
• Cost Target	$1000 / kWe
• Construction Target	24 months
• General Overhauls	30 days per 6 years
• Emergency Planning Zone	< 400 meters
• Plant Operating Life Time	40 years +
• Design Aircraft Impact (to survive)	Boeing 747 / 777
• Seismic requirement	0.4 g

Why the Pebble Bed reactor?

- Need for low fuel costs / avoidance of fuel transport favoured nuclear
- Current generation light-water reactors too large for SA grid (typically > 1000MWe), and seen as too expensive
- Small, modular reactor with passive safety seemed ideal → **HTRs**
- Pebble-bed technology selected because:
  - seen as most technically-successful HTR design
  - excellent and consistent performance from NUKEM fuel
  - modular designs in existence (from ABB and Siemens)
  - remaining expertise in German engineering and research facilities

Key strategies for the PBMR

- Standardisation
  - Minimise engineering cost for multi-region implementation
  - Establish common international licensing ‘norms’
- Small size
  - Shorten construction period (repetition in ≤ 6 months)
  - Maximise learning curve benefits
  - Facilitate inherent safety features (passive heat removal etc.)
- Simplification
  - facilitate inherent safety
  - simplify operation and maintenance

ESKOM's way forward

- Establish a separate design team (~100 personnel) as a sub-division of ESKOM Enterprises
- Conduct an initial feasibility study for ESKOM review and as a basis for discussions with potential investors
- Promote the concept within RSA and seek (informal) Government backing
- Seek international investment partners, ideally with relevant nuclear and generation experience
- Establish a project aimed at construction of a demonstration plant in South Africa

The PBMR Project

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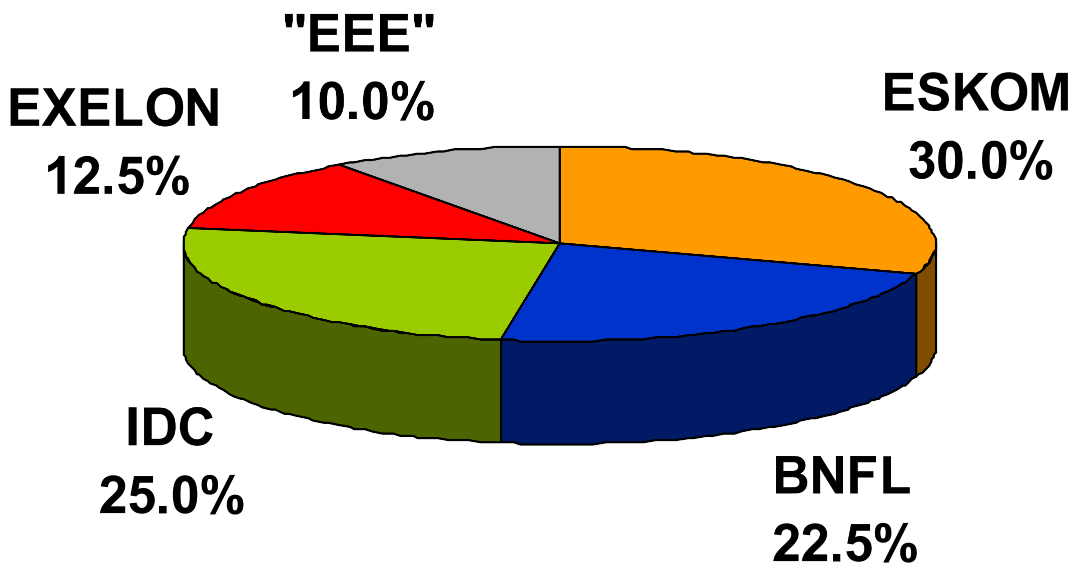
PBMR Detailed Feasibility Study

- Co-operation agreement signed between ESKOM, BNFL, EXELON, and IDC for a Detailed Feasibility Study (2000-2002)
- 10% is reserved for an Economic Empowerment Entity - currently held by ESKOM



PBMR project structure

- Design integration team based in Centurion, near Pretoria (including key personnel seconded from investors)
- Large design packages sub-contracted to major suppliers, e.g.
  - Mitsubishi Heavy Industries for turbines and generator
  - Westinghouse Reaktor (former ABB) for safety and control systems
- Fuel manufacturing technology team from Nuclear Energy Commission of South Africa (NECSA), based at Pelindaba

Project staff resources

• PBMR (including BNFL secondees)	280
• Sargent & Lundy / Murray & Roberts	40
• IST Nuclear	60
• MHI / Nukem / SGL / Westinghouse ...	90
• Eskom client office	30
TOTAL	~ 500

Total man-hours to date ~ 2,750,000

Total costs to date ~$150M

(~ $350M US equivalent)

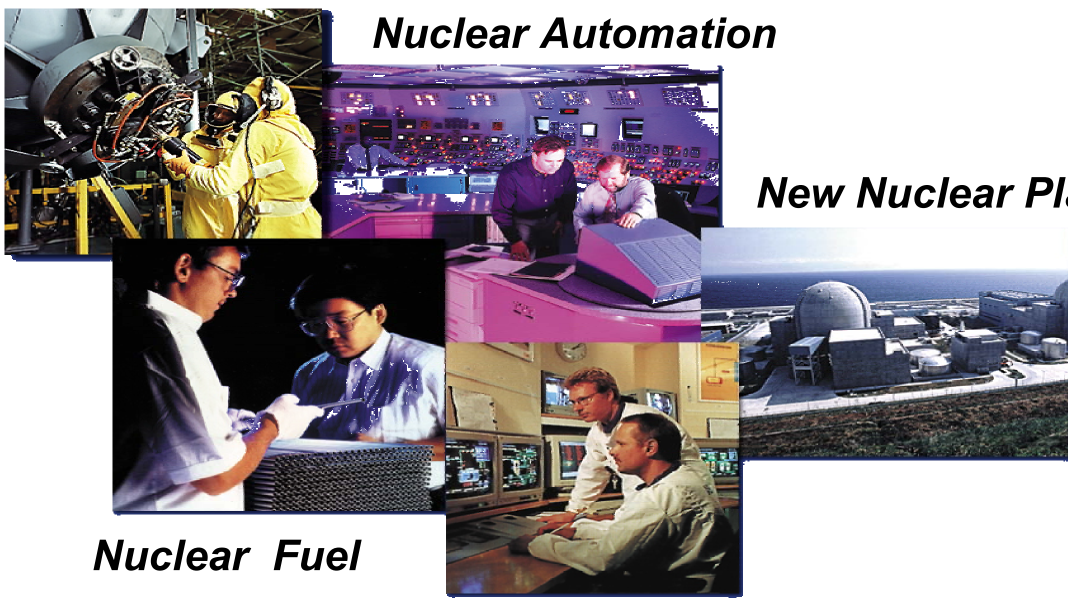
Project status

- Significant design enhancements over past 18 months to improve economics and reduce risk
- Design has converged to a more commercially viable plant from standpoint of economics, licensing and maintainability
- Detailed Feasibility phase and Business Plan completed: investors willing in principle to proceed (negotiations ongoing)
- South African Government review underway now to recommend best project configuration. Many options being studied, including:
  - appropriate for ESKOM to remain as both “producer” and customer?
  - conduct RSA investment through NECSA?
- South African government appears committed to the project: announcement expected in the next few months

Commercial / economic issues
(BNFL perspective)

Rationale for BNFL interest in PBMR

- BNFL Group front-end services are provided by Westinghouse
- Currently supporting new build programmes in Japan and South Korea, based on large PWR systems
- Recognition that light water reactor technology is mature, and alternative technologies may offer advantages
- Recognition that large monolithic plants are not well suited to all markets



Nuclear Automation

Nuclear Services

New Nuclear Plants

Nuclear Fuel

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Electricity supply industry: a new outlook

- Long-term centralised planning of electricity supply has been replaced in many countries by **short-term market-driven** decisions
- **De-regulation** of the electricity supply industry has led to increased producer risk (no guaranteed market), and a collapse in unit prices
- Large, capital-intensive projects are difficult to sustain for independent generators needing to raise private capital (at least in Western markets)
- Generators driven towards small, step-wise increases in capacity to minimise capital-at-risk and time interval between investment and income

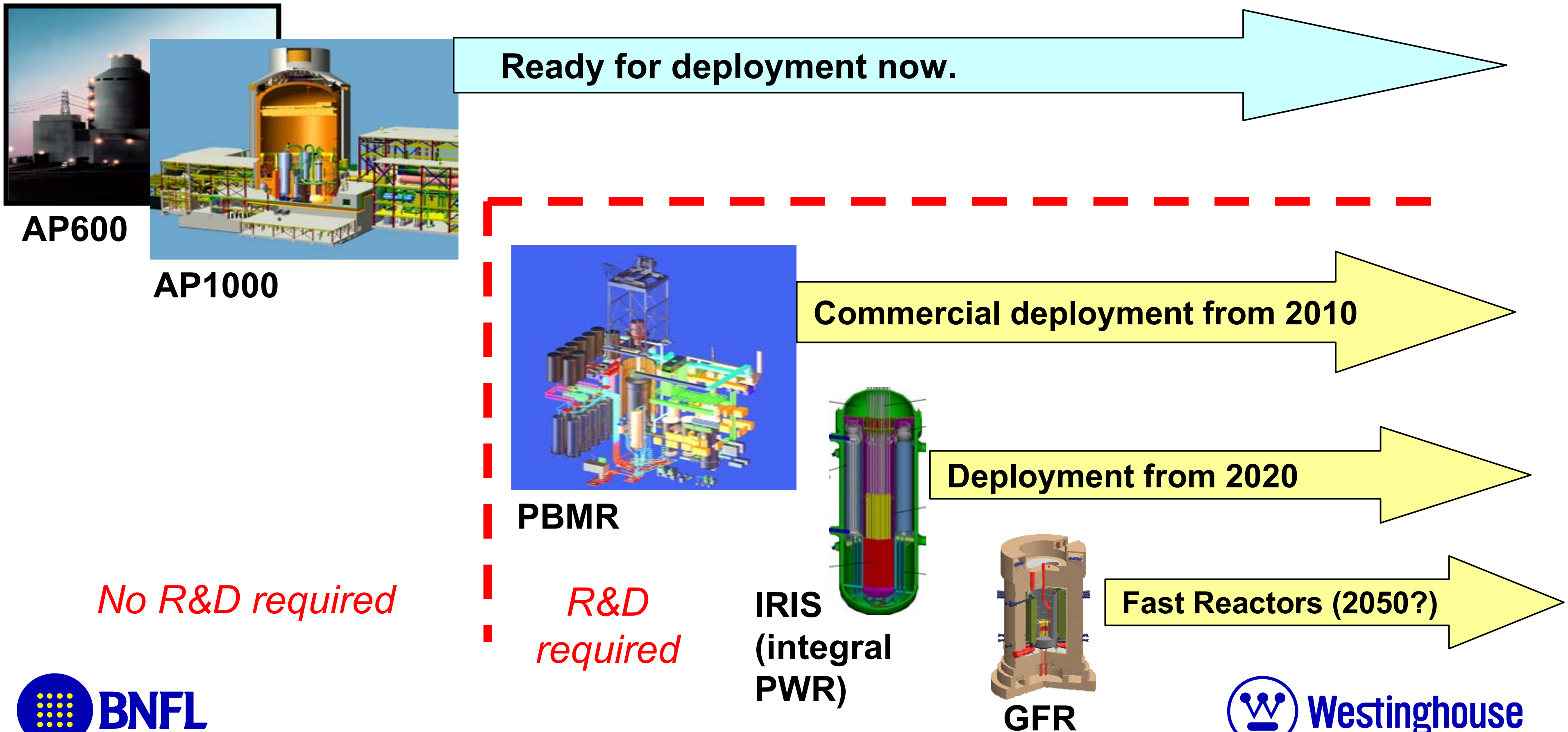
Key economic targets for new build

- First 'demonstration' unit will not be economically competitive because of 'one-off' First-of-a-Kind costs
- Must be able to show that series build can compete with lowest cost alternatives in potential markets
- Typical targets for Nth-of-a-Kind plants:
  - capital cost of around **$1000 per kWe**
  - production costs of around **3¢ per kW·h**

Projected costs for PBMR series build are consistent with these targets

BNFL portfolio of advanced nuclear systems

- BNFL Group reactor system portfolio covers a range of deployment time scales and system technologies



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PBMR Technology &
Safety Approach

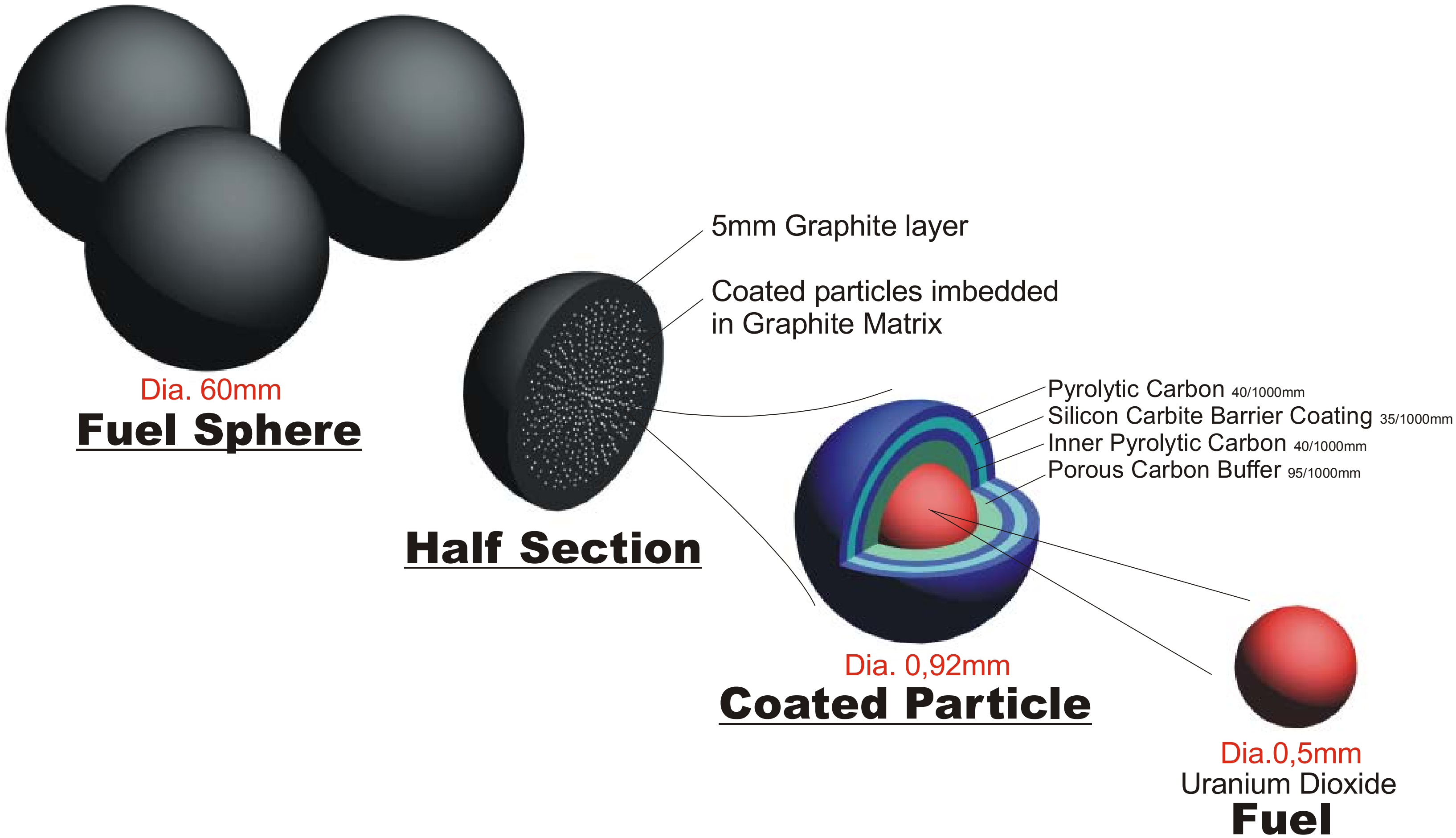
PBMR Technology

- PBMR is a small (nominal 400 MWt) modular pebble bed HTR
  - helium cooled, graphite moderated
  - direct cycle gas turbine - no secondary steam circuit
  - refractory core materials removes possibility of core melt accidents
  - high outlet temperature: 900°C
    - good thermal efficiency (~ 42%)
    - flexibility for alternative applications
  - high fuel average burnup (~ 80 GWd/tU initially, higher later)
  - very high degree of inherent safety
- Design based on ABB-THTR and HTR-100, and Siemens MODUL
- Direct cycle technology introduced by PBMR

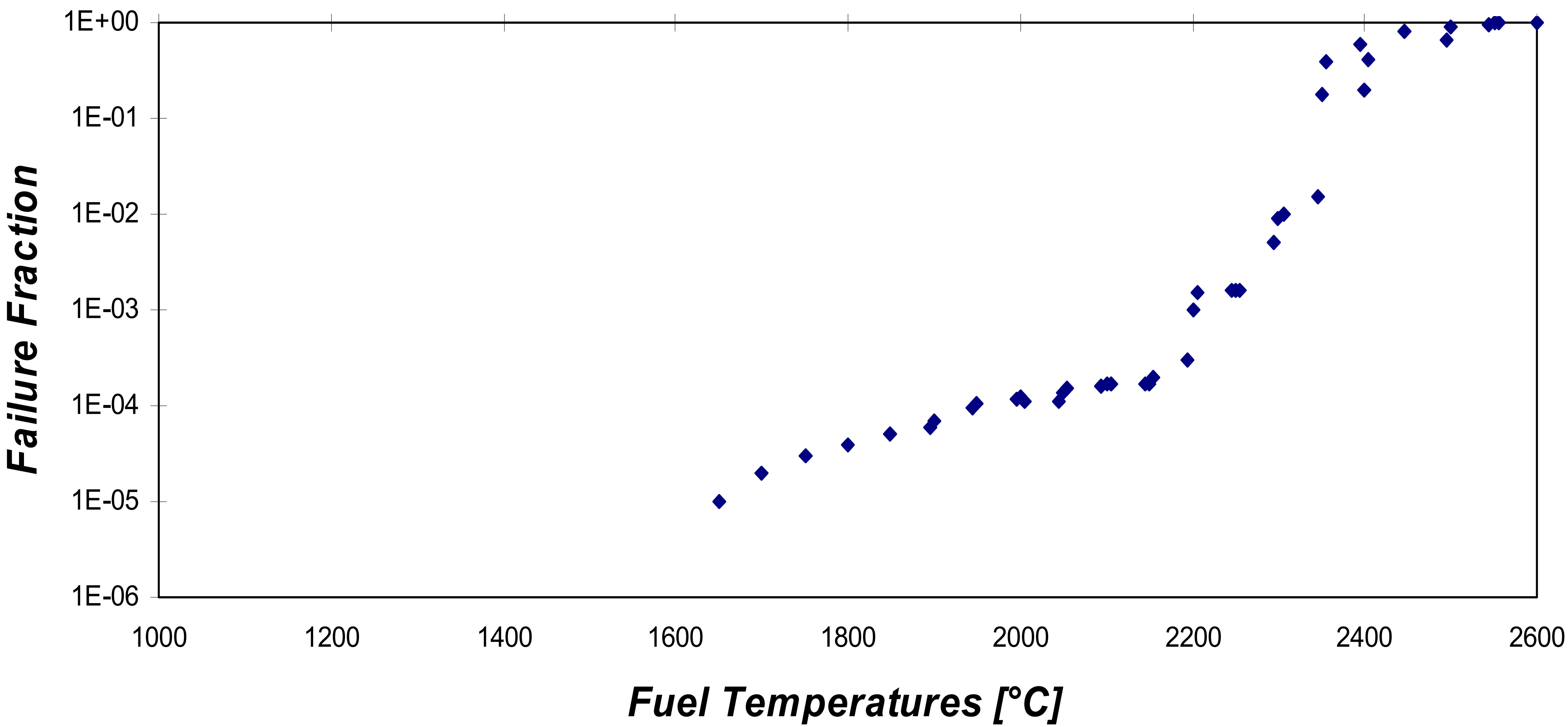
Comparison with previous HTR designs

	Dragon	Peach Bottom	AVR	Fort St. Vrain	THTR	HTR-Modul	PBMR
Country	UK	USA	Germany	USA	Germany	Germany	RSA
Operation	1966-1976	1967-1974	1967-1988	1976-1989	1985-1989	-	2010?
Fuel	Prismatic	Prismatic	Pebble	Prismatic	Pebble	Pebble	Pebble
Power (MWt)	20	115	46	842	750	200	400
Power Density (MW/m^3)	14	8.3	2.5	6.3	6.0	3.0	4.0
Gas Pressure (MPa)	2.0	2.4	1.1	4.8	4.0	6.0	9.0
Core Inlet Temp. (°C)	350	340	270	405	250	250	537
Core Outlet Temp. (°C)	750	725	950	785	750	700	900
Turbines	none	steam	steam	steam	steam	steam	Gas
RPV	steel	steel	steel	concrete	concrete	steel	Steel

PBMR fuel design



Fuel Performance



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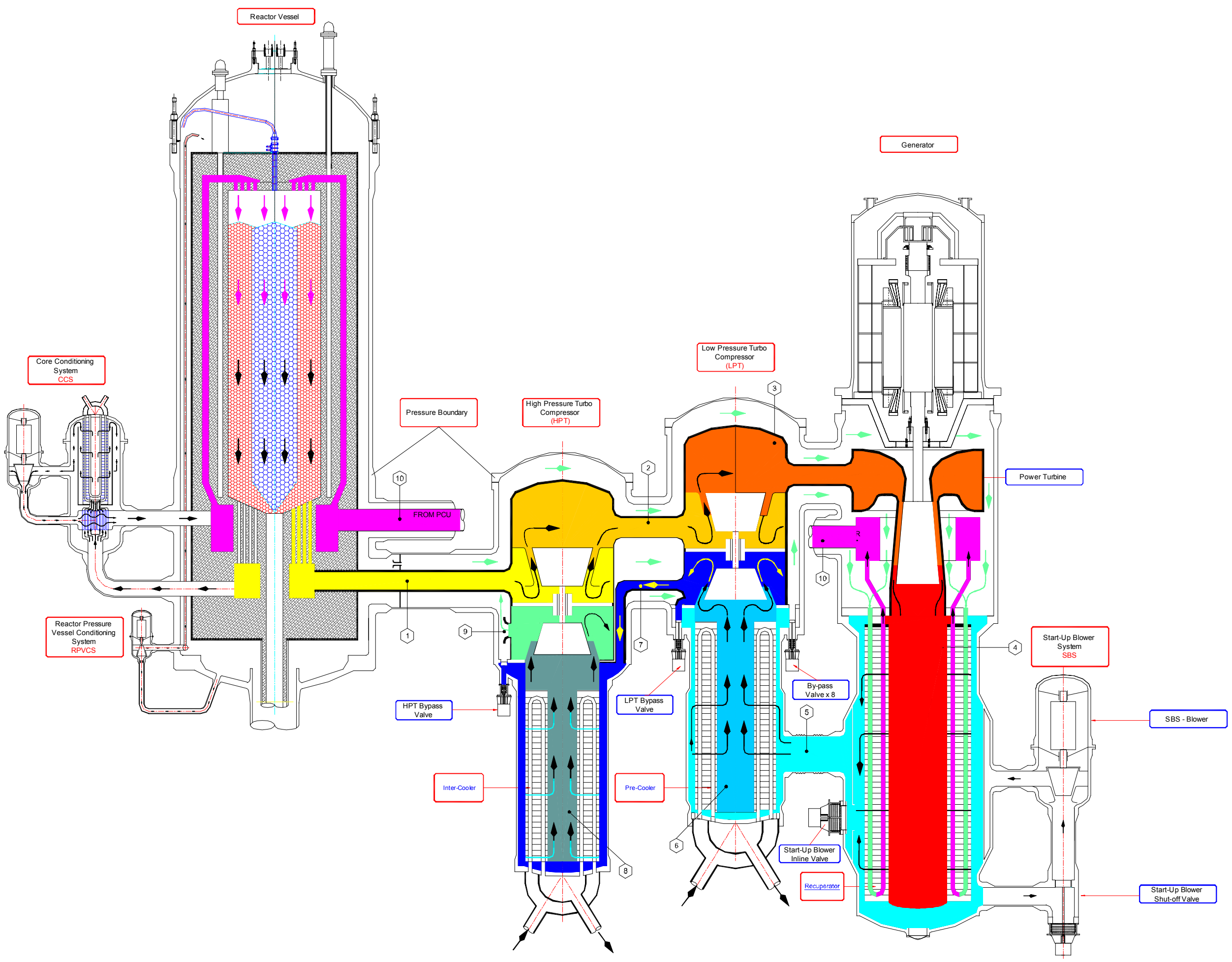
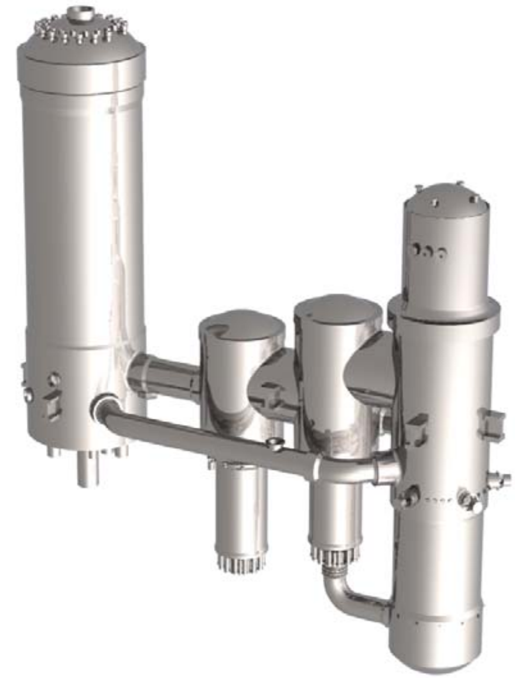
PBMR: circuit schematic





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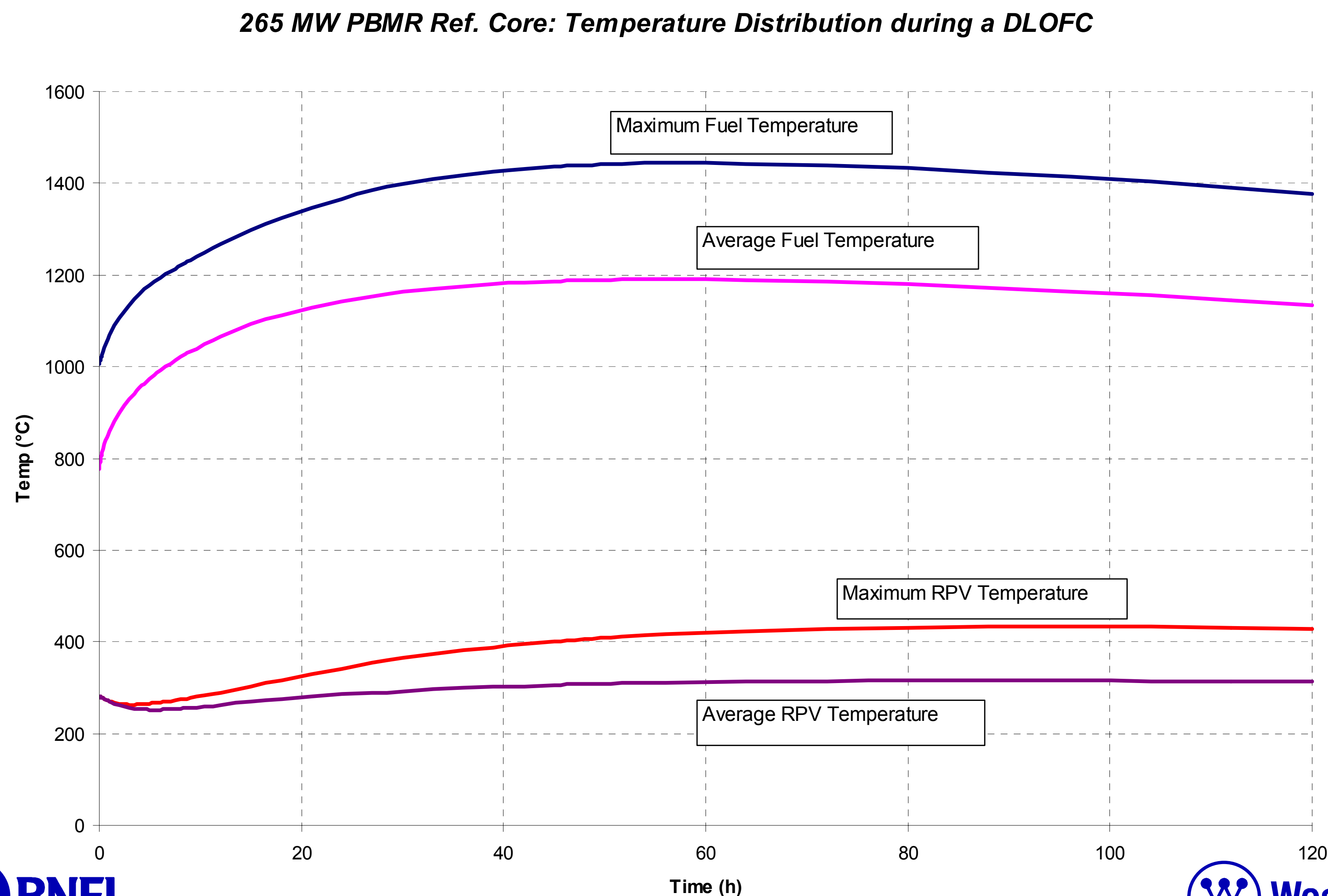
Loss of Coolant Event



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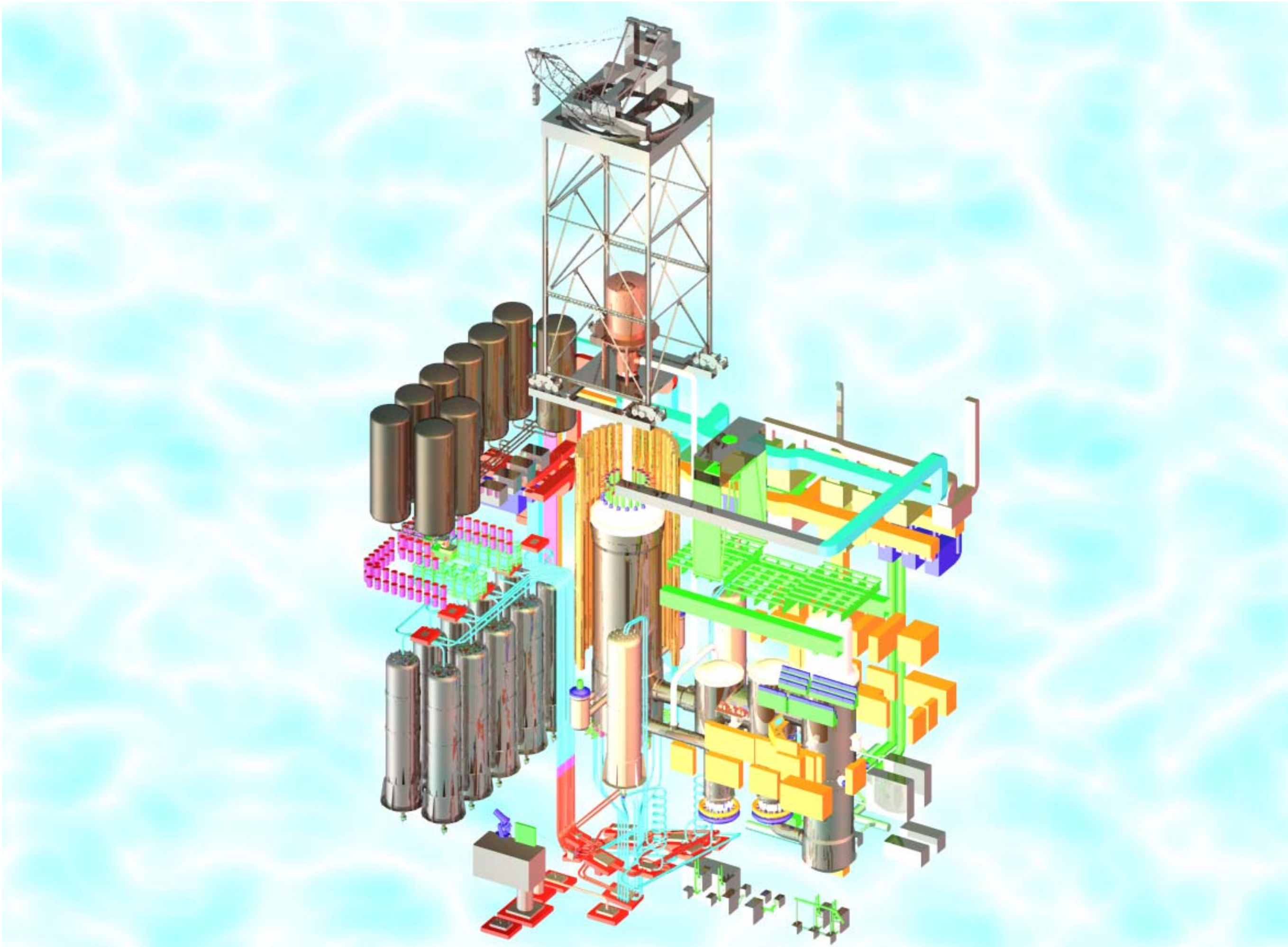
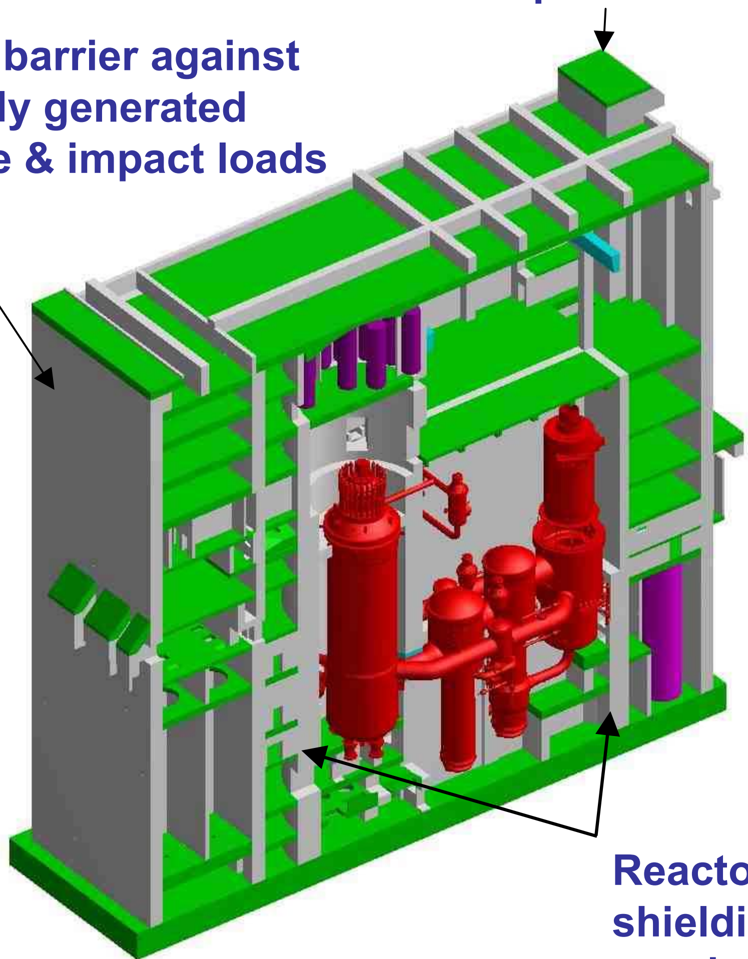
PBMR plant layout



Module building



Height total	62.9 m
Height above ground	40.9 m
Depth below ground	22 m
Width	37.0 m
Length	66.1 m
Levels (floors)	11
Material	40 MPa concrete
Seismic acceleration	0.4 g Horizontal

Aircraft crash:

(a) < 2.7 ton - no penetration;

(b) Limiting case (777):

predicted to penetrate outside barrier but not reactor cavity:

nuclear safety not compromised

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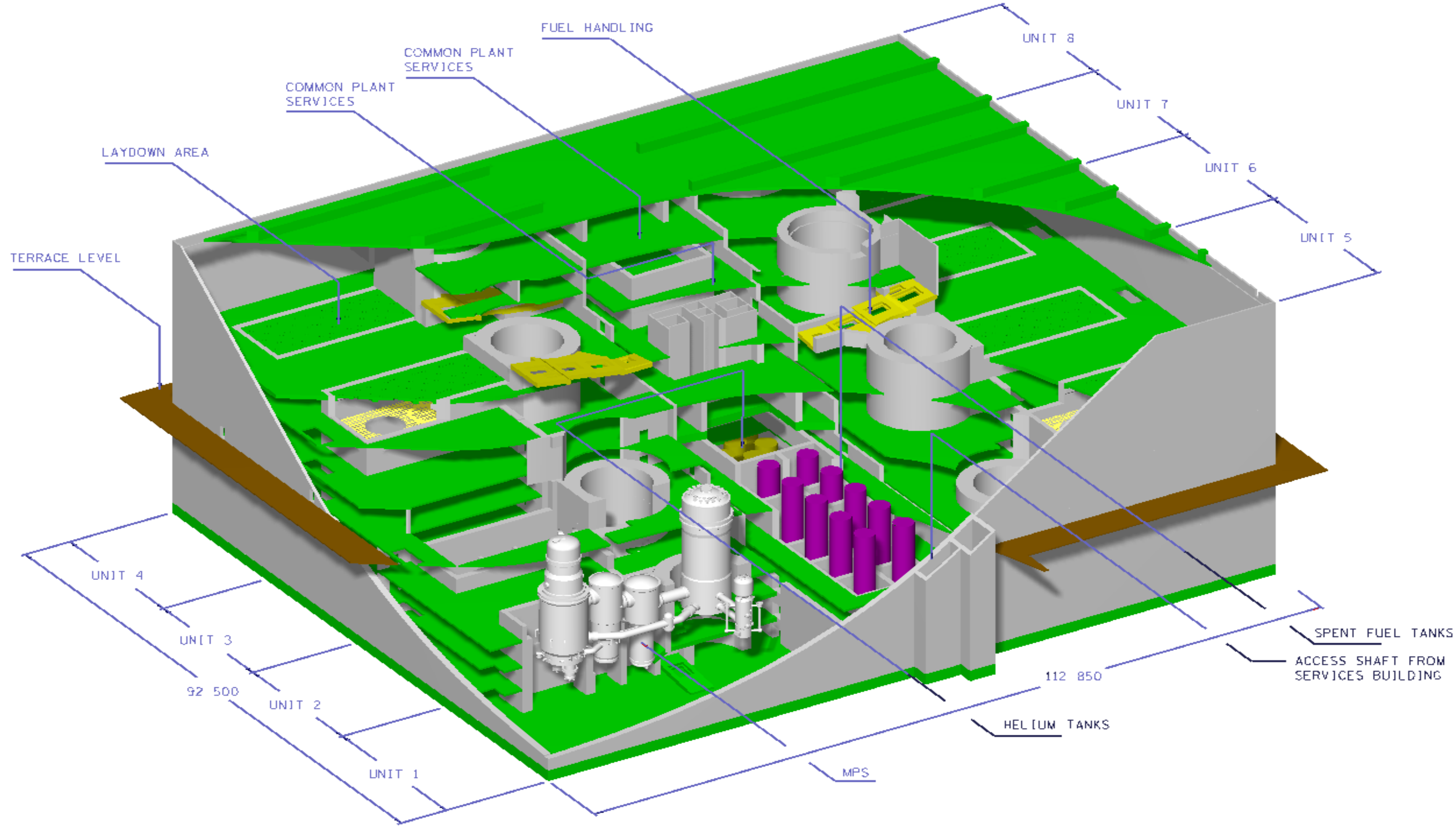
PBMR multi-module site



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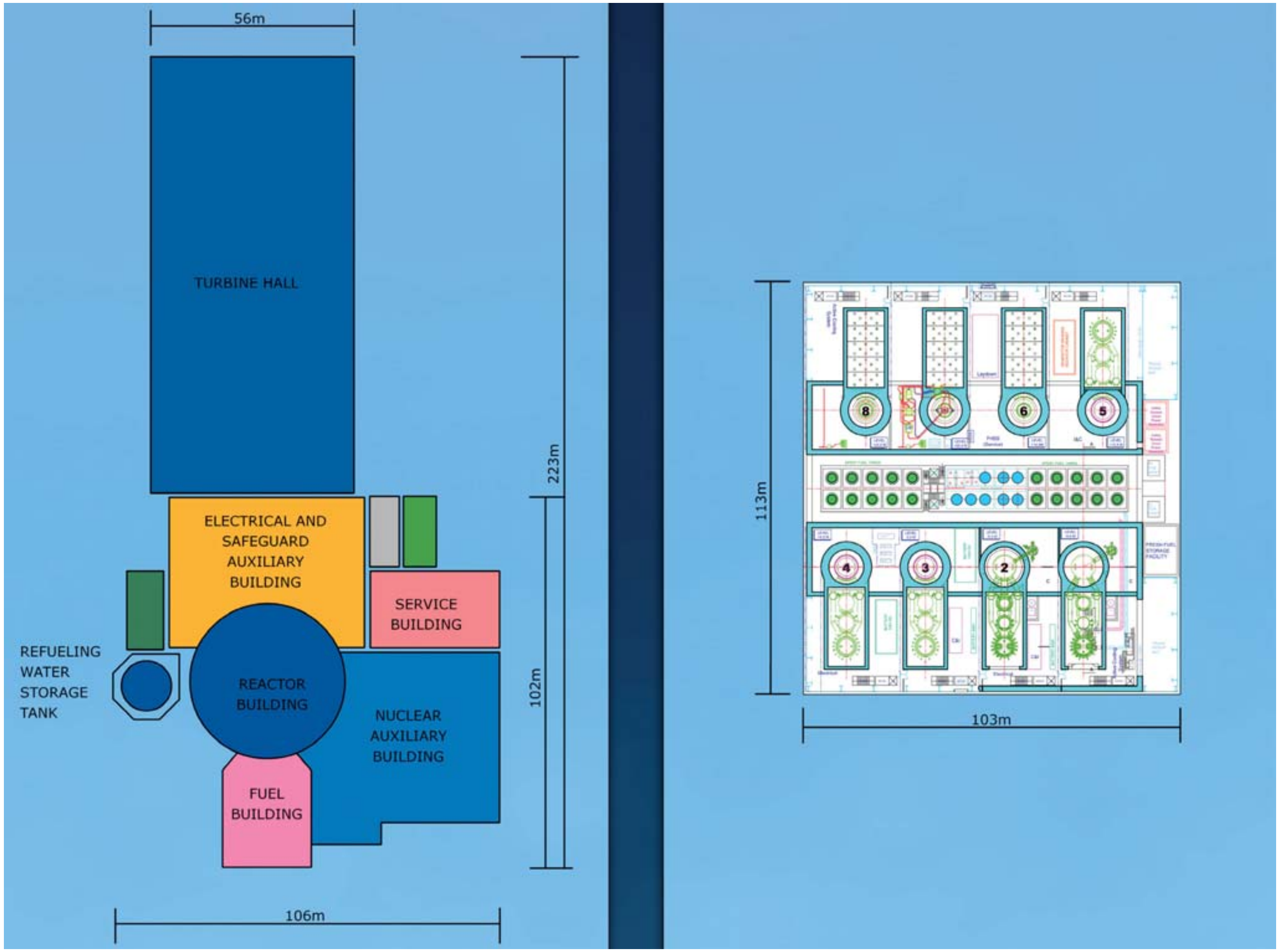
PWR and PBMR power station footprints

Typical PWR

1400 MWe



PBMR

1320 MWe Power Plant

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Summary of PBMR advantages

- **Safety**
  - can withstand very high temperatures (1600°C) without core or fuel degradation
  - strongly negative reactivity temperature coeff.
- **Economics**
  - elimination of secondary circuit, fewer safety grade components, and modular design/ factory-fabricated units all reduce capital cost
  - generating costs competitive with CCGT
- **Proliferation resistance**
  - highly stable fuel form - very difficult to recover fissile material
  - fuel is very well suited to long-term storage/ direct disposal in sub-surface vaults
- **Flexibility**
  - small, modular units (400 MWt / 170 MWe)
  - suitable for electricity production and high temperature process heat

PBMR Technology Development Status

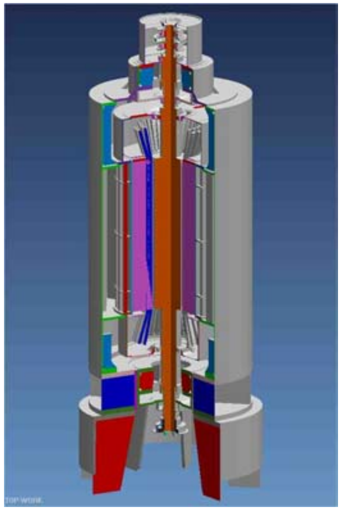
Key developments over last 18 months

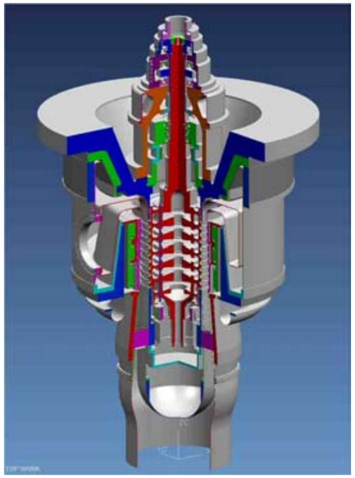
- Power turbine-generator
- Reactor core structures
- System integration
- Operation and maintenance
- Constructability
- Licensing (both in South Africa and Overseas)
- Materials properties (especially graphite)

Current status of technology issues: turbo-machinery

- Original submerged generator replaced with an external generator with a shaft seal - eliminates carbon dust problems and simplifies maintenance
- Replacement of electro-magnetic ‘catcher’ bearings with standard oil-lubricated thrust bearings: reduced technology risk and allows multiple run-down capability

TOTAL SHAFT LENGTH AND MASS	20.1 m / 88 t
GENERATOR	
Coolant	Air
Height (Inlet to Top)	17.2 m
Mass	326 t
Power output (50 Hz)	180 MW , 11kV
TURBINE	
Medium	Helium
Height (Inlet to Outlet)	4.4 m
Tip Dia. (typical)	2.1 m
Mass	338 t
Speed	3000 rpm
Stages	10
Efficiency	93.5%
Mass flow	194 kg/s





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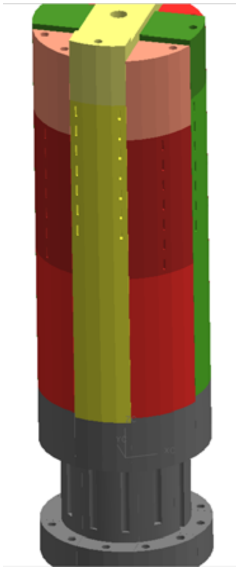
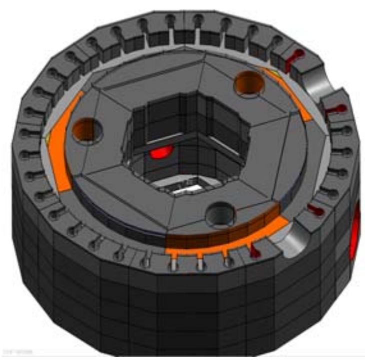
Current status of technology issues: reactor core structures

- Original design for core internal structures considered to require significant re-design
- PBMR Co undertaking re-design, assisted by consultants and Westinghouse Reaktor
- Key changes:
  - solid central reflector
  - increased size to accommodate new reference power level: 3.7 m ID x 10 m effective height
  - replaceable inner reflector
  - austenitic SS core barrel
  - CFC straps for core restraint
  - inlet plenum located in core support structure



Solid central column



New bottom reflector with 3 120° de-fuel chutes

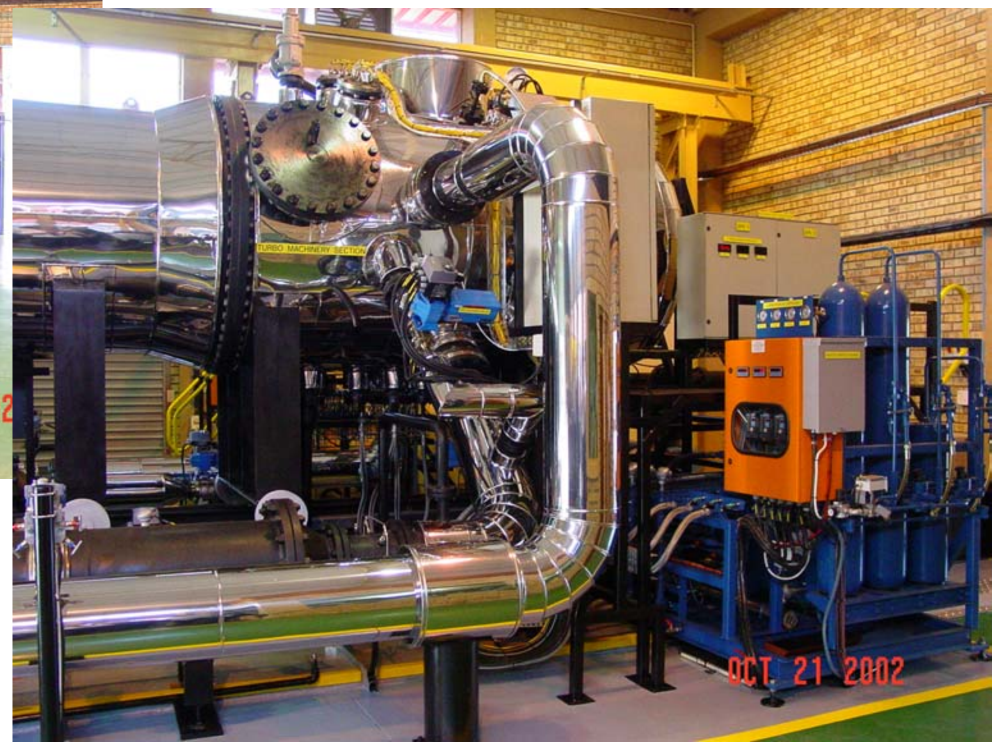
Testing programme

• Code Validation	
– Critical Core Test Facility	ASTRA (Moscow)
– Micro Turbine Model	Potchefstroom University
• Equipment Test Rigs	IST (and Gamma-Metrics)
• Fuel Manufacturing Equipment	NECSA (Pelindaba)
• Helium Test Loop	NECSA
• Fuel Qualification and Testing	
– First core	NIKIET (Russia)
– Longer-term	SAFARI (Pelindaba)

PBMR micro-model at Potchefstroom University

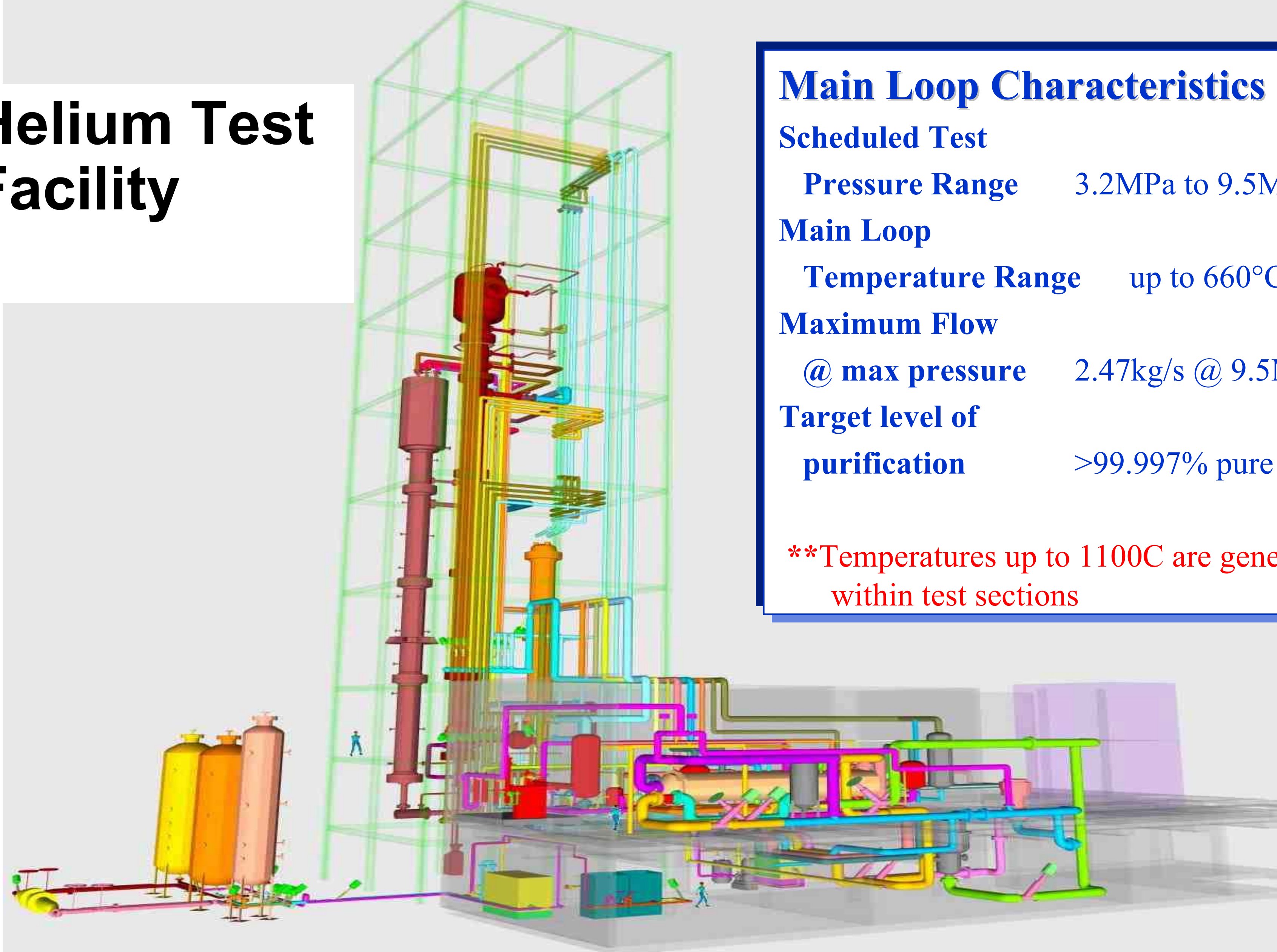
Operation of the PBMR micro-model has demonstrated the stable operating characteristics and control system for a 3-shaft Brayton cycle

Heater section



Turbo-machinery Section

Helium Test Facility



Main Loop Characteristics

Scheduled Test	
Pressure Range	3.2MPa to 9.5MPa
Main Loop	
Temperature Range	up to 660°C**
Maximum Flow	
@ max pressure	2.47kg/s @ 9.5MPa
Target level of	
purification	>99.997% pure He

**Temperatures up to 1100C are generated within test sections

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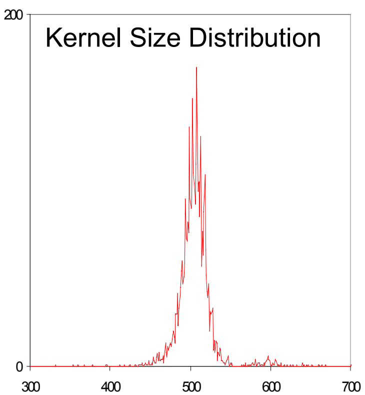
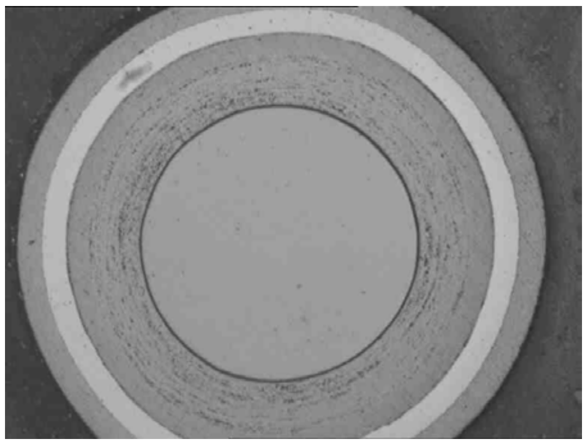
Fuel manufacturing labs at Palindaba



Kernel Casting



Particle Coating

Pebble Pressing

Other Systems and Components Testing

Gas Valve Actuation

T/G Dry Gas Seal

Turbo Machinery

Fuel Handling System

Heat Transfer

Air Ingress

Status of licensing in South Africa

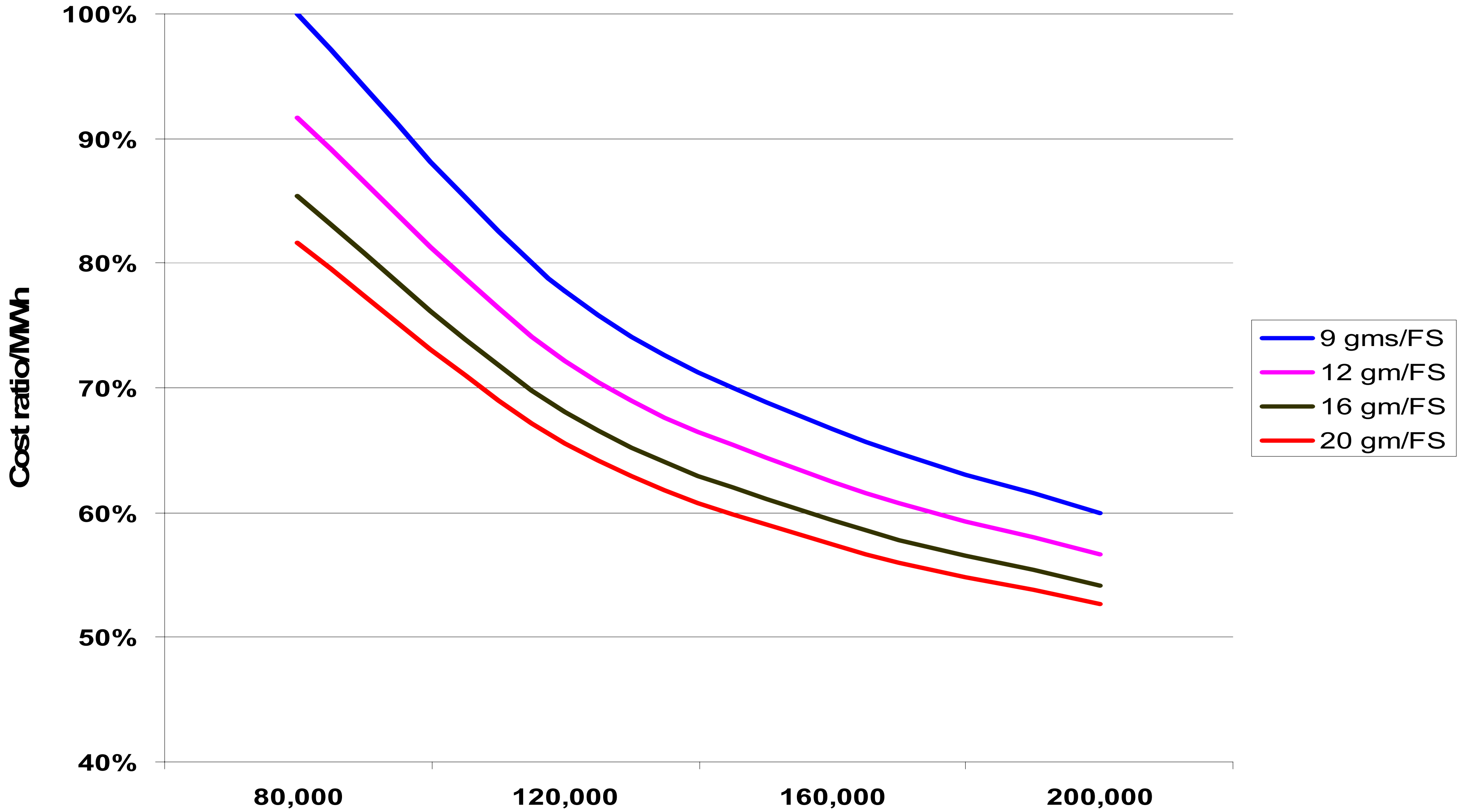
- Agreed licensing process, scope of submittals and schedule
- Agreed list of key licensing issues and strategy to address
- Safety Analysis Report Rev 1 submitted to NNR on 5 December 2001
- Formal questions from NNR on SAR Rev 1 issued and all responses submitted to NNR in November 2002
- Environmental Impact Assessment (EIA) Record of Decision (RoD) issued mid-2003 - positive outcome
- NNR Summary Progress Report on PBMR Licensing Process issued March 2003
- SAR Rev 2 submittal issued at the end of 2003

US Licensing Status

- NRC agreement on proposed approach
- Phase 1 of the Regulatory Guidance Review completed
- Fuel Test and Qualifications program progressed
- US Licensability Assessment completed
- Pre-application activities by Exelon documented; ready for reactivation
- Multiple Module Reactor Issues responded to by NRC
- Non-LWR issues and workshops continuing
- NRC Pre-application review to start in 2004
- Start of Design Certification planned for 2006; completion after startup of the Demonstration reactor

Future Developments

Impact of burnup/enrichment and U-loading per fuel sphere on fuel cost per MW.h



(~8.3%)

(~17%)

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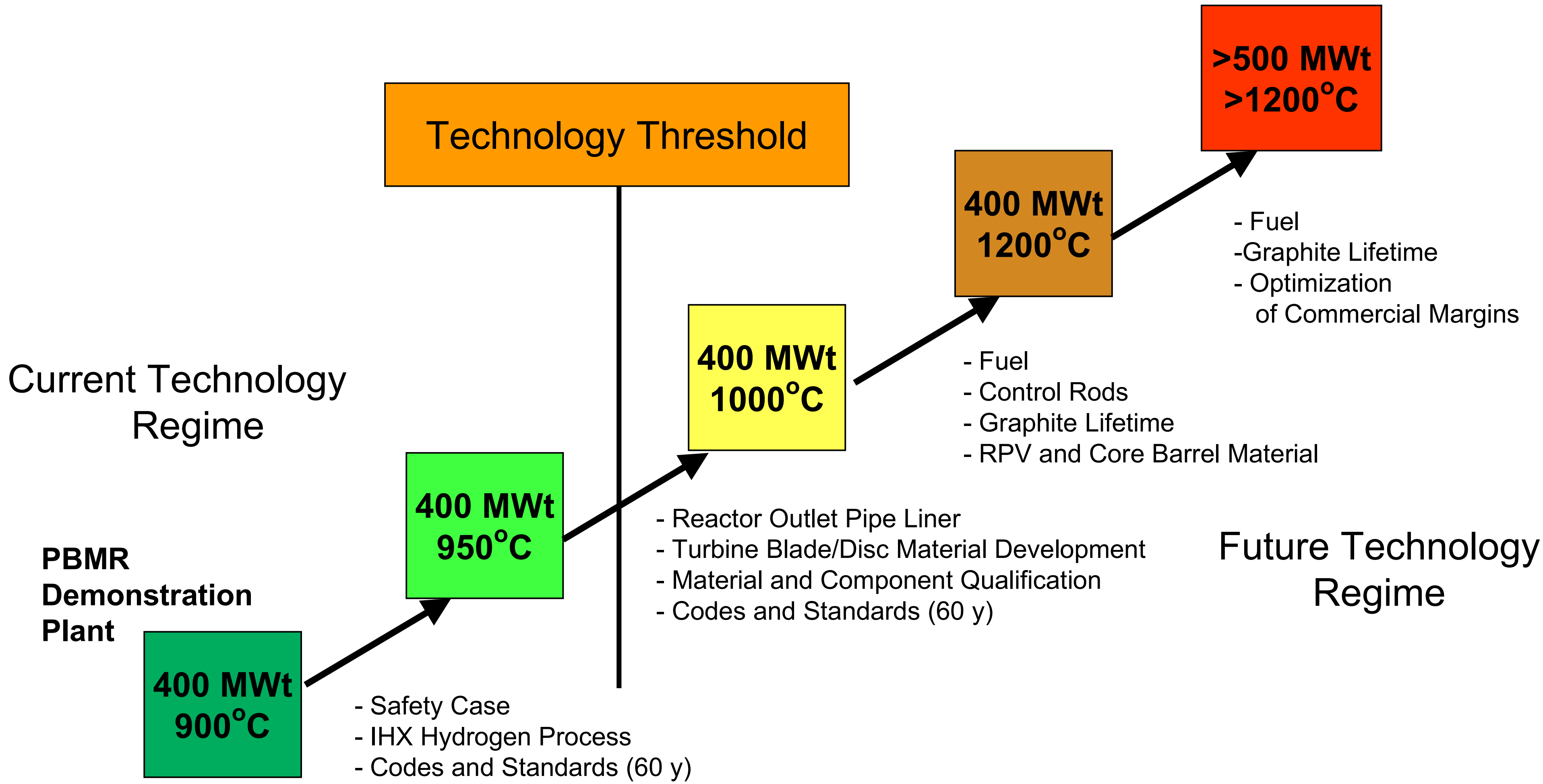
Future development path



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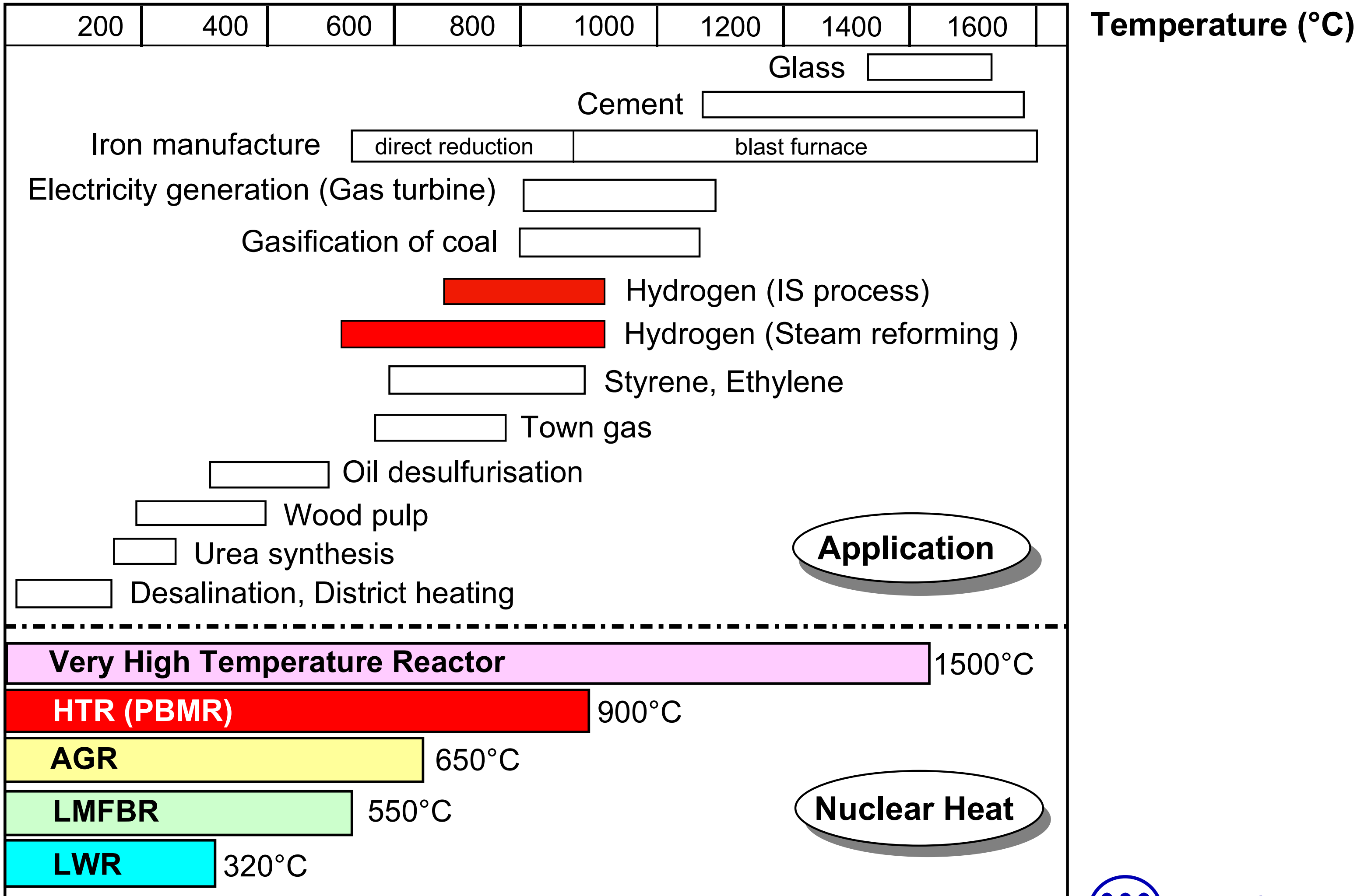
Future Prospects:
Alternative Applications

Alternative applications

Although modular HTRs offer good prospects for electricity generation, their high temperatures allow alternative and/or complimentary applications:

- Heat applications
  - **Hydrogen production**
  - Industrial process heat
  - District heating
- Management of nuclear materials (e.g. Pu)

Heat applications & temperatures



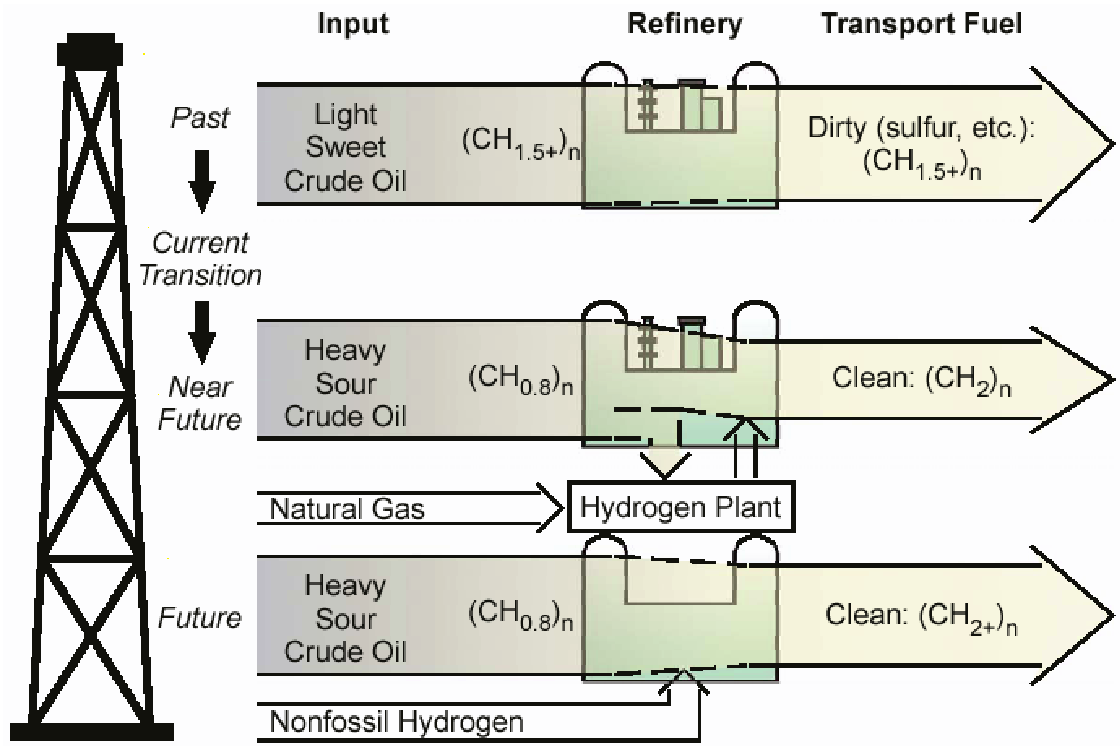
Hydrogen overview

Hydrogen has several advantages as an energy carrier:

- It can release energy with minimal pollution: the only by-product of combustion is water.
- It can produce both heat and electricity (in fuel cells).
- It can transfer more energy per unit mass than fossil fuels.
- It is readily transported by pipelines, and can be converted to forms suitable for storage.
- Nuclear power offers the almost unique position of large-scale, reliable hydrogen production with near-zero emissions

Applications for hydrogen

- Current world production: 50 million tonnes / annum: forecast to grow at 5-10% /year
- Current major use is in ammonia production
- Largest rate of growth in consumption is in the oil industry (cracking and pre-treating of reformer feeds)
- Estimated that in 10-20 years, energy used to produce hydrogen in the US may exceed current nuclear energy production



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Current and future production routes

CO_2 from process and heat source

Fossil-fired steam reformation of methane

(97%)

Electrolysis (3%)

development

Steam reformation with nuclear heat
(reduced CO_2 emissions)

High temperature electrolysis
(zero emissions with nuclear)

Thermo-chemical water splitting
(zero emissions with nuclear)

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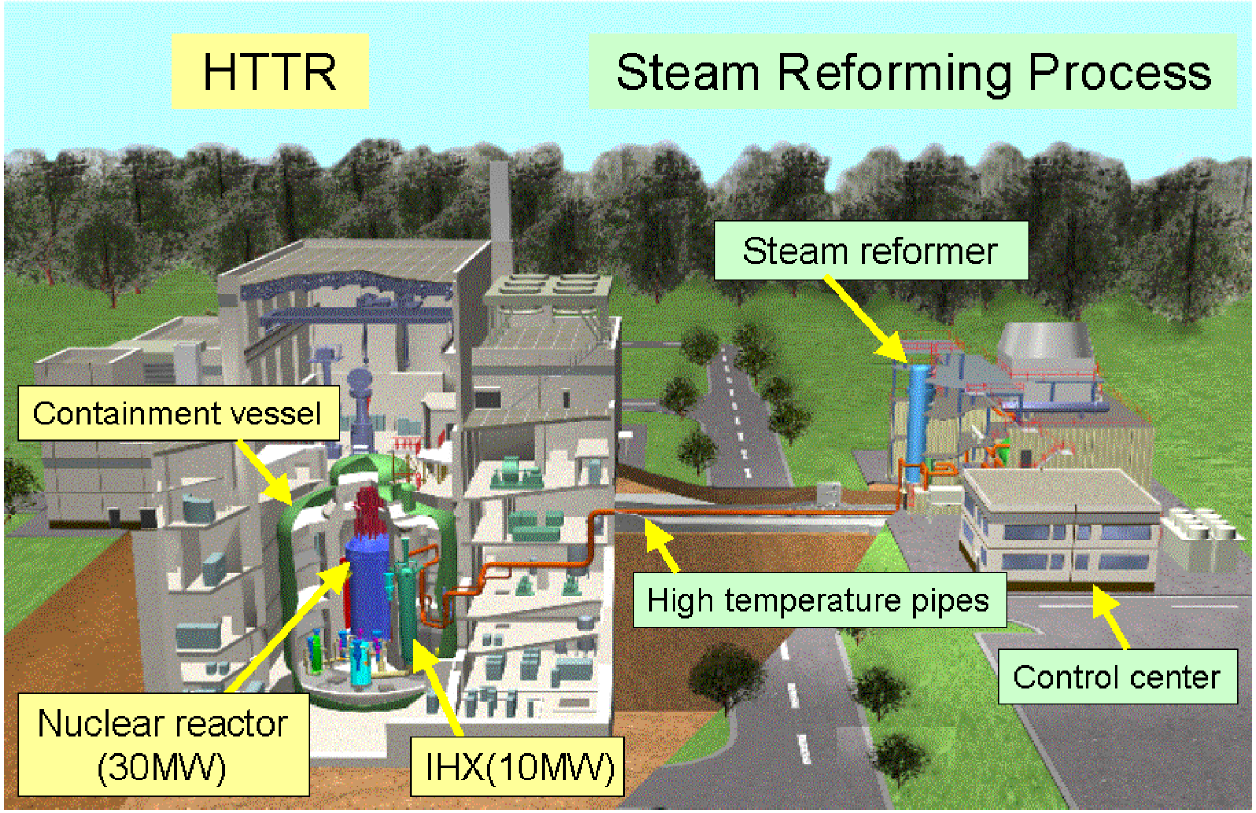
Hydrogen production by electrolysis

- Currently produces around 3% of annual consumption
- High cost due to electrical demand; used only for high purity H_2
- Suitable for over-night production using low-cost base-load nuclear electricity
- AECL have investigated siting of reactors close to US border:
  - sale of electricity to USA during the day
  - hydrogen production by electrolysis at off-peak hours
- High temperature electrolysis could significantly improve efficiency, but R&D required

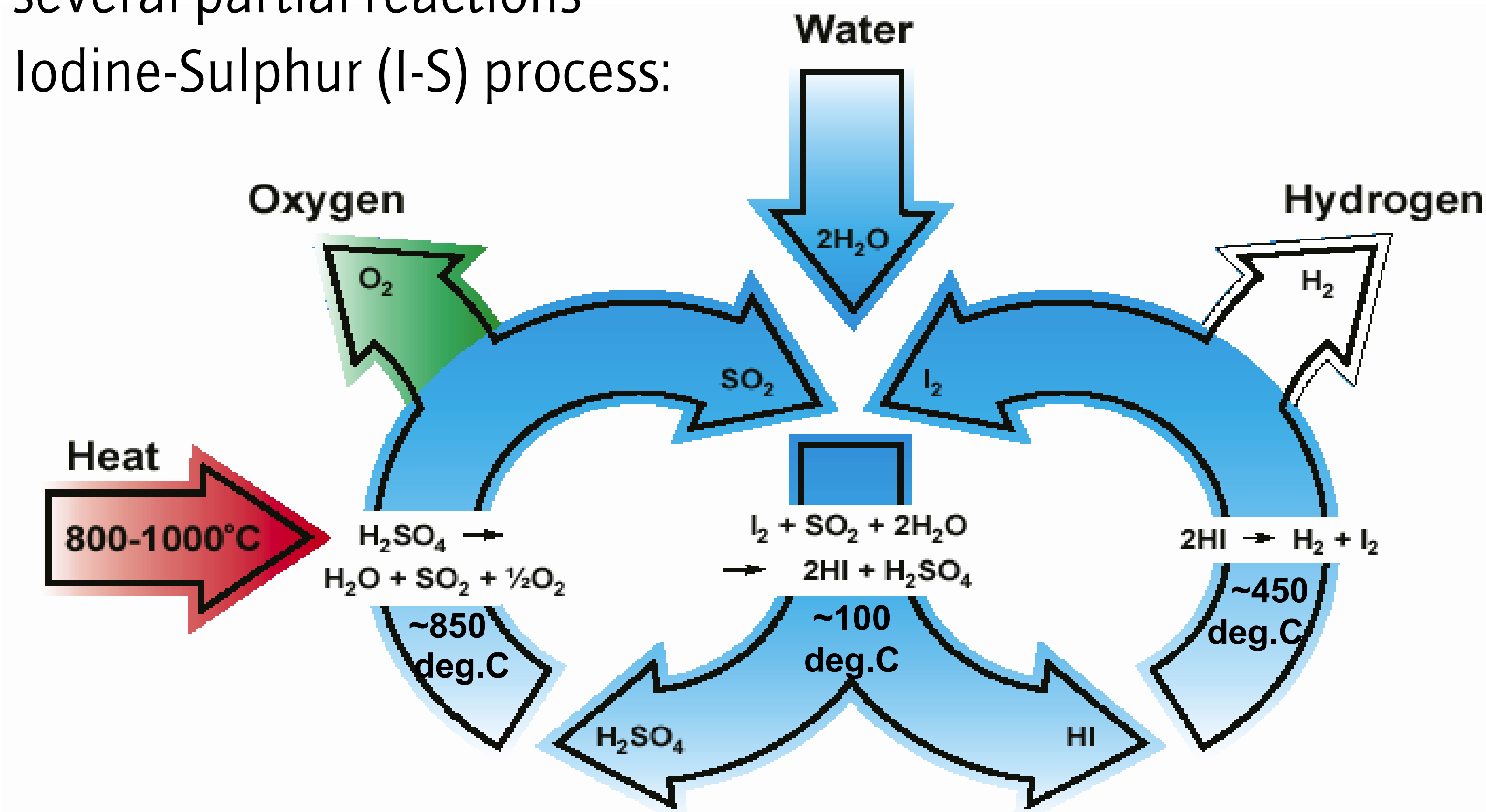
Hydrogen production by steam reformation

- Most hydrogen is currently produced by steam reforming of methane (using heat from fossil fuels)
- Requires heat at >750ºC (typically around 900 ºC)
- Produces CO_2 as a by-product
- JAERI propose a demonstration of nuclear steam reforming circa. 2008



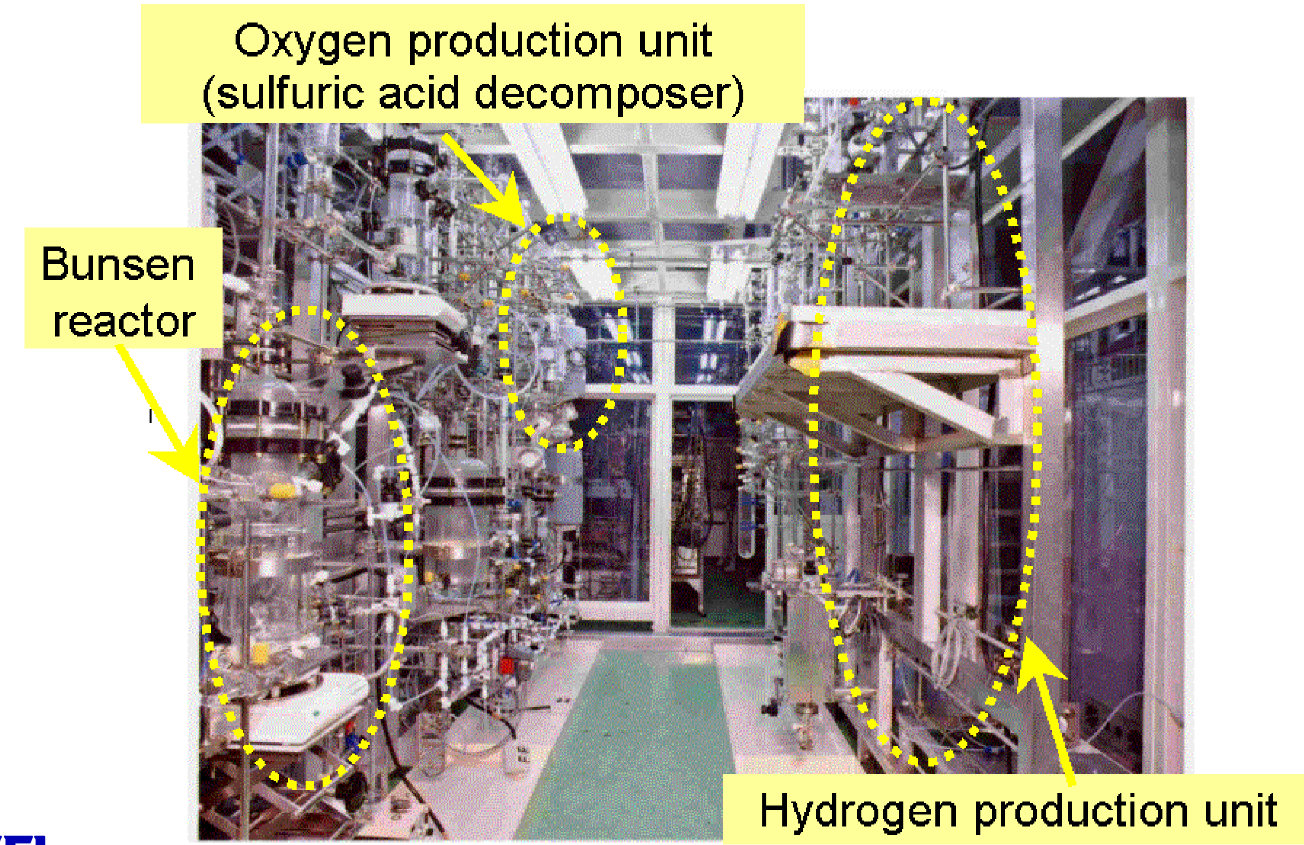
H_2 production by thermo-chemical water splitting

- Replaces thermal decomposition of water (requiring > 3000ºC) with several partial reactions
- Iodine-Sulphur (I-S) process:



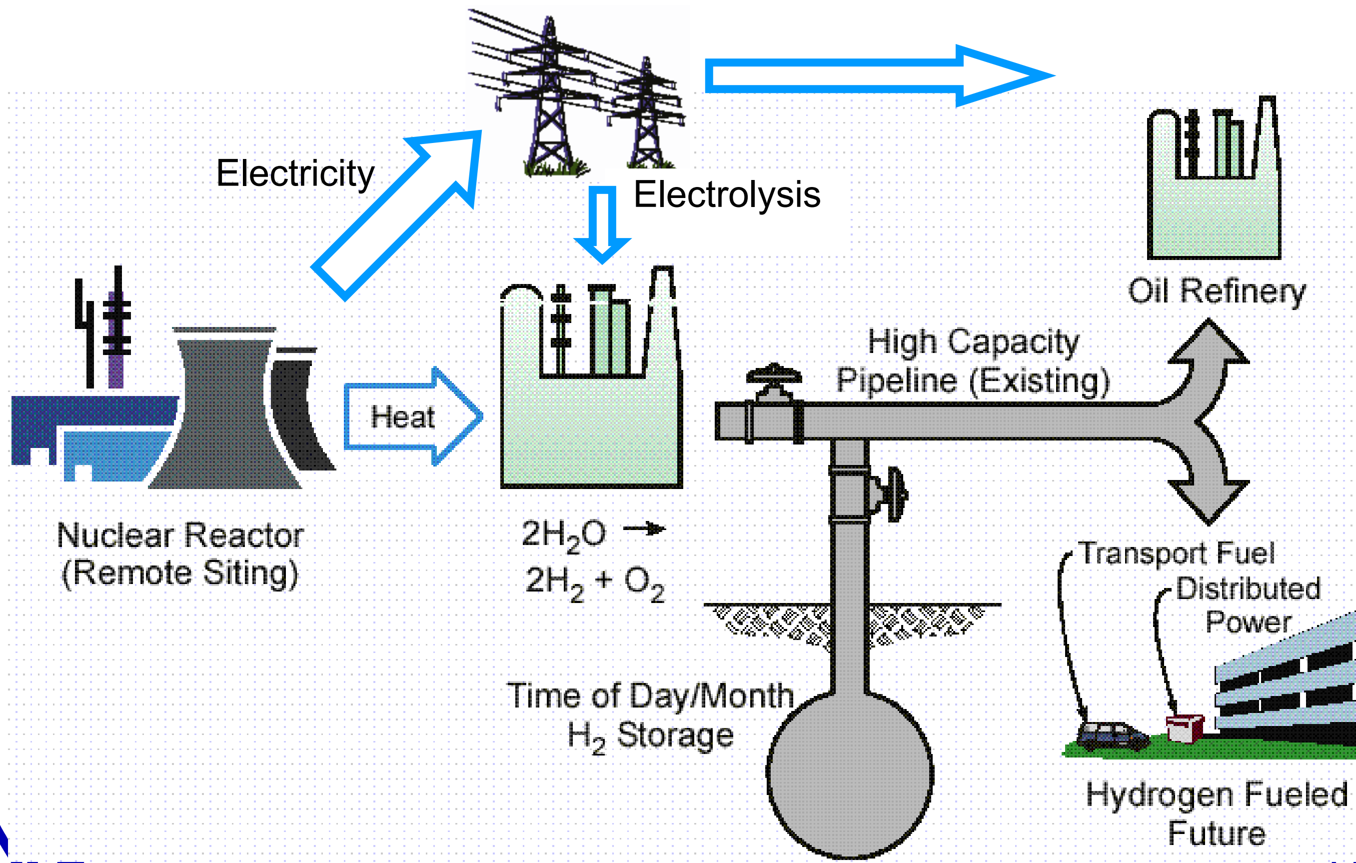
Japanese prototype I-S plant

- JAERI investigating the I-S process for emissions-free hydrogen production using nuclear heat



Hydrogen production compatible with nuclear

- Near-zero emissions technology; remote siting of production facility
- Storage allows de-coupling between production and use, allowing dual-purpose stations: electricity and hydrogen production



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A future for nuclear hydrogen production?

- Nuclear offers:
  - a near-zero emissions option
  - demonstrated and established technology
  - near-term demonstration of direct coupling with H_2 production
- Nuclear should not be the only solution (others include solar & biological processes) but is likely to be an important contributor
- Temperatures available from current reactors (predominantly light-water) limit production method to electrolysis
- High temperature gas-cooled modular reactors (e.g. PBMR) offer a safe, flexible, and economic future energy source

Summary

Summary

- Market conditions appear to favour small,flexible, modular units
- Detailed Feasibility Study indicates a technically achievable project: technical development of the PBMR has progressed well, and the system shows good potential to operate with very high levels of safety, and to support a range of applications
- Business Case suggests the PBMR will be able to meet the challenging capital and production cost targets required by the investors
- BNFL (and the other investors) intend to continue with the project, subject to satisfactory negotiations and Govt Approval
- Meanwhile, discussions are ongoing with other investors who have expressed an interest in joining the Project.