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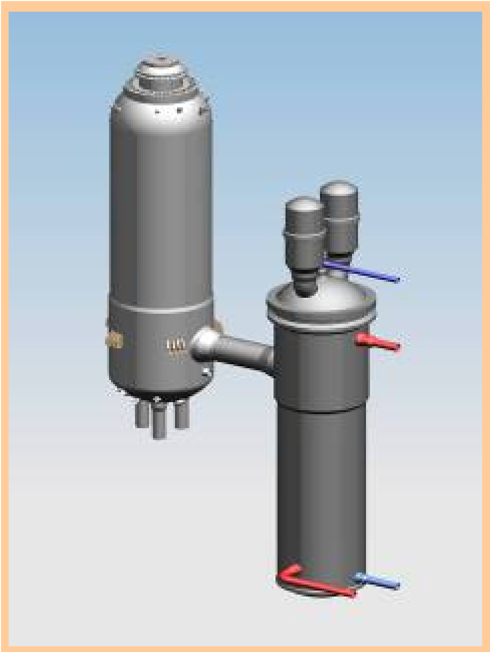
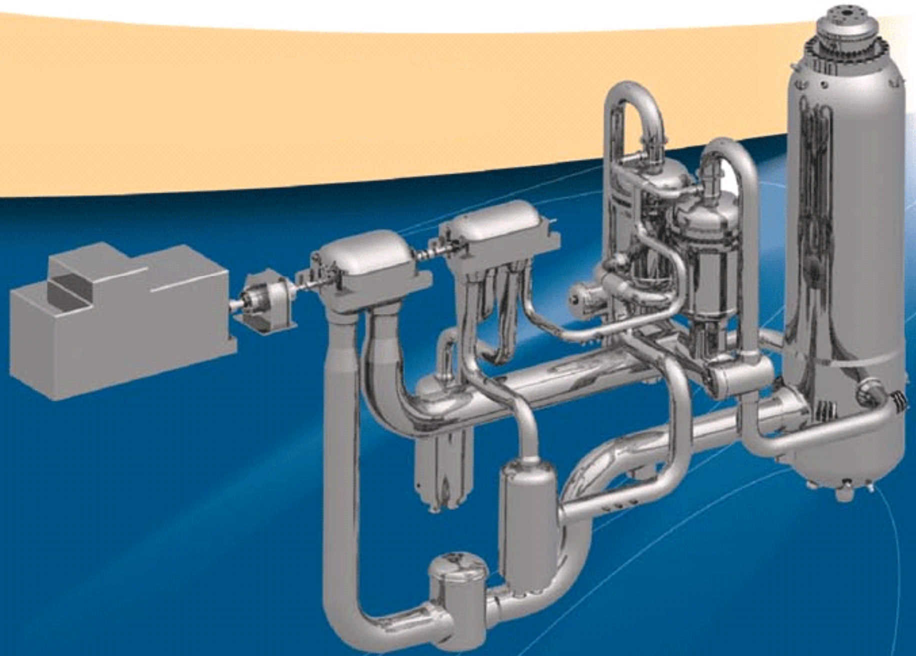
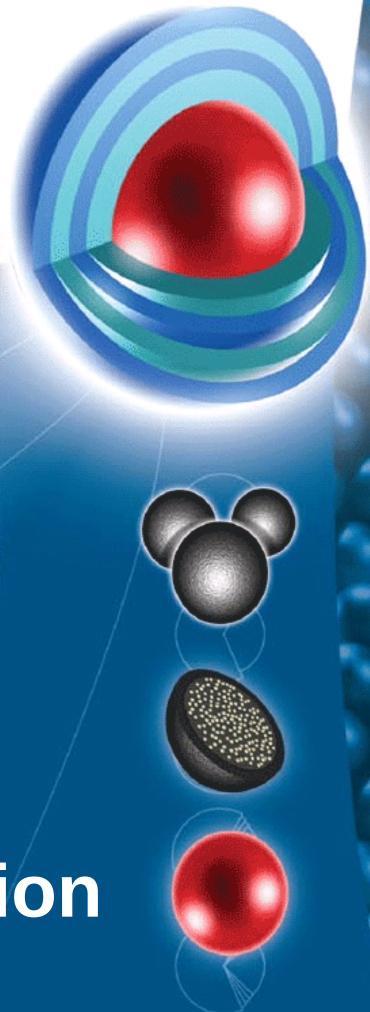




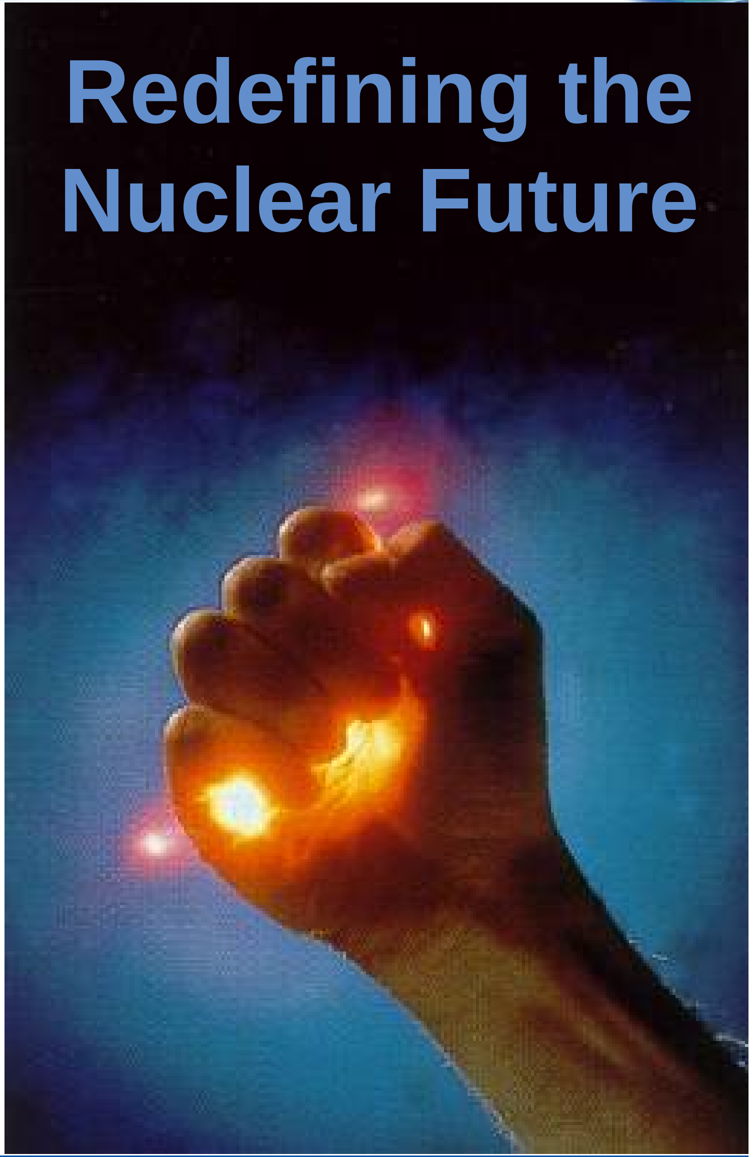


Role of HTRs in Synthetic Fuel Production

Presented by Mr. Willem Kriel - PBMR (Pty) Ltd.

Outline

- **Energy Challenge**
- **PBMR Technology**
- **Hydrogen Production**
- **HTR Synfuel Opportunity**
  - Coal-to-Liquids
  - Coal-to-Gas
  - Steam-Methane-Reforming
- **Summary**



Introduction

- **Global concern for**
  - Increased energy demand
  - Increased cost of natural gas and oil
  - Energy security
  - Environmental sustainability

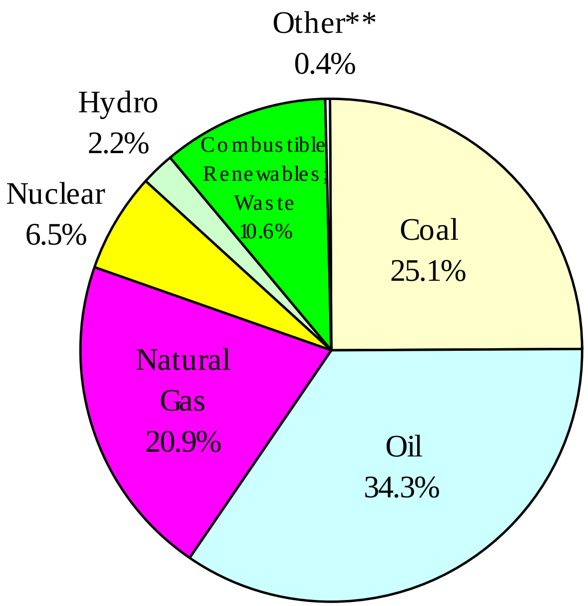
  are stimulating investments in energy sources & technologies that will contribute to **clean, secure and affordable energy**

- **Nuclear energy can play key role to address these concerns**

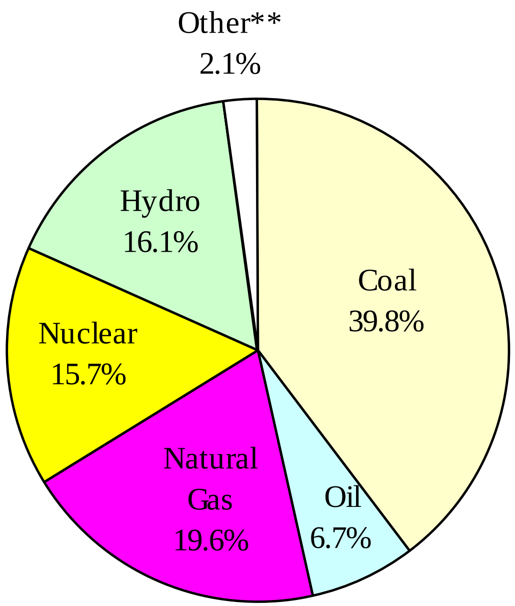
- **Specifically, PBMR technology can be applied to:**
  - Electricity generation
  - Variety of process heat applications, including **Synfuel Operations**

Global Energy Supply

- **Fossils supply ~ 80% of global primary energy**
- **Continued use of fossils is constrained by increasing cost of available reserves and its negative environmental footprint**



World Primary Energy Supply [2004]



World Electricity [2004]

http://www.iea.org/textbase/nppdf/free/2006/key2006.pdf.

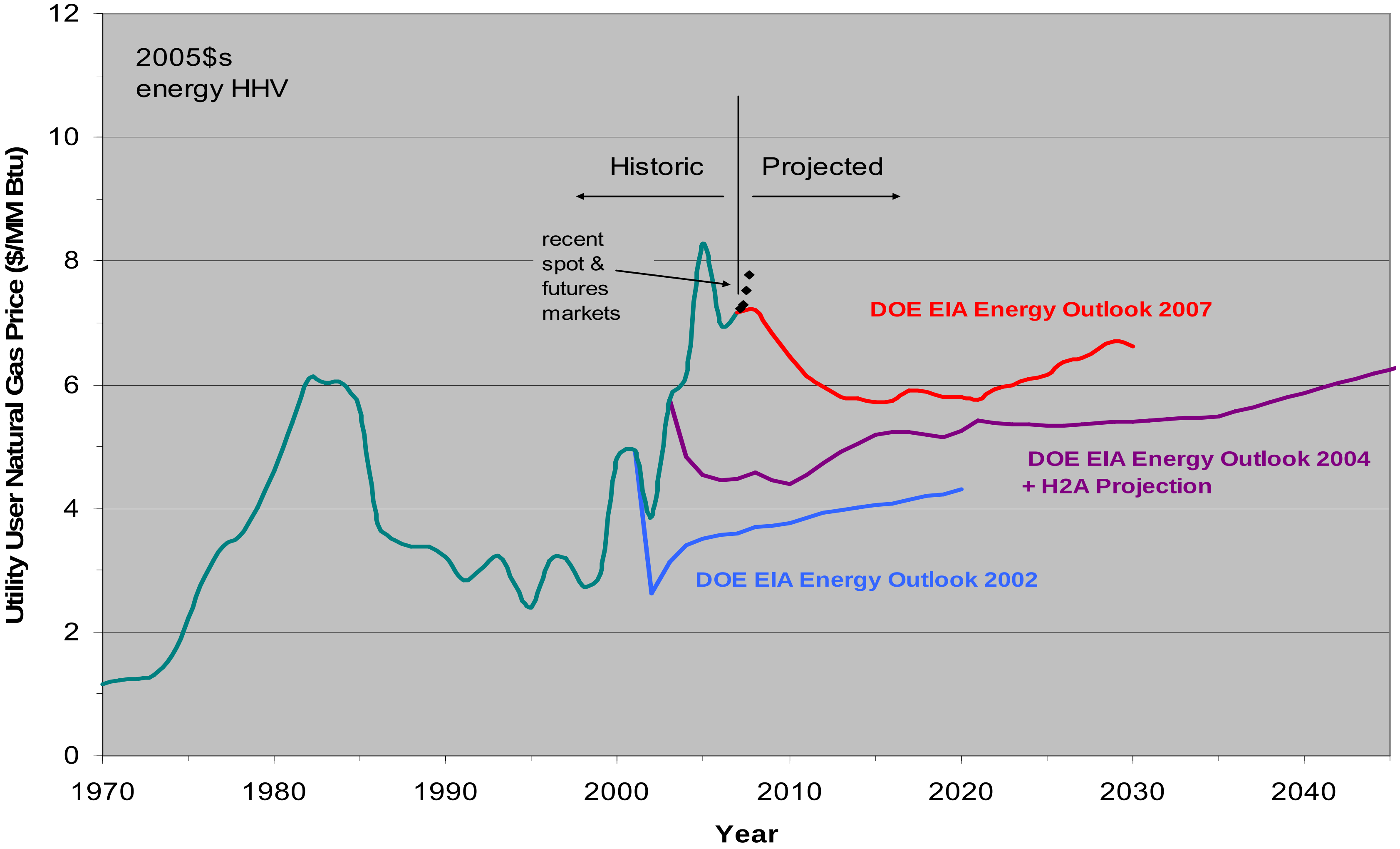
Coal

- **Coal provides ~25%[1] of global primary energy, which is used for:**
  - Some 40% of global electricity production
  - Some 66% of global steel production
  - Cement manufacturing
  - Various others
- **Coal reserves are widely available and one of the most affordable resources**
- **Its continued use is expected to be subject to incentives to reduce its environmental footprint through**
  - Technological advancements and/or
  - Operational advancements

Lignite Coal Mine

Gas

Natural Gas Price Actuals and Forecasts per EIA



Oil

- **Oil use**
  - provides ~34%[1] of global primary energy
  - 96% of all energy used in transport sector

- **Various governments are seeking for the transport sector:**
  - Energy independence
  - Reduced environmental footprint

- **Solution?**
  - **Hydrogen Economy** - replacement of liquid transportation fuels by H_2
  - **Synthetic Liquid Fuels** – produce local liquid fuels from coal and/or gas
  - **Electric/hybrid cars** with clean power generation

Hydrogen Economy

Use of H_2 to better utilise current hydrocarbon resources

- **H_2 today is mainly produced from natural gas, tightening gas supplies and generating CO_2**
- **Hydrogen (if derived from a clean energy source and sustainable H_2 feedstock) will:**
  - Reduce dependence on natural gas in refining sector
  - Reduce GHG emissions
  - Support option to utilise fuel cell cars
  - Support conversion of coal to synthetic liquids without GHG emissions
- **Solution for clean hydrogen production is to use:**
  - Nuclear energy as clean energy source
  - Water as clean and sustainable hydrogen feedstock

Synthetic Liquid Fuels

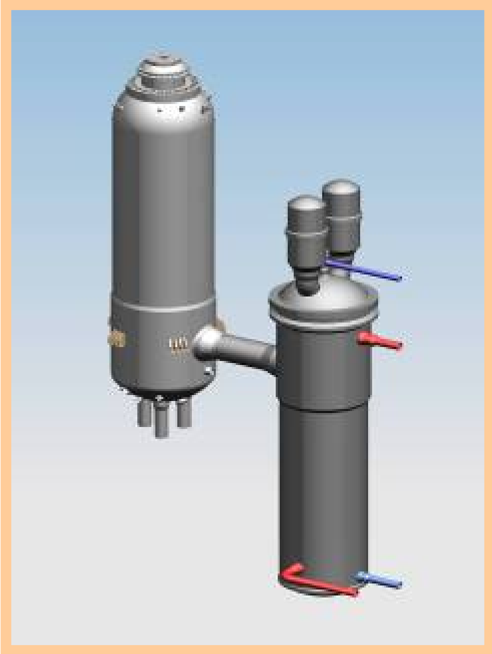
- **Oil prices & energy security concerns have stimulated interest in coal-based liquid fuels** (expected to rise from 150,000 bpd today to 1.8 million bpd in 2030[2])
- **Synthetic liquid fuels (produced from coal) can augment conventional transportation fuels and reduce petroleum imports**
- **Conventional coal-to-liquids (CTL) processes convert almost half of the coal to CO_2 in order to produce needed hydrogen**
- **CTL were developed in Germany in the 1920s to produce liquid fuels from coal**
  - Only commercial-scale CTL plant currently in operation is Sasol's Fischer-Tropsch process (produces some 40% of the gasoline and diesel fuels for South Africa)
- **In the News…**
  - Sasol is planning two CTL plants in China
  - In the USA some nine states are actively considering CTL plants
  - Waste coal-to-diesel processing plant recently announced for construction in Mahanoy, PA

Resurgence of Nuclear Energy


30 nuclear plants are being built today in 12 countries around the world, and over 100 planned

Why PBMR for Process Heat?

- Right process temperatures
- Right size and outputs
- Multiple Project initiatives underway
- Economic
- Safe
- Clean

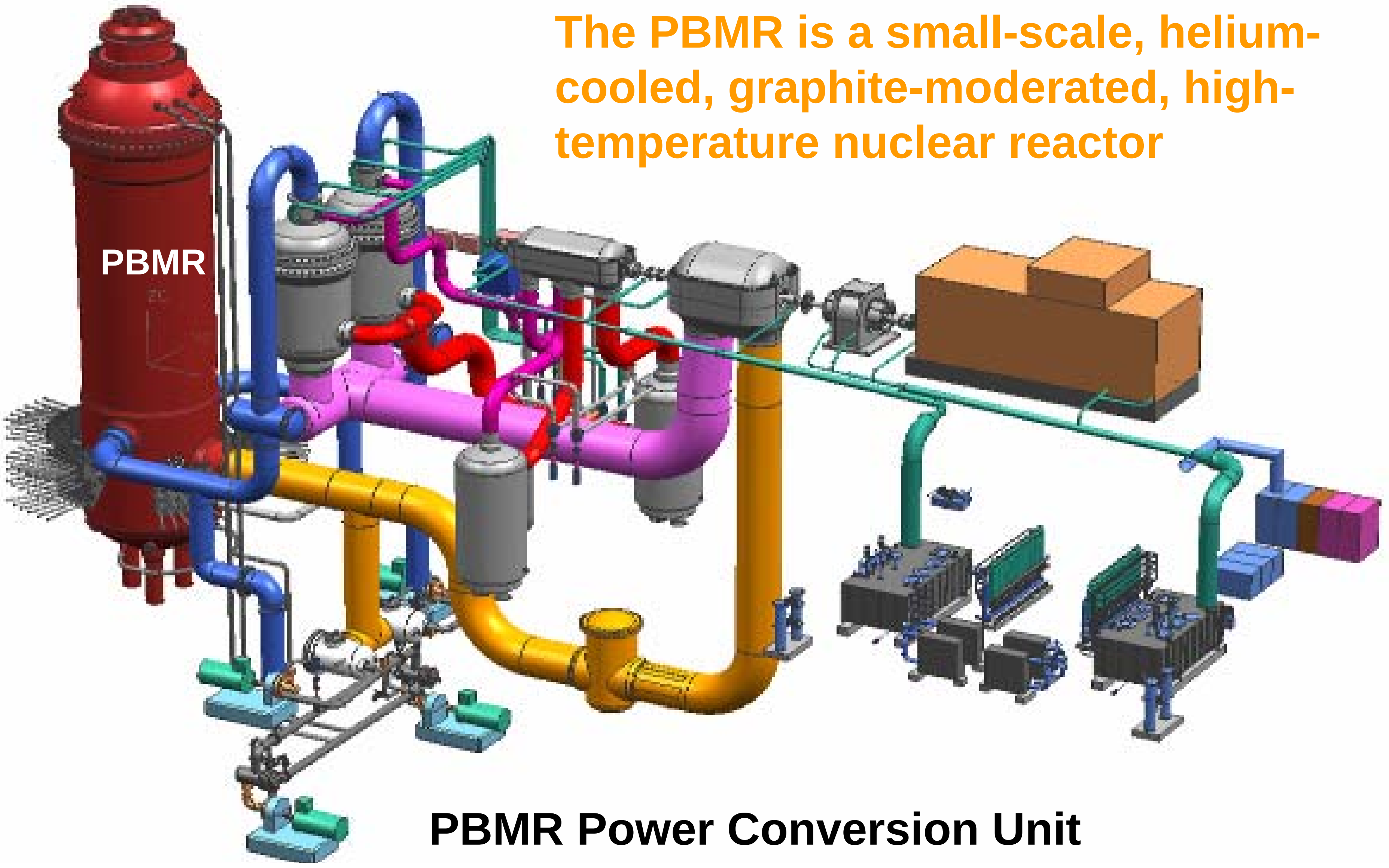


- A Perfect Fit:

*"The challenges facing the energy industry are to find sources that are **accessible, reliable, affordable, proliferation resistant, safe and environmentally friendly**."*

What is the PBMR?

The PBMR is a small-scale, helium-cooled, graphite-moderated, high-temperature nuclear reactor



PBMR Power Conversion Unit

PBMR Mission

- **Mission**
  - To build a commercial size (165 MWe) Demonstration Power Plant near Cape Town by 2012
  - To build a Pilot Fuel Plant near Pretoria

- **This project has been identified as a National Strategic Project by the South African Government**

PBMR Features

- Inherent Safety (design rules out a core melt)
- Distributed generation due to small size
- Modularity (additional modules can be added)
- Low impact on the environment
- Lower capital cost during construction
- Smaller capital cost increments
- Small emergency planning zone
- High efficiency (> 41%)
- Short construction times
- Load following
- On-load refueling
- Low proliferation risk

Process Heat Applications

- **Steam Generation**
  - Oil Sands
  - Cogeneration
- **Steam Methane Reforming**
  - Hydrogen
  - Ammonia
  - Methanol
- **Water-Splitting (H_2 & O_2)**
  - Bulk Hydrogen
  - Coal-to-liquids
  - Coal-to-methane
- **Desalination**

P B M R

Process Heat Team

- **Shaw, Westinghouse and PBMR have teamed to produce clean, secure and economic hydrogen**

Nuclear Hydrogen Production (Water-Splitting)

- **Several proposed Water-Splitting (WS) technologies including**
  - Conventional Water Electrolysis
  - High-Temperature Steam Electrolysis
  - Hybrid Sulfur Process
  - Sulfur Iodine Process

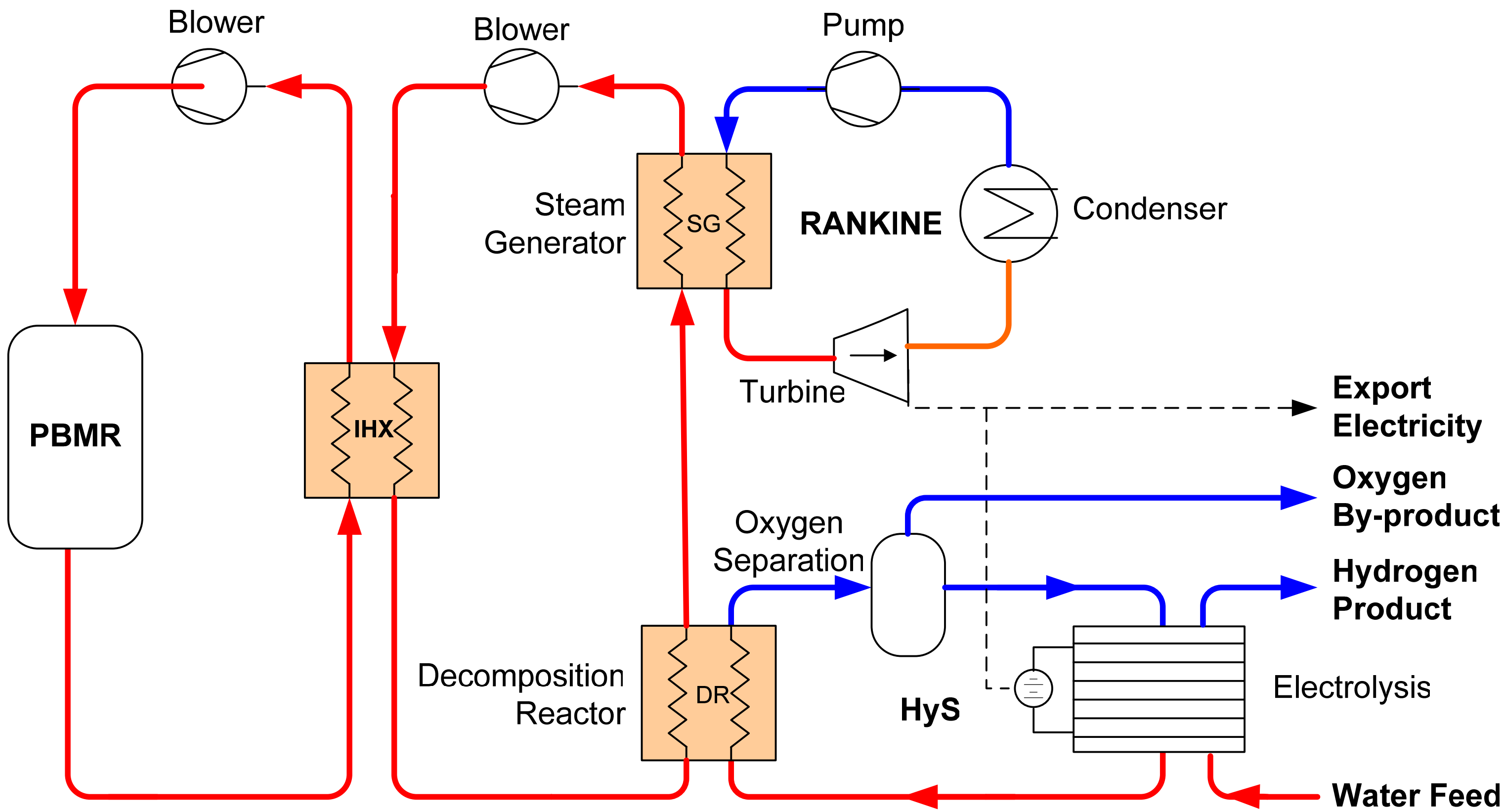
- **PBMR is looking for the most promising WS technology**

- **At present, PBMR selected the Hybrid Sulfur Process as reference cycle:**
  - $H_2SO_4 \leftrightarrow SO_2 + H_2O + \frac{1}{2} O_2$ (>800°C heat required)
  - $2H_2O + SO_2 \rightarrow H_2 + H_2SO_4$ (electrolytic at 100°C)

- **However, technology development is required to commercialize Hybrid Sulfur (HyS) WS**

PBMR Hydrogen via HyS Process

- **PBMR heat (950°C) used for high temperature decomposition**
- **PBMR electricity used for low-temperature electrolysis**



Nuclear Synfuel Opportunity

- **To date, there has been little dialog or interaction between nuclear and coal proponents**

- **However, evolving circumstances are increasing interest:**
  - Continuing increases in liquid fuel imports
  - The elusiveness of the hydrogen economy
  - The potential for plug-in hybrid vehicles
  - The potential for coal to liquid fuel conversion with minimal environment impact (potential availability of clean cost effective hydrogen)

- **Opportunities**
  - Coal-to-Liquids
  - Coal-to-Gas
  - Steam-Methane-Reforming

Fischer-Tropsch (F-T) Process (basis for CTL)

- **F-T is essentially a process in which H_2 and CO are used as building blocks to "manufacture" hydrocarbons**

- **Basic equation:**
  - $(2n + 1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$

- **For long-chain molecules, material balances can be approximated by:**
  - $CO + 2H_2 \rightarrow CH_2 + H_2O$

Note: Feed syngas must have a H_2 to CO molar ratio of at least 2

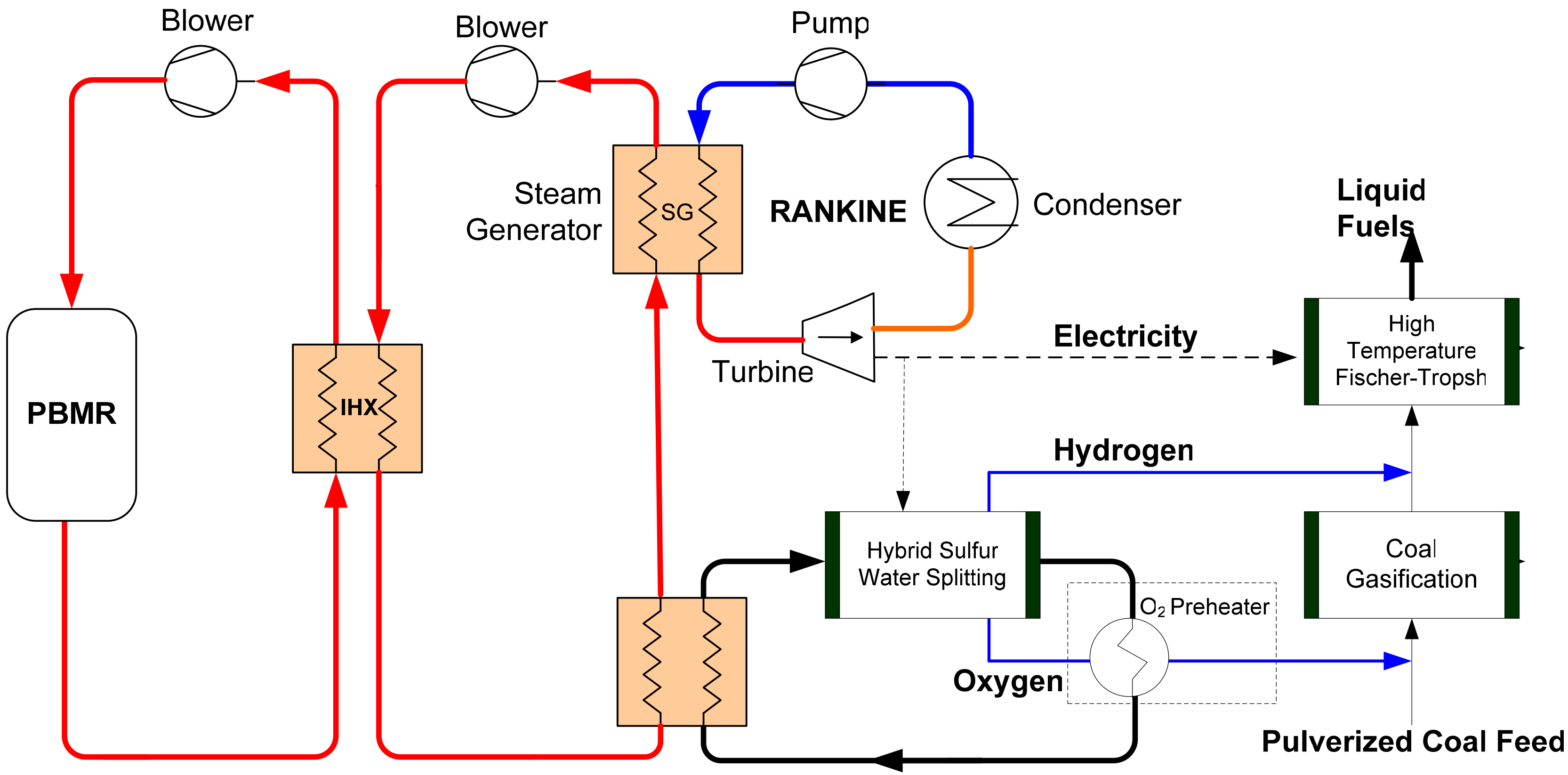
Syngas from Coal

- **Syngas (a mixture of CO and H2), which is the input to the F-T process is conventionally produced by a combination of partial oxidation (POX) and steam reforming (SR)**
- **When the starting point is coal, which has a typical hydrogen-to-carbon ratio of 0.8, these equations can be written as follows:**
  - POX: $CH_{0.8} + 0.7\ O_2 \rightarrow CO + 0.4\ H_2O$
  - SR: $CH_{0.8} + H_2O \rightarrow CO + 1.4\ H_2$
- **With coal as input, neither the POX nor SR reaction provides an acceptable H_2 to CO ratio**
- **This is adjusted using the WGS reaction:**
  - WGS: $CO + H_2O \rightarrow CO_2 + H_2$
- **Note that one mole of CO_2 is produced for each mole of H_2**

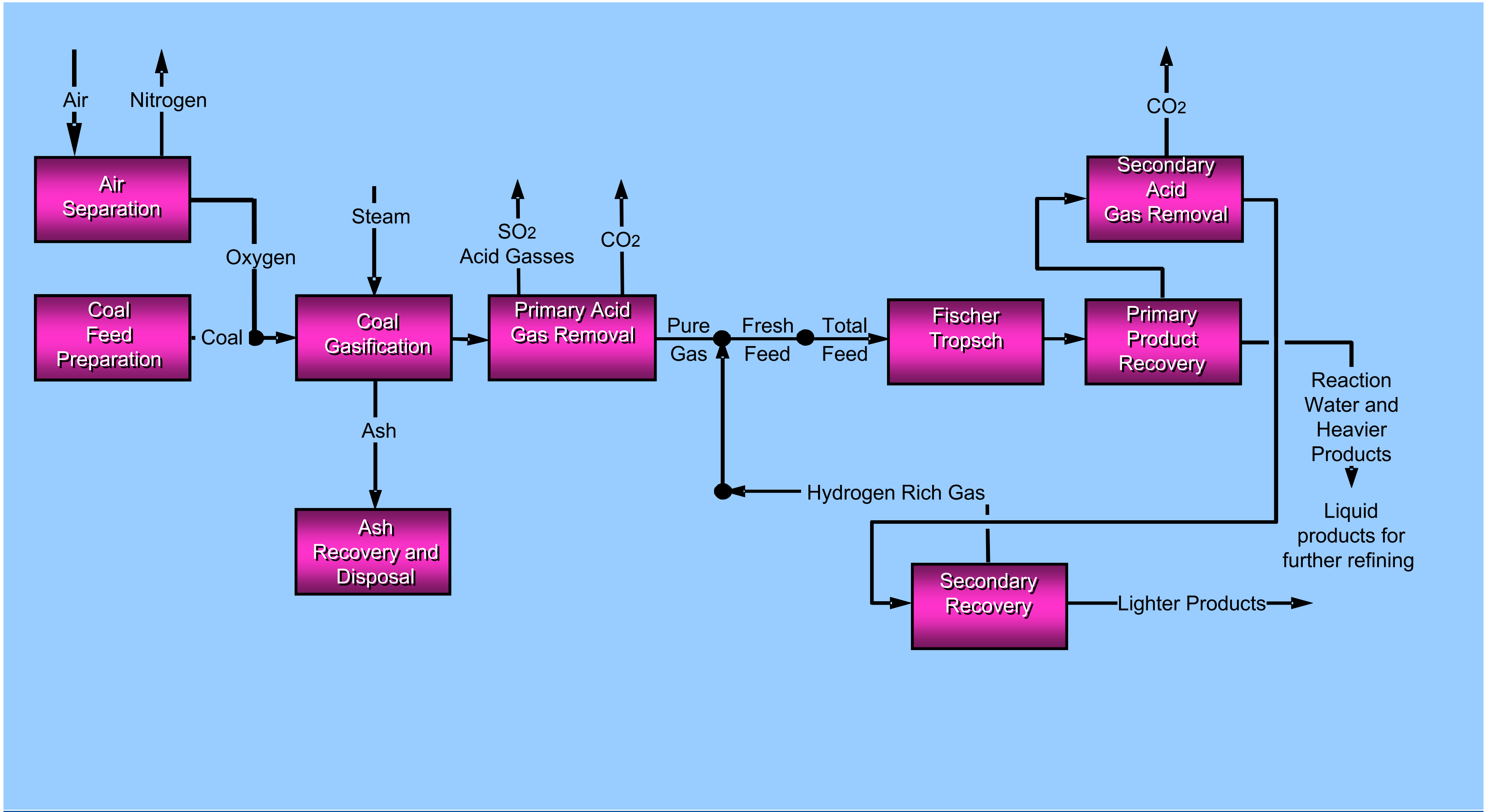
HTR CTL proposal

- **While conventional coal-to-liquid conversion addresses liquid fuel supply and security issues, the large quantities of byproduct CO_2 raises environmental concerns**
- **If an independent source of H_2 and O_2 were available, however, the steam reforming (SR) and water gas shift (WGS) reaction steps would not be required**
- **This would eliminate the only significant source of CO_2 from the CTL conversion process itself**
- **Nuclear energy offers such an alternative**
  - Nuclear electricity + electrolysis
  - High-Temperature Reactor + high-temperature electrolysis or thermo-chemical water splitting

PBMR Hydrogen via HyS Process coupled to CTL

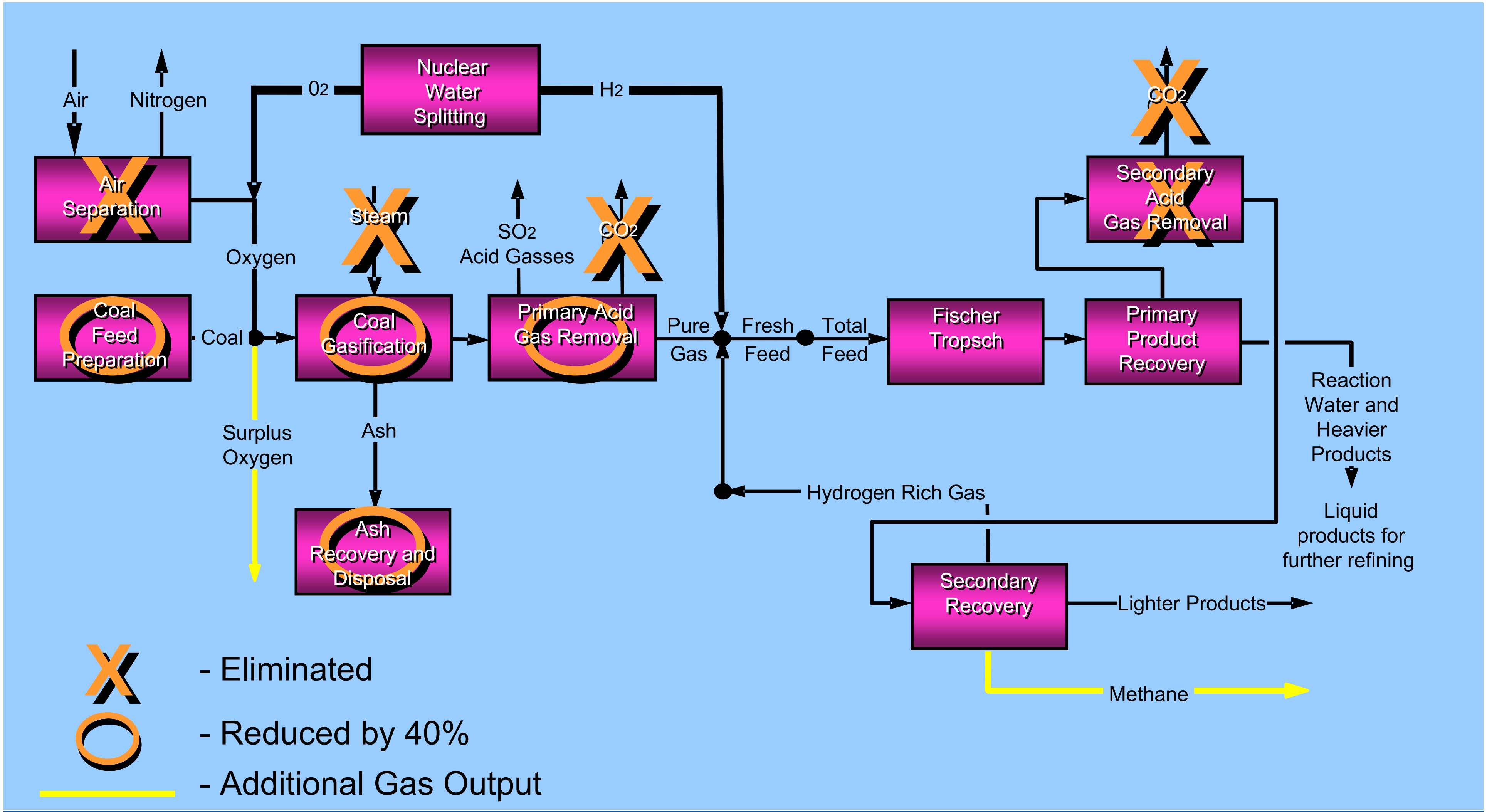


Conventional Coal-to-Liquids with Water Splitting



Nuclear Assisted Coal-to-Liquids with Water Splitting

Savings include capital, coal, O&M, CO_2



HTR CTL Benefits

- **Extend coal resources (cuts coal use by over 40% by using water as hydrogen feedstock instead of coal)**

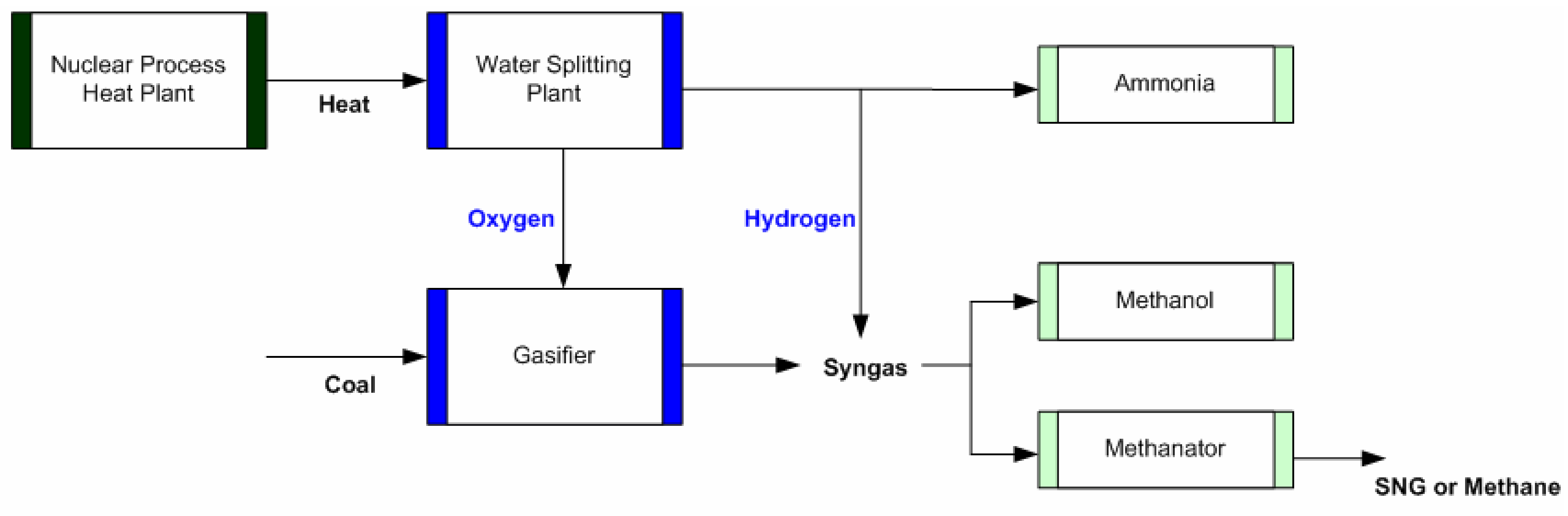
- **Overall process simplification**
  - Reduces size of coal handling and gasifiers needed (by 40+%)
  - Eliminates air separation / oxygen plant (capital and power consumption costs)
  - Eliminates need for input steam (capital and energy costs)

- **Environmental benefits**
  - Nearly eliminates CO_2 emission in producing liquid fuels
  - Reduced waste streams

- **Economic drivers**
  - Production cost of oxygen and hydrogen
  - CO_2 credits
  - Displacement of coal
  - Major off-sets in CTL capital and operating cost
    - Eliminates approximately half of gasification and all CO_2 sequestration systems when combined with water-splitting

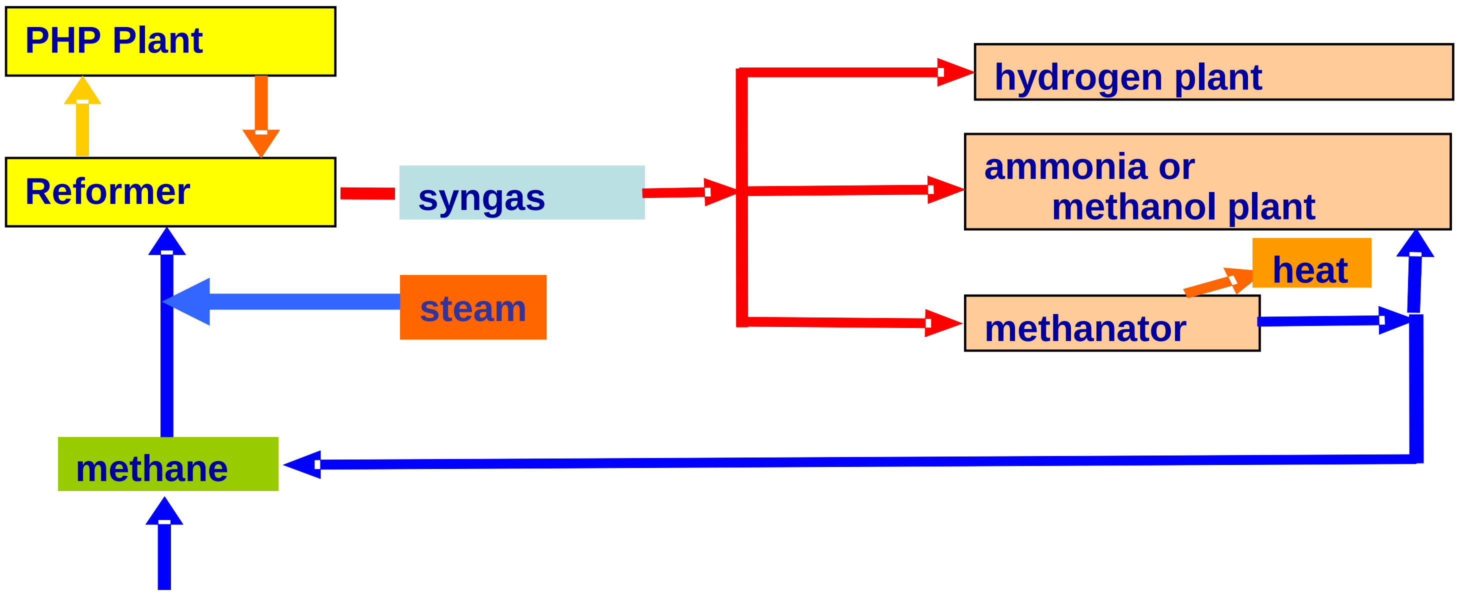
Coal-to-Gas

- **The same benefits outlined above for coal-to-liquids (CTL)**
  - Potentially, with even greater incentives, depending upon the form and H to C ratio of the required product



Steam-Methane-Reforming

- **Reforming Reaction**
  - $CH_4 + H_2O \rightarrow CO + 3H_2$ (> 800°C heat required)
- **PBMR provides heat for the reformer, which will**
  - Displace 30% of natural gas requirement
  - Reduce CO_2 emissions by 30%



Summary

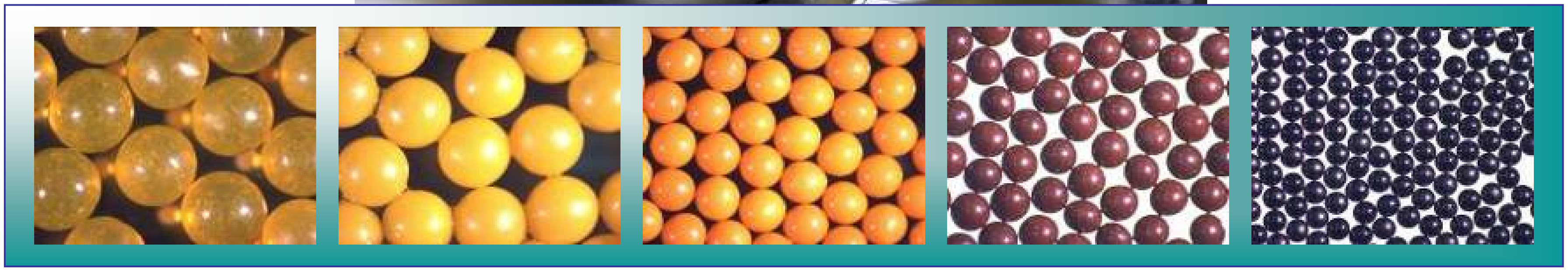
- **The combination of coal conversion to liquids or methane with nuclear water splitting improves carbon efficiencies, eliminating CO_2 emissions**
- **HTR technology, such as the PBMR, can play a key role in cleanly generating hydrogen to be used**
  - In short term for reducing gas consumption in conventional hydrogen plants (steam methane reforming)
  - In medium term for clean liquid fuel and gas production from coal resources
  - In longer term to produce bulk hydrogen as a fuel
- **PBMR technology can leverage planned needs for hydrogen and coal conversion by supplying high-temperature process heat for syngas production, hydrogen and oxygen through water splitting, or heat for steam generation**
- **Nuclear water splitting requires further R&D to reduce capital and operating costs.**
- **The PBMR Process Heat Team is presently evaluating the potential of nuclear integrated CTL and CTG system designs and economics**

Back-up Slides

References

- [1] http://www.iea.org/textbase/nppdf/free/2006/key2006.pdf.
- [2] NEWSWEEK, Special Energy Edition, Dec 2006- Feb 2007.

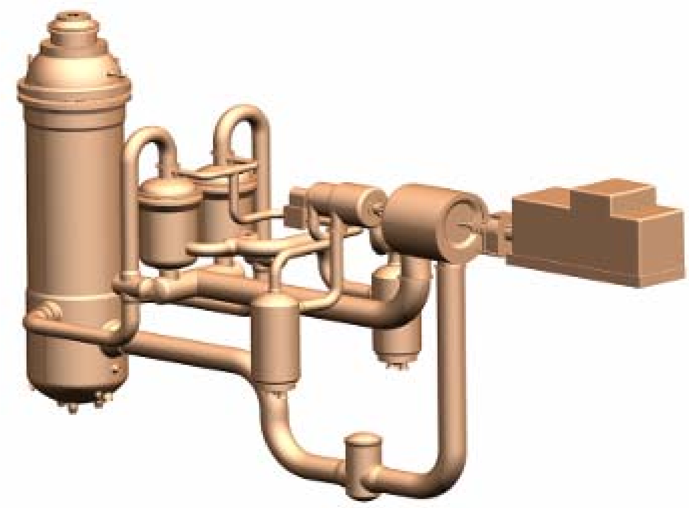
Pebble Fuel



Cast Aged Dried Calcined Sintered

PBMR Demonstration Power Plant Project Status

- Basic design completed; detailed design started
- International supply team in place
- Extensive test programs underway
- Construction scheduled 2008; criticality 2011-2012
- South African utility Eskom issued letter of intent for follow-on electric plants

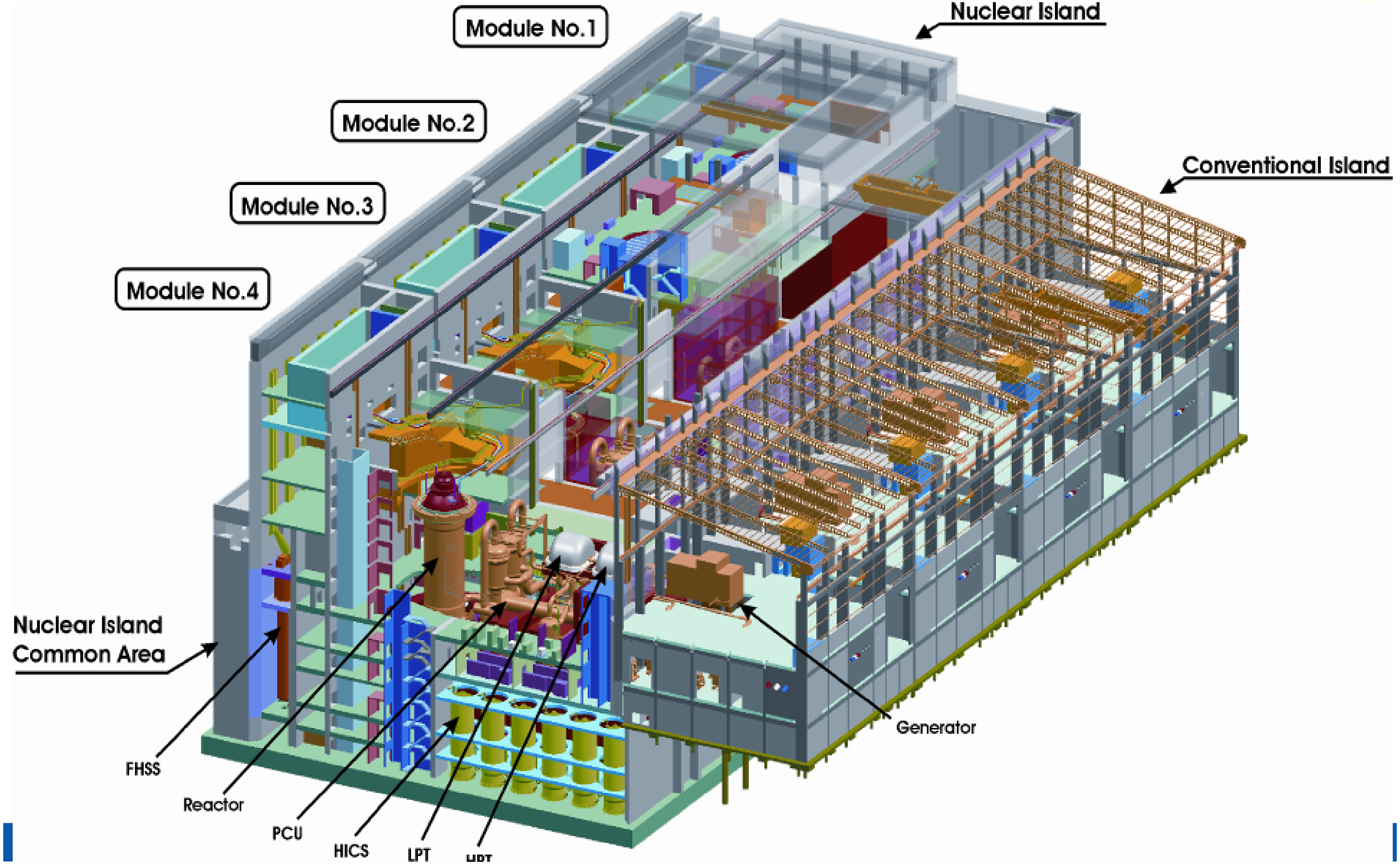


Koeberg Nuclear Power Plant Site, Cape Town

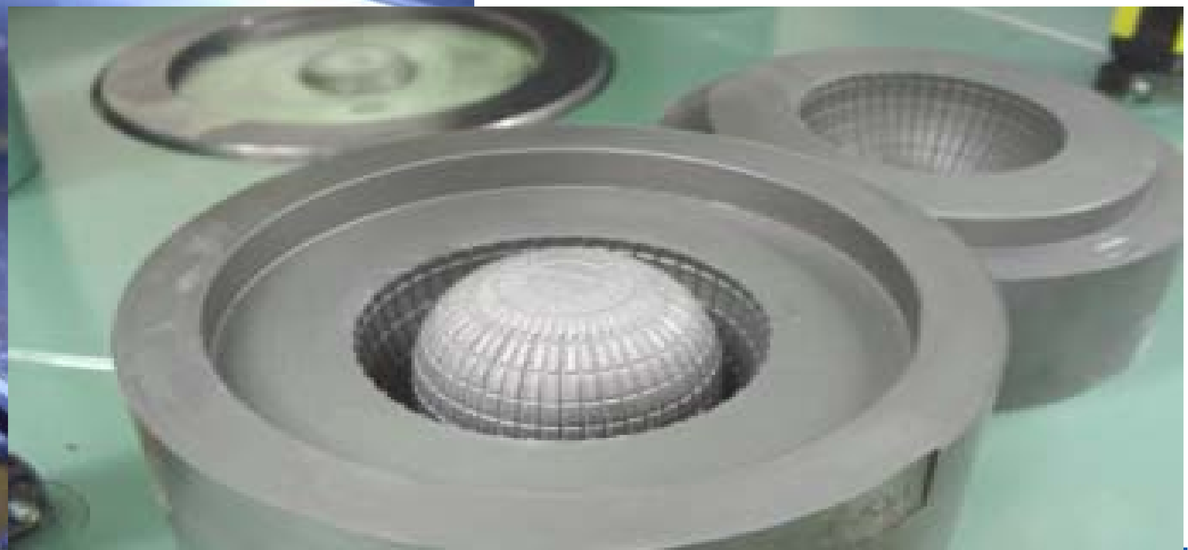
Investors in PBMR (Pty) Ltd.

- South African Government
- Industrial Development Corporation (IDC) of South Africa
- Eskom (National Utility)
- Westinghouse

Multi Module Concept



Fuel Manufacturing at Pelindaba

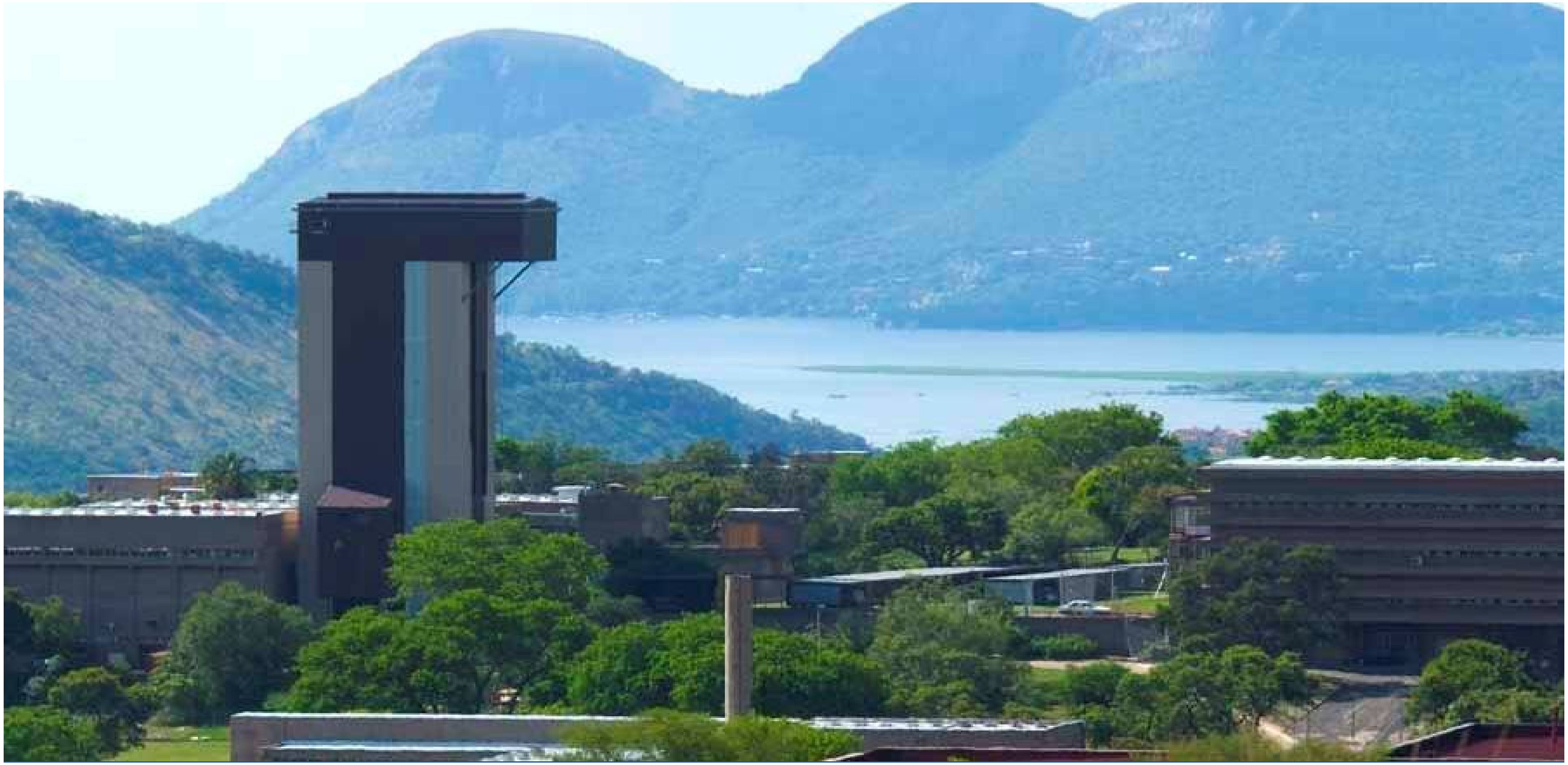


Safety Features

- Inherent safety features proven during public tests
- New Generation IV “safe design” technology
- System shuts itself down
- No need for off-site emergency plans
- Minimal 400 meter safety zone
- No need for safety grade backup systems
- Helium coolant is chemically inert
- Coated particle provides excellent containment for the fission product activity

Extensive Test Programs:
Helium Test Facility at Pelindaba

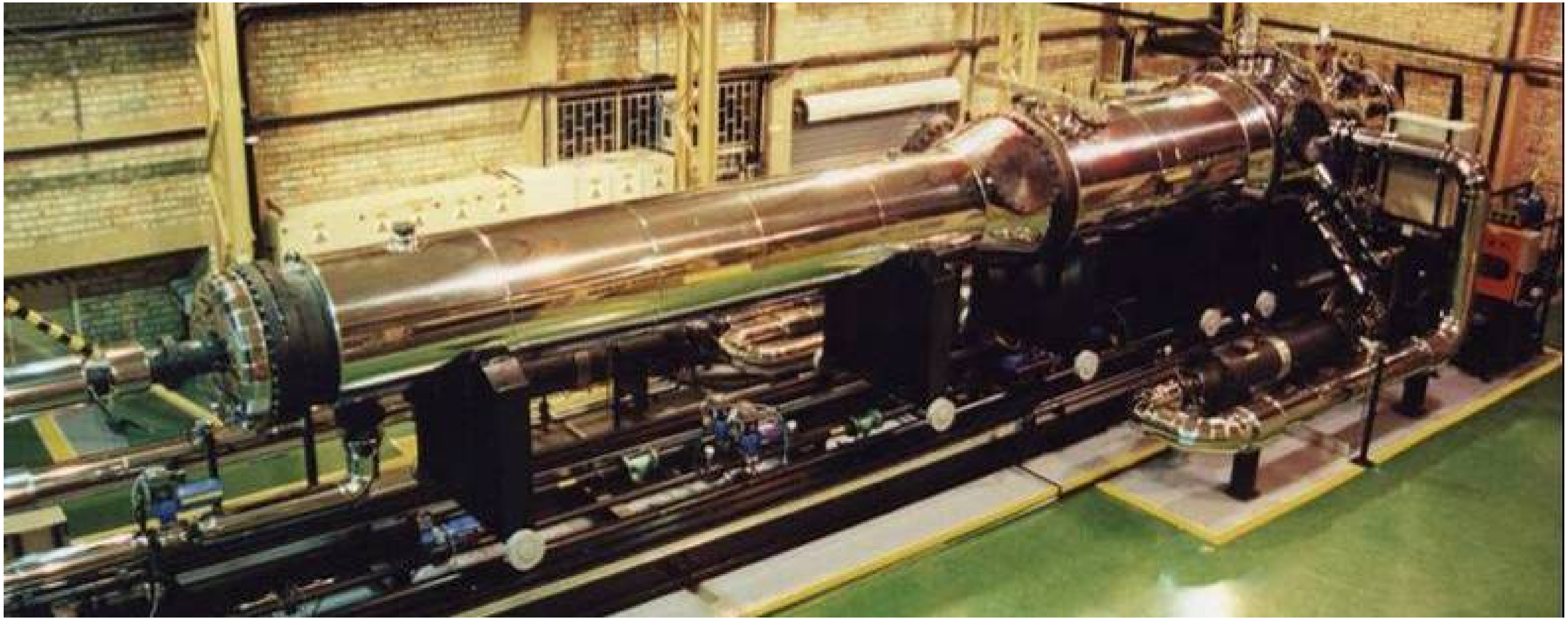
- **Helium blower, valves, heaters, coolers, recuperator and other components to be tested at pressures up to 95 bar & 1200 °C**



Extensive Test Programs:
Helium Test Facility at Pelindaba

Extensive Test Programs:
Micro Model

- Validate operation and control of 3-shaft Brayton concept



Extensive Test Programs:
Heat Transfer Test Facility