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# Nuclear-Power Ammonia Production

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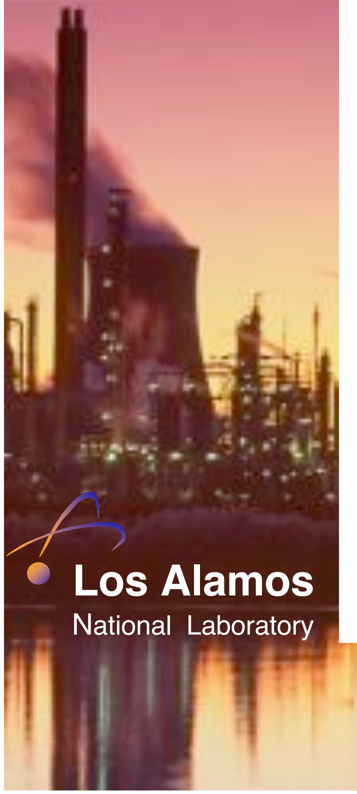

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# *Why Nuclear-Powered Ammonia Production?*

- **Many in the nuclear community are interested in nuclear-powered hydrogen production**
  - **Interest primarily motivated by talk of a hydrogen economy**
  - **Focusing on a hydrogen economy makes commercialization dependent on the economics of hydrogen-powered cars**
- **It would be better to focus on current markets for hydrogen**
  - **If nuclear-powered is not economical source of hydrogen for current users, it will not be an economical source of transportation fuel**
- **Ammonia production is the logical place to begin commercializing nuclear-powered hydrogen production**
  - **Ammonia is the largest consumer of hydrogen in the world**

# *Topics for Discussion*

- **Large centralized nuclear-powered ammonia production (2000 tonne / day plants)**
- **Ammonia production powered by small nuclear reactors (IAEA defines small as <300 $MW_e$)**
- **Transportable nuclear-powered hydrogen production (if time permits)**

# Process Design

# *Major Process Decisions*

- **Which process should be used to produce hydrogen?**
  - Water electrolysis (existing technology)
  - Steam electrolysis (developmental)
  - Thermochemical cycles (developmental)
  - Hybrid cycles (developmental)
- **Which process should be used to produce nitrogen?**
  - Cryogen air separation (existing technology)
  - Pressure-swing absorption (existing technology)
  - Burning hydrogen to remove oxygen (existing technology)
- **What type of nuclear power system should be used?**
  - Pressurized water reactor (PWR) (existing technology)
  - Boiling water reactor (BWR) (existing technology)
  - High temperature gas cooled reactor (HTGR) (developmental)
  - Other high temperature reactors (developmental)

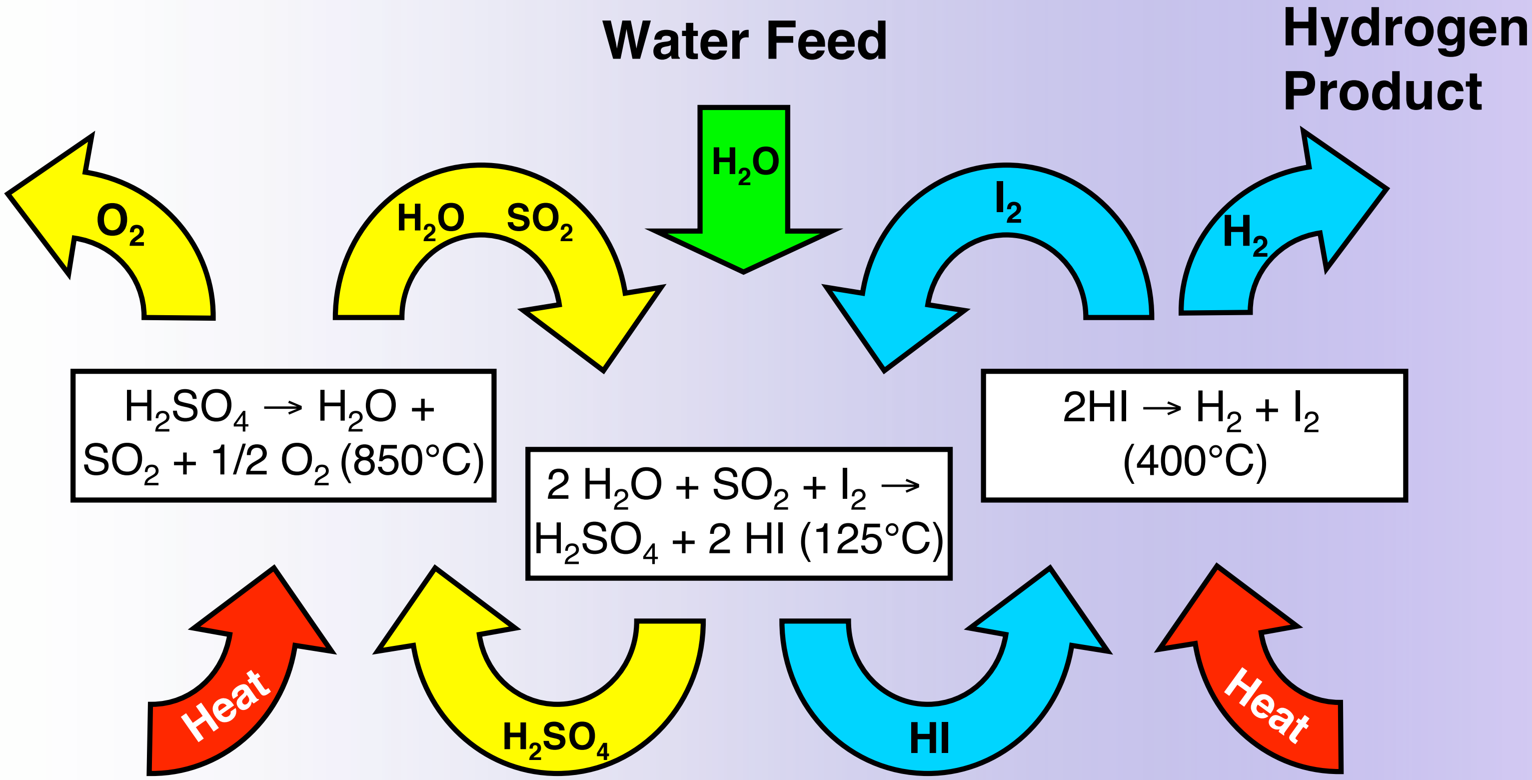
# *Electrolytic Hydrogen Production*

- **Water electrolysis**
  - **Commercial technology**
  - **Produces pure hydrogen**
  - **Could be operated using existing nuclear reactors**

- **Steam electrolysis**
  - **Both Idaho National Laboratory (INL) and the Japanese have developed processes**
  - **Produces a hydrogen-steam mixture and pure oxygen**
  - **Efficiencies of 40 - 50% are possible when powered by an high-temperature gas-cooled reactor (HTGR)**

# *Hydrogen Production Using Thermochemical Cycles*

## The Iodine Sulfate Cycle



**Water Feed**

**Hydrogen Product**

**$O_2$**

**$H_2O$ $SO_2$**

**$H_2O$**

**$I_2$**

**$H_2$**

$H_2SO_4 \rightarrow H_2O$ + $SO_2$ + 1/2 $O_2$ (850°C)

2 $H_2O$ + $SO_2$ + $I_2 \rightarrow$ $H_2SO_4$ + 2 HI (125°C)

2HI $\rightarrow H_2 + I_2$ (400°C)

**Heat**

**$H_2SO_4$**

**HI**

**Heat**

# *Thermochemical and Hybrid Cycles*

- **Theoretical efficiencies of 50% - 65% have been reported in the literature**
  - **Literature efficiency estimates often neglect the energy consumed by the separation processes**
  - **Integrated process studies in the literature indicate efficiencies of 40% - 45% are more realistic**
- **Requires very high temperatures**
  - **HTGR and molten salt reactors are the only types of nucelar reactors that can supply the required temperatures**
- **Capital cost of a iodine-sulfate process is about 8 times that of a seam electrolysis process**

# *Choice for Hydrogen Production*

- Steam electrolysis is the primary choice for hydrogen production
  - The efficiency is greater than water electrolysis
  - The efficiency is comparable to the practical efficiencies of thermochemical processes if powered by an HTGR
  - Steam electrolysis can be powered by a pressurized water reactor (PWR) or a boiling water reactor (BWR)
  - Capital costs are significantly lower than thermochemical processes

- Water electrolysis evaluated as a possible option
  - Less efficient than steam electrolysis
  - Capital cost are lower than steam electrolysis
  - Proven technology

# *Nitrogen Production*

- **Commercial ammonia production requires large volumes of high-purity nitrogen**
- **Removing oxygen, carbon dioxide, and water are the primary concern**
  - **Water should be <150 ppm**
  - **Oxygen and oxygen containing compounds must be <10 ppm**
  - **Argon does not need to be removed**

# Nitrogen Plant Selection Based on Purity and Capacity

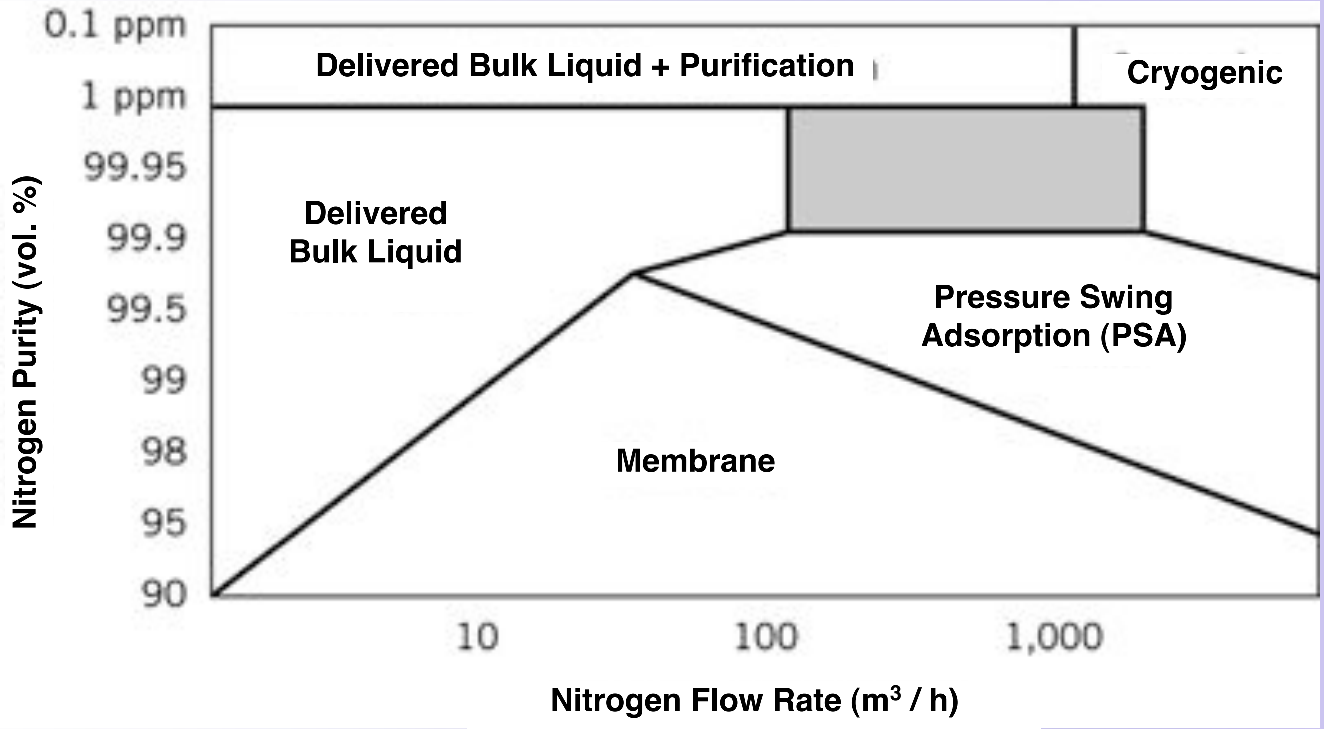


Figure reproduced from *Kirk-Othmer Encyclopedia of Chemical Technology*

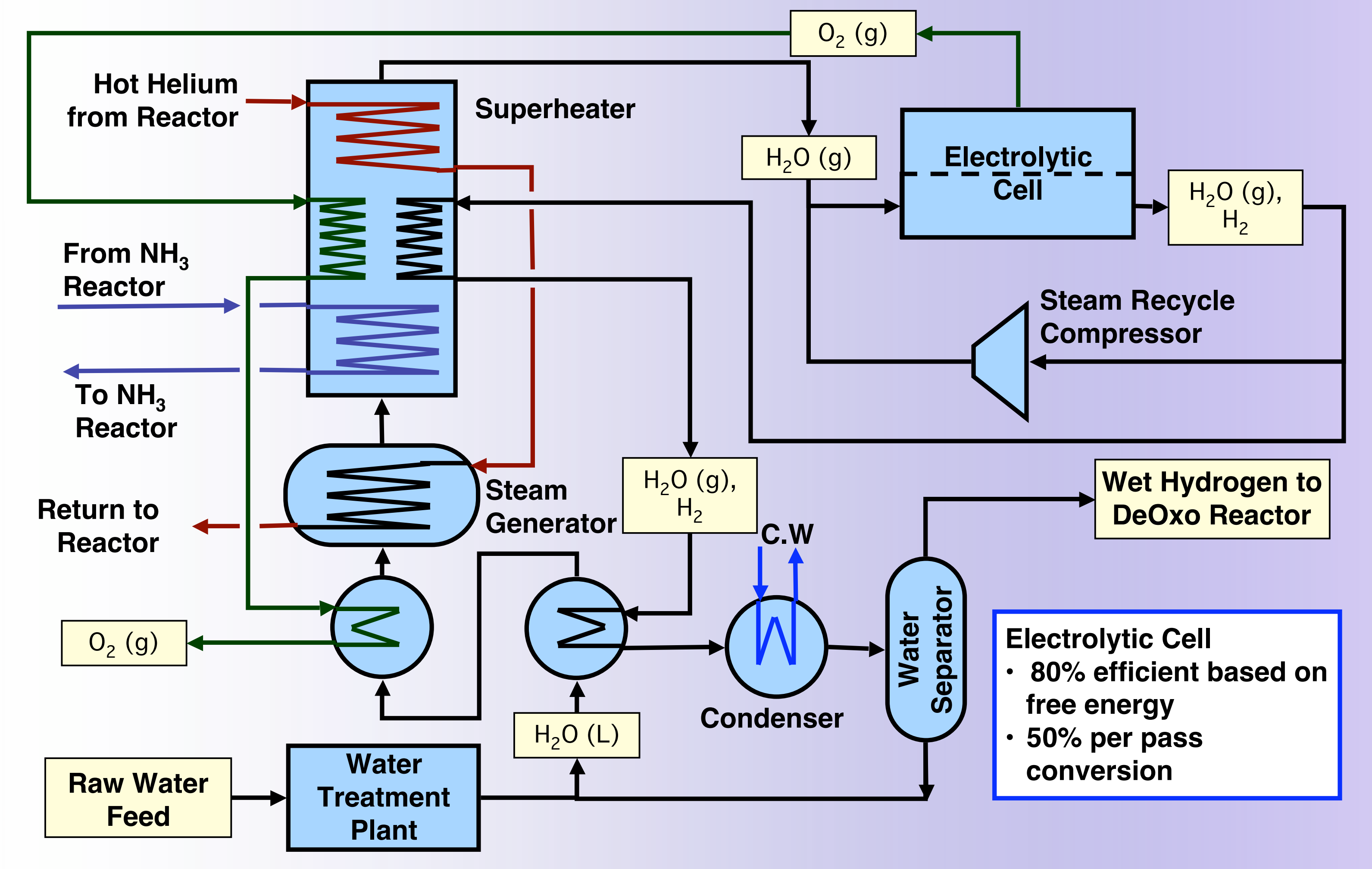
# Pressure Swing Adsorption Will Be used for Nitrogen Production

- **Pressure swing adsorption (PSA) and cryogenic air separation are appropriate processes for producing large volumes of nitrogen**
- **PSA produces lower purity nitrogen than cryogenic air separation**
  - **Removes carbon dioxide, but …**
  - **The nitrogen product contains 0.1 - 2% oxygen**
- **Nitrogen with ppm levels of oxygen can be obtained from PSA by reacting the oxygen with hydrogen**
- **The energy required for PSA plus the hydrogen for removing the residual oxygen is much less than cryogenic air separation**

# *Choice of Nuclear Power System*

- **A HTGR with a Brayton cycle is the primary choice for the nuclear power system**
  - **An HTGR has the highest operating temperatures which favors high cycle efficiencies**
  - **Brayton cycle is better suited for a HTGR than a Rankine cycle**
- **A GE Advanced Boiling Water Reactor (ABWR) with a Rankine cycle also evaluated as a possible option**
  - **Less efficient than an HTGR**
  - **An example of proven technology**

# *Baseline Process Design: Steam Electrolysis Flowsheet*



**Electrolytic Cell**
- 80% efficient based on free energy
- 50% per pass conversion

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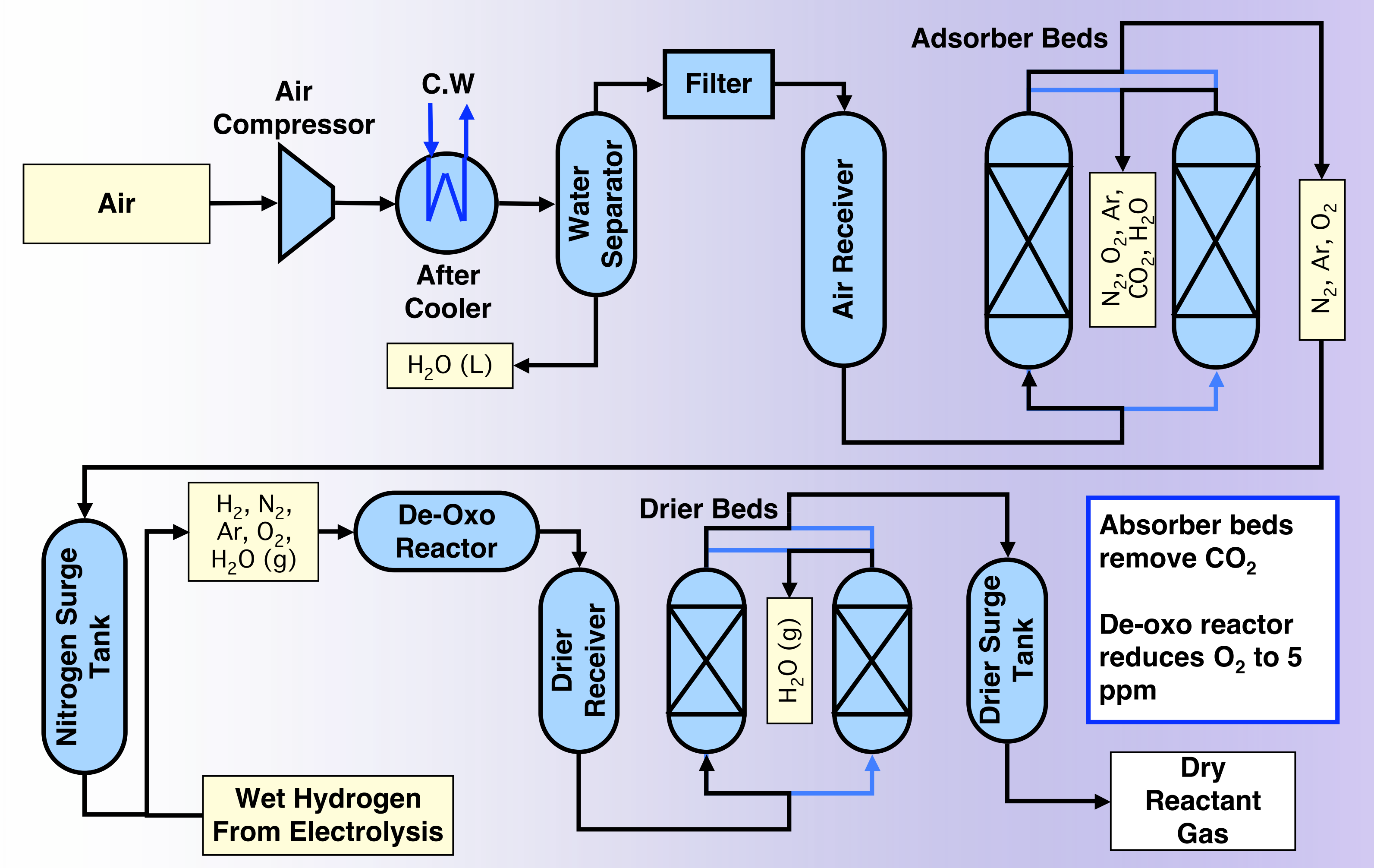
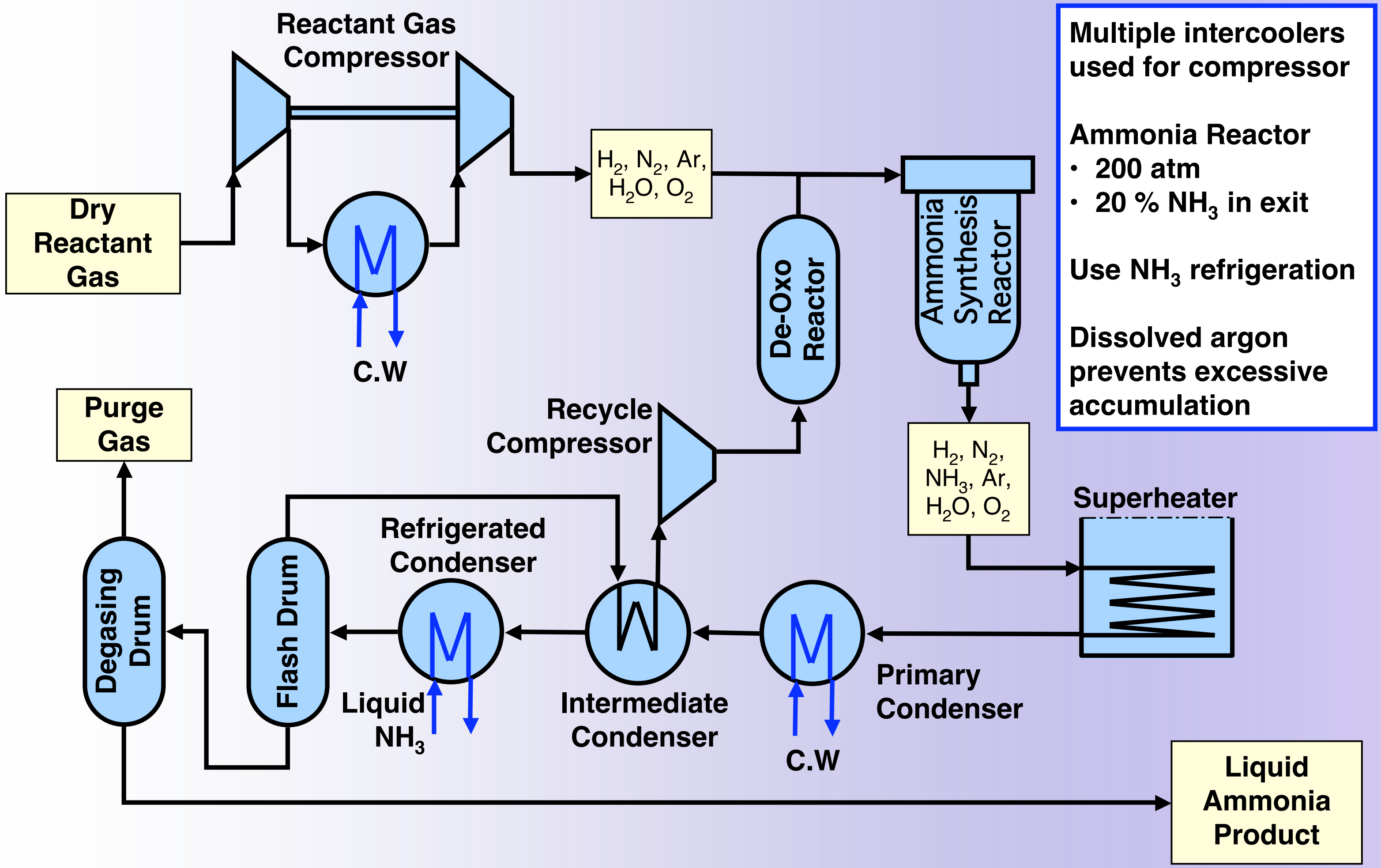
# Baseline Process Design: Pressure Swing Adsorption Flowsheet



**Absorber beds remove $CO_2$**

**De-oxo reactor reduces $O_2$ to 5 ppm**

# Baseline Process Design: Ammonia Process Flowsheet



**Multiple intercoolers used for compressor**

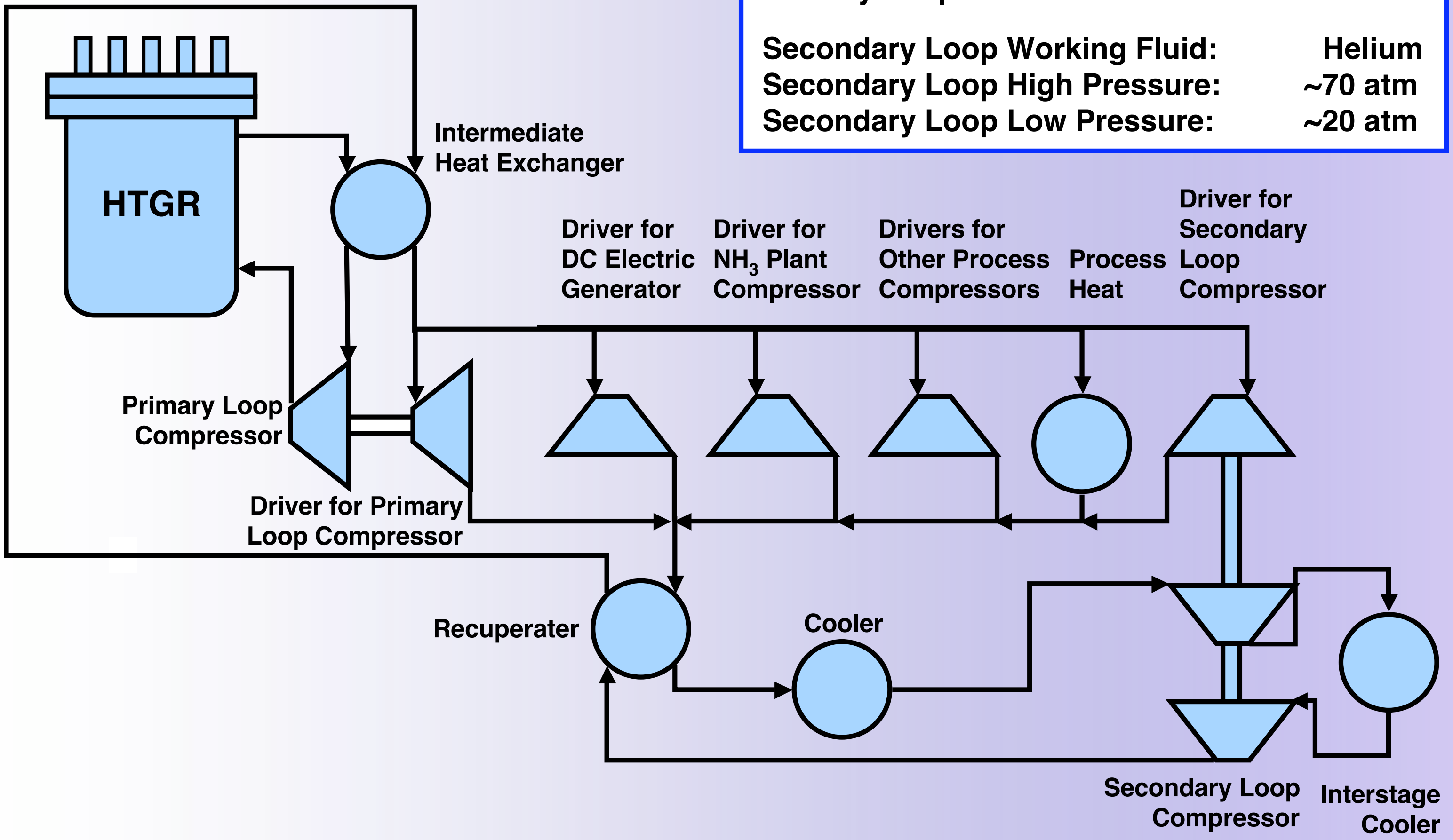
**Ammonia Reactor**
- **200 atm**
- **20 % $NH_3$ in exit**

**Use $NH_3$ refrigeration**

**Dissolved argon prevents excessive accumulation**

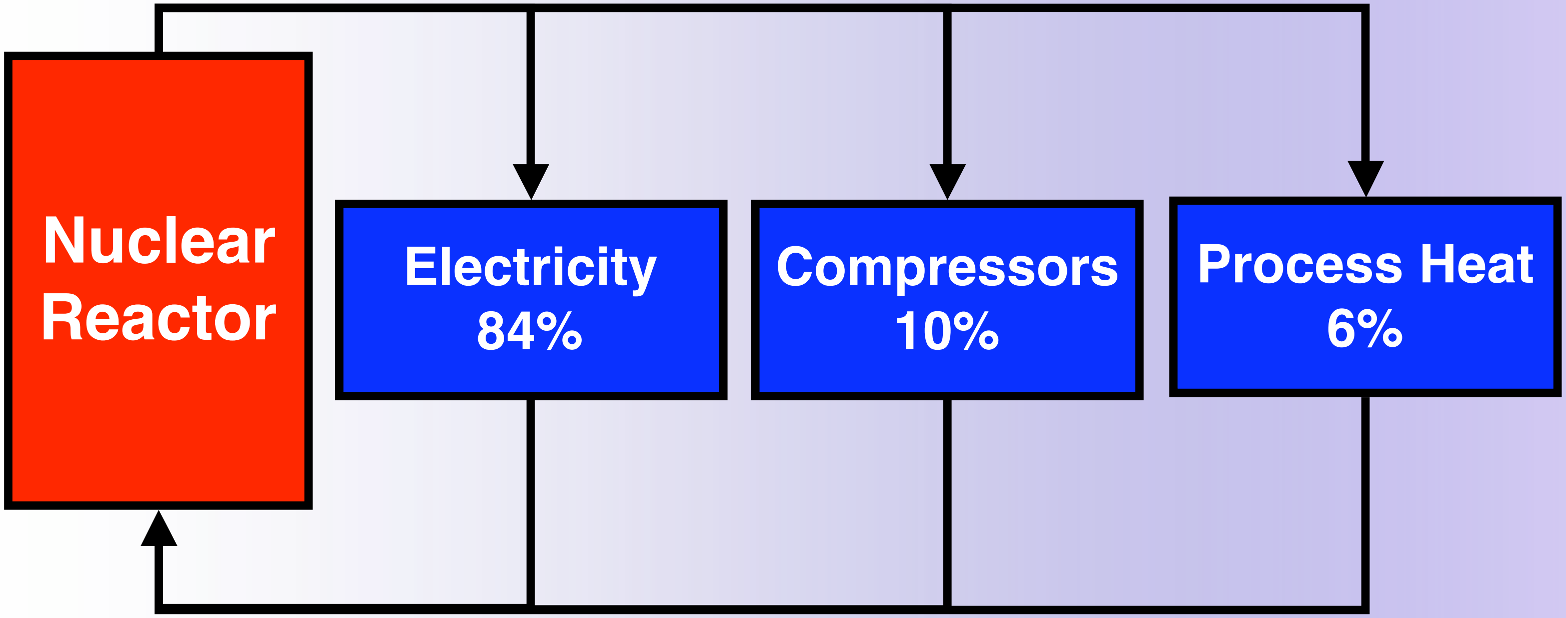
# Baseline Process Design: Fully Integrate Brayton Cycle

| | |
|---|---|
| **Primary Loop Working Fluid:** | **Helium** |
| **Primary Loop Pressure:** | **~70 atm** |
| **Secondary Loop Working Fluid:** | **Helium** |
| **Secondary Loop High Pressure:** | **~70 atm** |
| **Secondary Loop Low Pressure:** | **~20 atm** |



# Large Centralized Production

# Energy Consumption for HTGR-Powered Ammonia Process with Steam Electrolysis



**Nuclear Reactor**

**Electricity 84%**

**Compressors 10%**

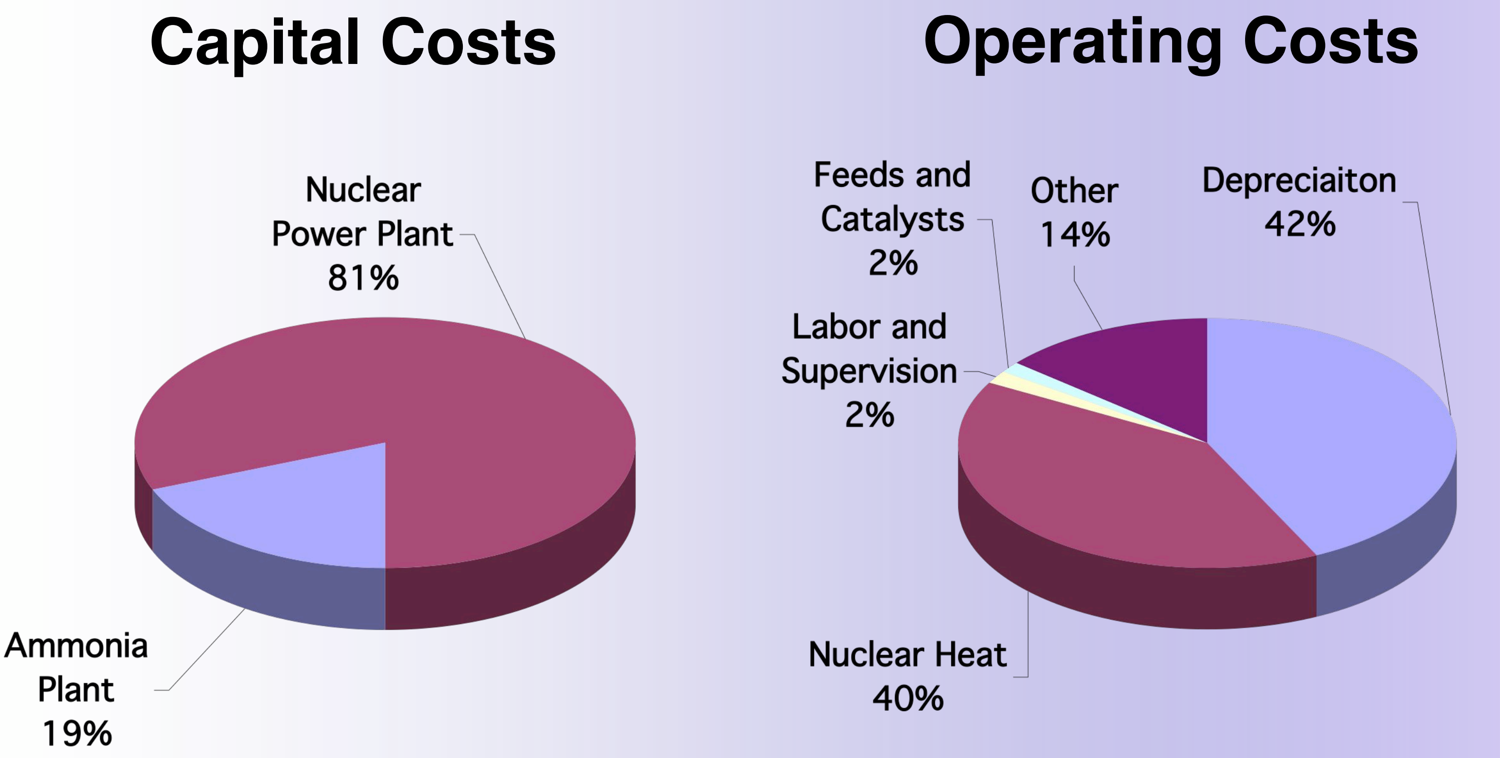
**Process Heat 6%**

# *Performance and Costs of Large Nuclear-Powered Ammonia Plants*

| Reactor Type | Hydrogen Process | Efficiency (MJ fuel* / $MJ_T$) | Capital Investment (million $) | Production Cost ($/tonne) |
|---|---|---|---|---|
| **HTGR with heat integration** | **Steam Electrolysis** | 0.48 | 1440 | 172 |
| **HTGR with no heat integration** | **Steam Electrolysis** | 0.41 | 1570 | 189 |
| **HTGR** | **Water Electrolysis** | 0.37 | 1590 | 187 |
| **ABWR with heat integration** | **Steam Electrolysis** | 0.29 | 1540 | 196 |
| **ABWR** | **Water Electrolysis** | 0.23 | 1680 | 200 |

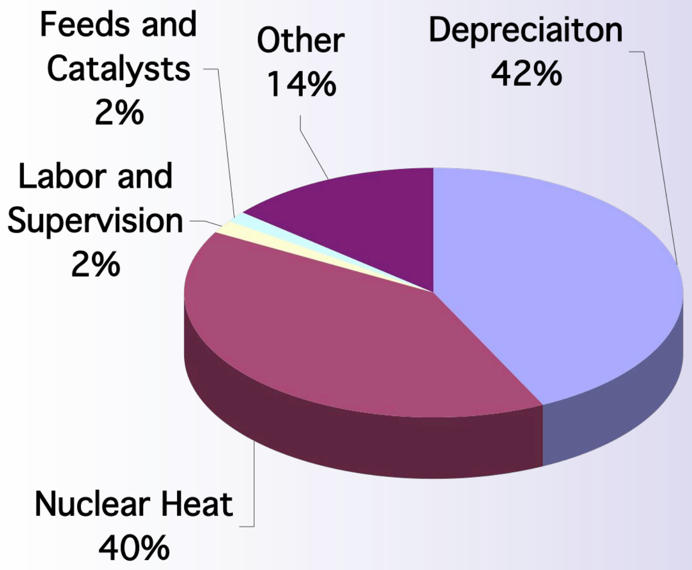
* Fuel value based on higher heating value

# Cost Breakdown for HTGR-Powered Steam-Electrolysis Plant

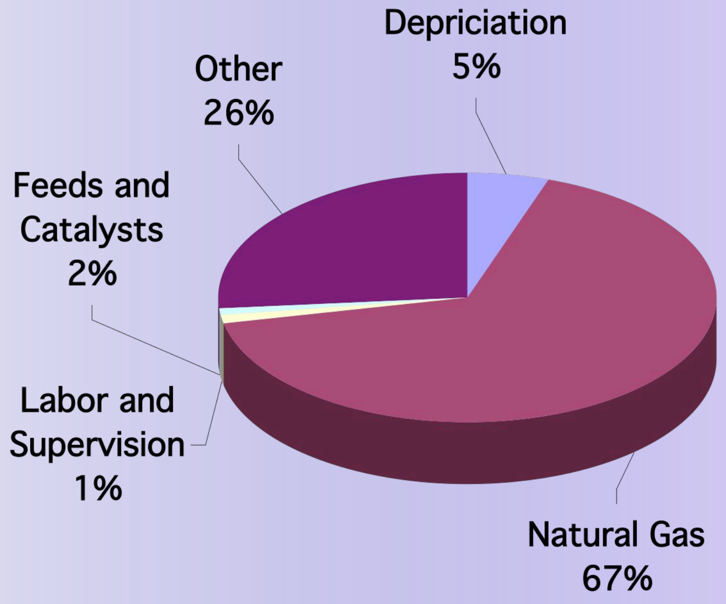


# Depreciation is the Largest Component of Operating Costs for a Nuclear-Powered Ammonia Plant

## HTGR-Powered Plant



## Steam Reforming Plant



# *Lessons for Study of Large Nuclear-Powered Ammonia Plants*

- **Efficiency is not the most important factor affecting the economic viability of a nuclear-powered ammonia plant**
  - **Efficiency varied by a factor of 2 for cases studied**
  - **Capital investment and operating costs only varied by 16%**
- **None of the options considered in this study was clearly superior to the others**
  - **Accuracy of the estimates is ±30%**
  - **Capital costs of steam electrolysis and water electrolysis differ by <10%**
  - **Capital costs of an HTGR and a ABWR differ by <10%**

# Small Modular Reactors

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# *The US Department of Energy's Global Nuclear Energy Partnership (GNEP)*

- **The goal of GNEP is to expand the worldwide use of economical, environmentally responsible nuclear energy to meeting growing electricity demand while virtually eliminating the risk of nuclear material misuse**

- **An important element of the GNEP program is grid-appropriate reactors**
  - **Small, proliferation-resistant reactors suitable for developing countries**
  - **Built in standardized modules that generate 50 - 300 $MW_e$**
  - **Feature fully passive safety systems**
  - **Simple to operate**
  - **Highly secure**

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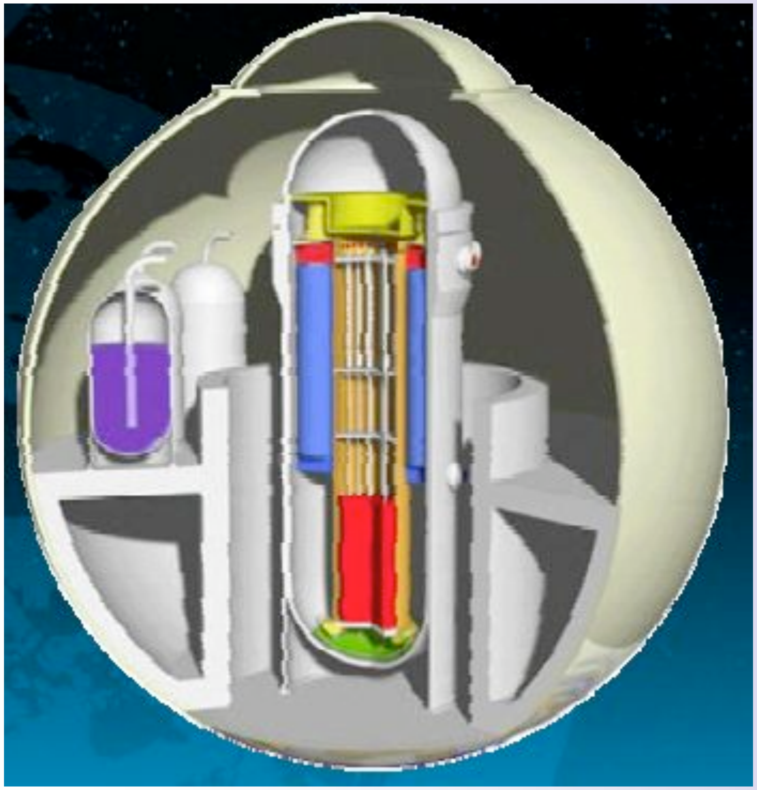
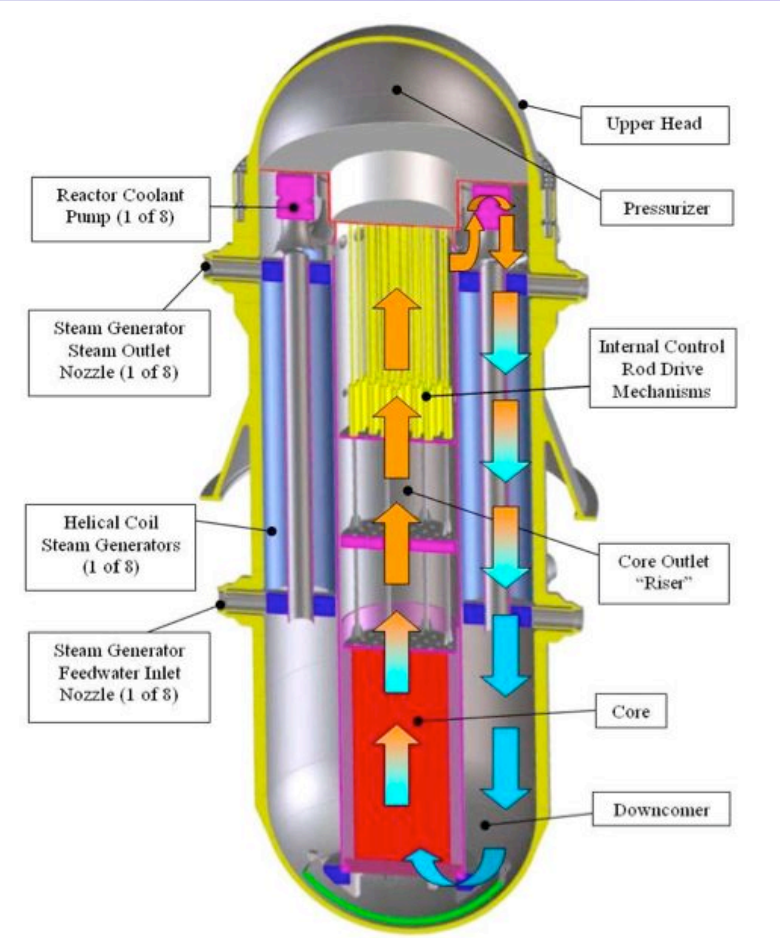
# *The International Reactor - Safe and Secure (IRIS) is an Example of a Grid-Appropriate Reactor*

**IRIS is a Westinghouse-designed PWR that generates up to 335 MW$_e$**





# *Other Modular Reactor Designs*

| Reactor | Manufacturer Country | Type | Power ($MW_e$) | Efficiency (%) | Temperature (°C) |
|---|---|---|---|---|---|
| **IRIS** | **Westinghouse<br>USA** | **PWR** | **50 - 335** | **33.5** | **328** |
| MSBWR | GE<br>USA | BWR | 50 & 200 | - | - |
| GT - MHTR | General Atomics<br>USA | HTGR | 285 | - | - |
| VBER-150 | Russia | PWR | 110 | 31.5 | - |
| CAREM | CNEA & INVAP<br>Argentina | PWR | 27 | 27.0 | - |
| SMART | South Korea | PWR | 100 | 30.3 | - |
| MRX | JAERI<br>Japan | PWR | 50 -300 | - | - |
| **GTHTR** | **JAERI<br>Japan** | **HTGR** | **300** | **47.0** | **850** |
| HTGR-PM | Chinergy<br>China | Pebble Bed Reactor | 195 | - | 700 |
| NP-300 | Techocatome<br>France | PWR | 100 -300 | - | - |

# *Performance and Costs of Nuclear-Powered Ammonia Plants*

| Reactor Type | Production (tonne $NH_3$/day) | Efficiency (MJ fuel* / $MJ_T$) | Capital Investment (million $) | Production Cost ($/tonne) |
|---|---|---|---|---|
| **IRIS** | 1120 | 0.29 | 580 | 201 |
| **GTHTR** | 1080 | 0.42 | 700 | 227 |
| **HTGR** | 2100 | 0.48 | 1440 | 172 |
| **ABWR** | 2100 | 0.29 | 1540 | 196 |

* Fuel value based on higher heating value

# Comparison of Alternatives

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# *Alternatives to be Considered*

- **Nuclear options**
  - **Large HTGR with steam electrolysis**
  - **ABWR with steam electrolysis**
  - **IRIS with steam electrolysis**
  - **GTHTR with steam electrolysis**

- **Non-nuclear options**
  - **Steam reforming natural gas with and without carbons sequestration and a natural gas price of $7.25 / MMBTU**
  - **Partial oxidation of coal with and without carbons sequestration and a coal price of $35 / short ton**
  - **Wind-powered plant based on water electrolysis**

# *Comparison of Alternatives*

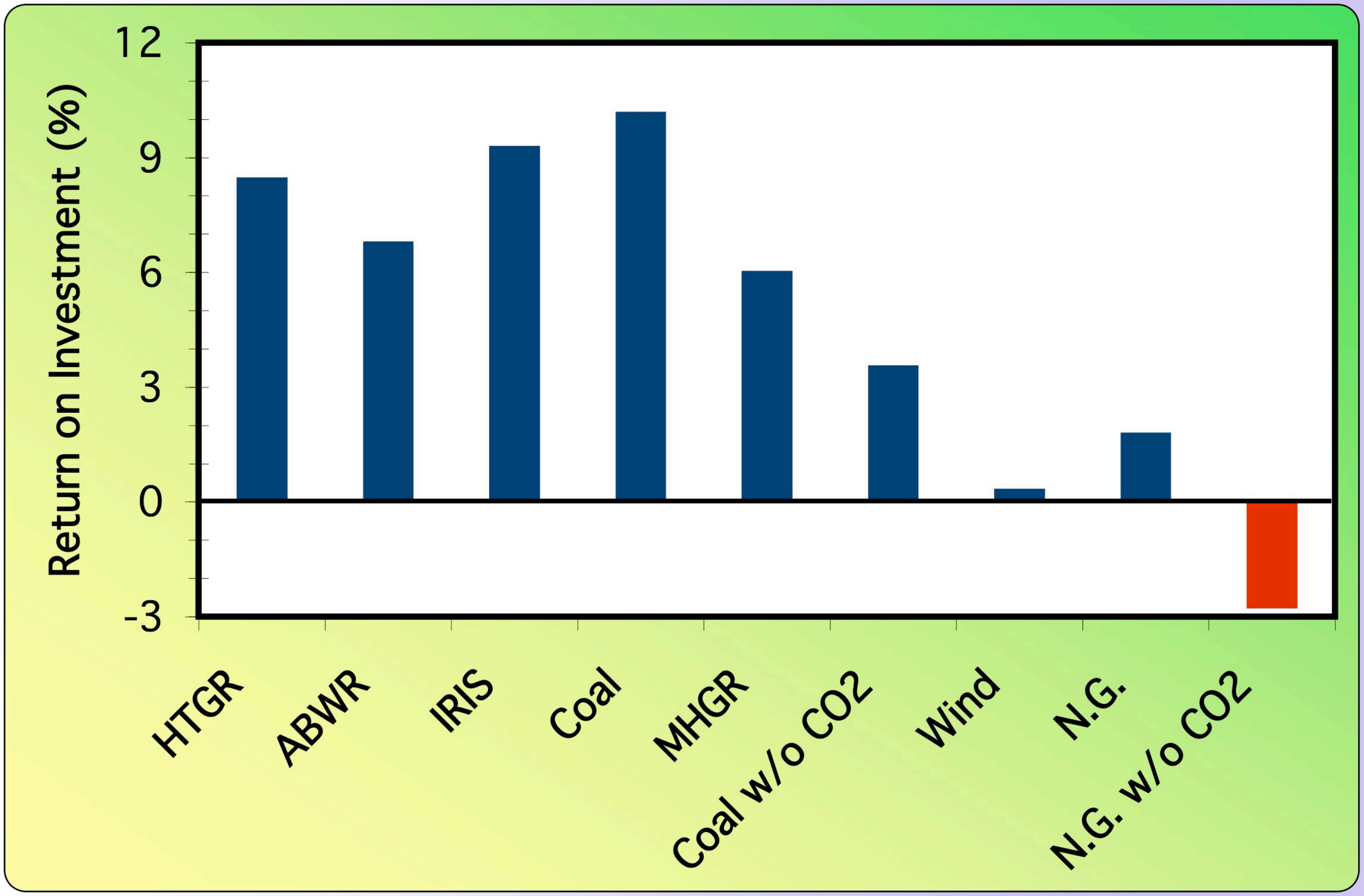
| Process | Production (tonne $NH_3$/day) | Efficiency (MJ fuel* / $MJ_T$) | Capital Investment (million $) | Production Cost ($/tonne) |
|---|---|---|---|---|
| Historic Average | - | - | - | 165 |
| HTGR | 2100 | 48.3 | 1440 | 172 |
| ABWR | 2100 | 29.4 | 1540 | 196 |
| IRIS | 1120 | 28.7 | 580 | 201 |
| Coal | 2100 | 42.7 | 870 | 218 |
| GTHTR | 1080 | 41.5 | 700 | 227 |
| Coal w/sequestration | 2100 | 39.5 | 1000 | 291 |
| Wind | 2100 | - | 4000 | 321 |
| Natural Gas | 2100 | 79.0 | 360 | 331 |
| June 2006 Price | - | - | - | 340 |
| Natural gas w/ Sequestration | 2100 | 76.4 | 420 | 356 |

* Fuel value based on higher heating value

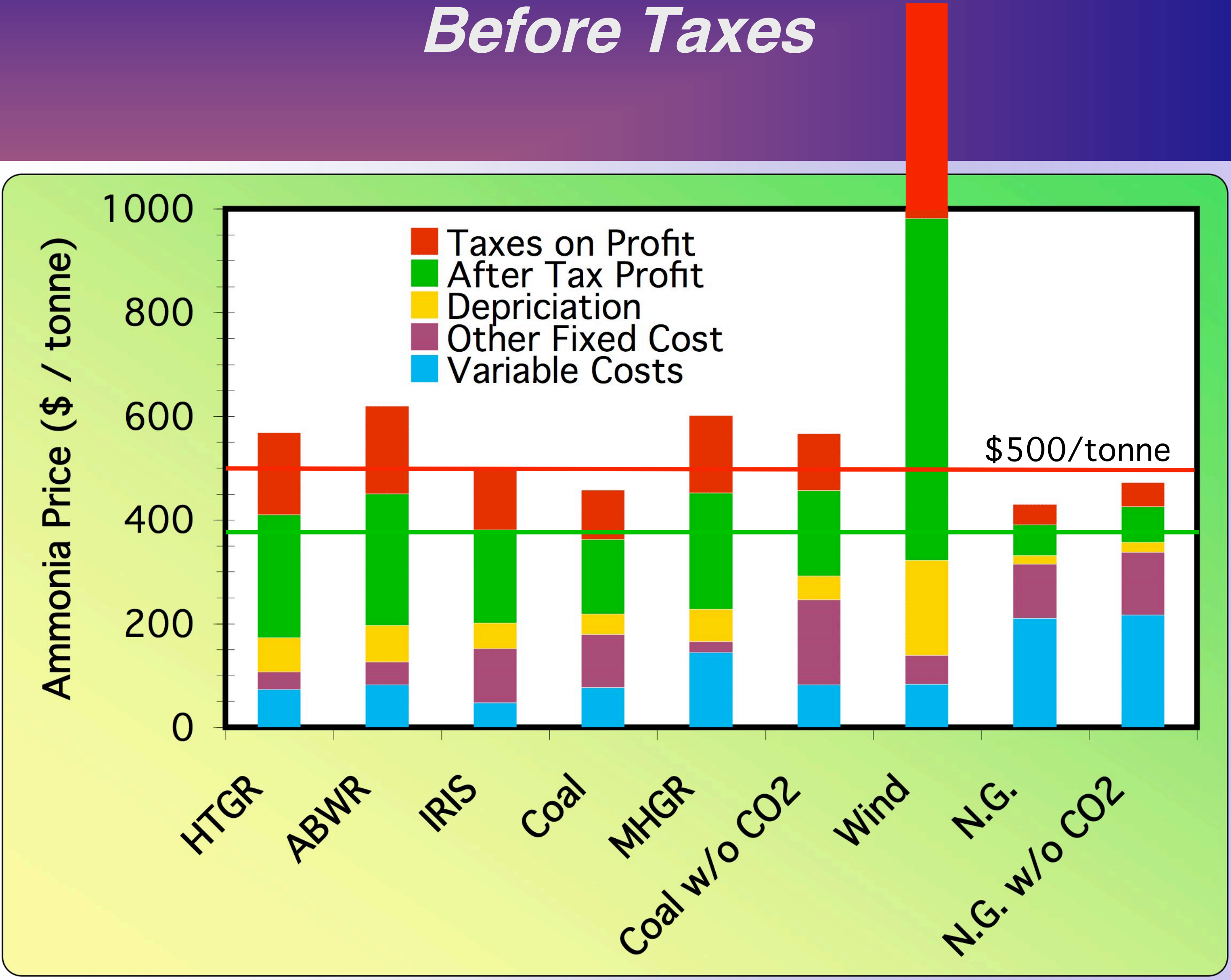
# Observations

- **Nuclear-powered ammonia production has the lowest operating costs**
  - **10 - 20% less than partial oxidation of coal**
  - **40 - 50% less than steam reforming methane**
- **Nuclear-powered ammonia production has the highest capital costs**
  - **65 - 75% more than partial oxidation of coal**
  - **400 - 430% more than steam reforming methane**
- **Efficiency is not a good indicator of operating costs or capital costs**
  - **Efficiency of ABWR plant 60% less than HTGR plant**
  - **Capital investment for ABWR plant only 7% greater**
  - **Production costs for ABWR plant only 14% greater**

# Before Tax Return on Investment Assuming an Ammonia Price of $340 / tonne



# *Ammonia Price Needed to Earn a 20% ROI Before Taxes*



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# *Observations*

- **At $340 / tonne, an ammonia plant is not an attractive investment**

- **An IRIS-powered plant may be the best method of producing ammonia without carbon dioxide emissions**
  - **Highest rate of return at current ammonia prices**
  - **Price to earn 20% ROI is comparable to natural gas with carbon sequestration**
  - **ROI is not sensitive to fluctuations in natural gas and ammonia prices**
  - **Does not required exotic technologies**

- **Capital investment, not efficiency, is the most important factor governing the economics of nuclear-powered ammonia production**

# *Summary and Conclusions*

- **The main advantages of nuclear-powered ammonia production are**
  - **Uses readily available raw materials (air and water)**
  - **Low, stable operating costs**
  - **No carbon dioxide production**

- **High capital costs are the major disadvantage of nuclear-powered ammonia production**

- **Smaller, standardized modular reactors could reduce capital costs**
  - **Reduce construct cost and time**
  - **Reduce licensing cost and time**

# Transportable Ammonia Production

# *Ammonia is a Possible Petroleum-Free Military Fuel*

- **Advantages**
  - **Readily available world-wide**
  - **Can be produced from a variety of raw materials**
  - **Can be used in a variety of power systems (diesel, turbines, fuel cells)**
  - **Could be produced in or near the theater of operations from air and water**

- **Disadvantages**
  - **More difficult to handle and transport than hydrocarbon fuels**
  - **Not a good fuel for aircraft**

# Some Considerations When Producing Ammonia in the Theater of Operation

- **Would like to maximize production, so yield is a more important consideration than capital cost**
- **Would like to maximize flexibility**
  - **Obtain power from local electrical grid if available**
  - **Use transportable nuclear reactor if local power unreliable**
- **Need a transportable ammonia plant and reactor**
- **Would like to simplify set-up and operations**

# Configuration for a Transportable Nuclear-Powered Ammonia Plant

- **The proposed ammonia plant is electric powered and uses steam electrolysis to produce hydrogen**
  - **Can be powered by a nuclearreactor or the local electrical grid**
  - **Simplifies the interface between the reactor and ammonia plant**
  - **Steam electrolysis plant consumes ~20% less power than a water electrolysis plant**

- **The ammonia plant will be powered by a small 10-MWt gas-cooled reactor**
  - **A pebble-bed reactor is the most likely choice**
  - **Power generated a a Brayton cycle or Stirling cycle**

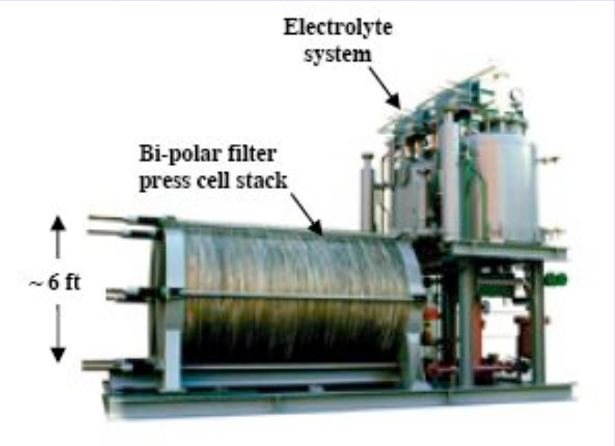
# Efficiencies of a Small Ammonia Plant Powered by a 10 $MW_t$ Reactor

| Reactor Type | Reactor Outlet Temperature (°C) | Production Rate (tonne/day) | Efficiency ($MJ_{fuel}$ / $MJ_t$) |
|---|---|---|---|
| **Pebble Bed** | **950** | **16** | **0.42** |
| **Pebble Bed** | **850** | **15** | **0.39** |
| **PWR** | **328** | **11** | **0.28** |

# *Skid Mounted Sections of a Small Ammonia Plant Commercially Available*

- **Commercially available equipment**
  - **Electric-powered boilers**
  - **PSA nitrogen plants**
  - **Ammonia refrigeration**
  - **Compressor**
- **Other equipment expected to be small**
  - **Electrolyzers**
  - **Ammonia reactors**

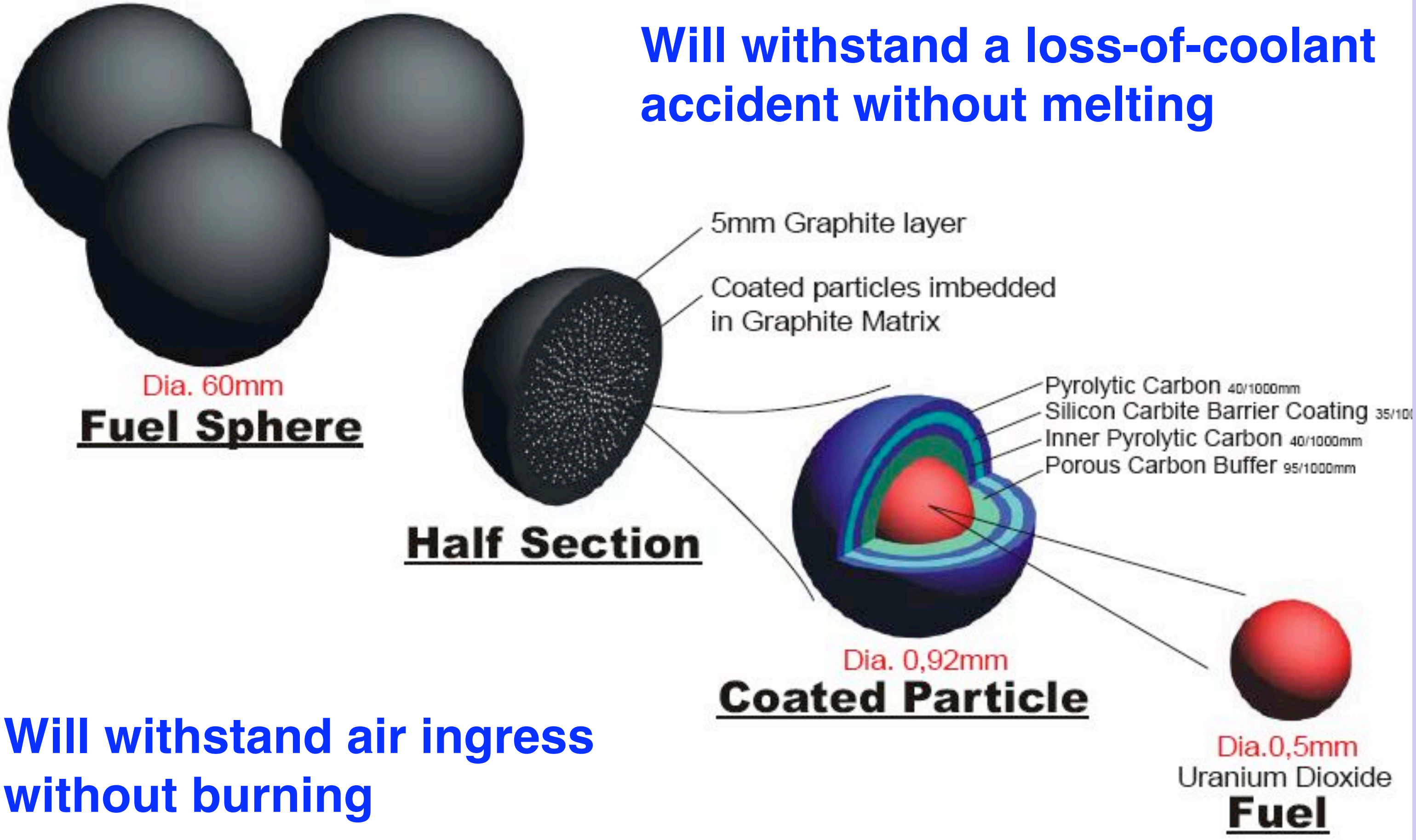
**Small PSA nitrogen plant**



**Likely scale of electrolyzers**

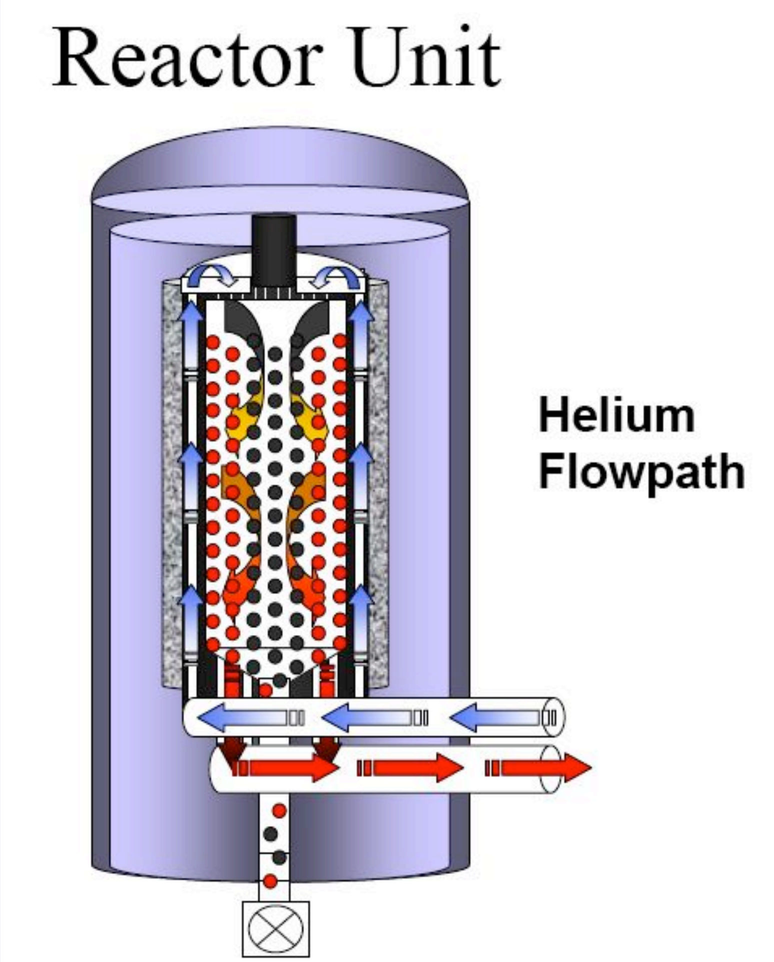
# *The TRISO Fuel Particles Used in a Pebble Bed Reactor Are the Primary Barriers to the Release of Radioactive Materials*

**Will withstand a loss-of-coolant accident without melting**



**Will withstand air ingress without burning**

# A Proposed Pebble Bed Reactor Design



# Reactor Shielding Provided by an Earthen Barrier