LA-UR-06-1846

An Analysis of a Nuclear-Powered Ammonia Plant

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April 2006

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Why Ammonia?

- **The ammonia industry is currently the largest consumer of hydrogen in the world**
  - Annual domestic ammonia production is 18,500,000 tons
  - Annual global ammonia production is 123,000,000 tons
- **Ammonia is a potential hydrogen carrier**
  - **Has more than twice the energy density of liquid or compressed (10,000 psig) hydrogen**
  - **A well developed technology exists for transporting, storing, and handling ammonia safely**
  - **Could be burned in an internal combustion engine or used in an ammonia fuel cell**
  - **Could be reformed to produce hydrogen for use in a fuel cell**

PROCESS FLOWSHEET

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)

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**
  - **Capital costs likely to be significantly lower than thermochemical processes**

- **Water electrolysis evaluated as a possible option**
  - **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**

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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 consumes less energy that a cryogen air separation plant but produces lower purity nitrogen**
  - **Removes carbon dioxide, but …**
  - **The nitrogen product contains 0.1 - 2% oxygen**

- **In commercial PSA plants, oxygen is reduced to ppm levels by a catalytic reaction with hydrogen**

Choice of Nuclear Power System

- **Cycle efficiency is the primary consideration**
  - **The efficiency of generating electricity is the dominant factor affecting overall process efficiency**
- **A high-temperature gas-cooled reactor (HTGR) with a Brayton cycle is the 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 PWR with a Rankine cycle also evaluated as a possible option**
  - **Less efficient than an HTGR**
  - **Proven technology**

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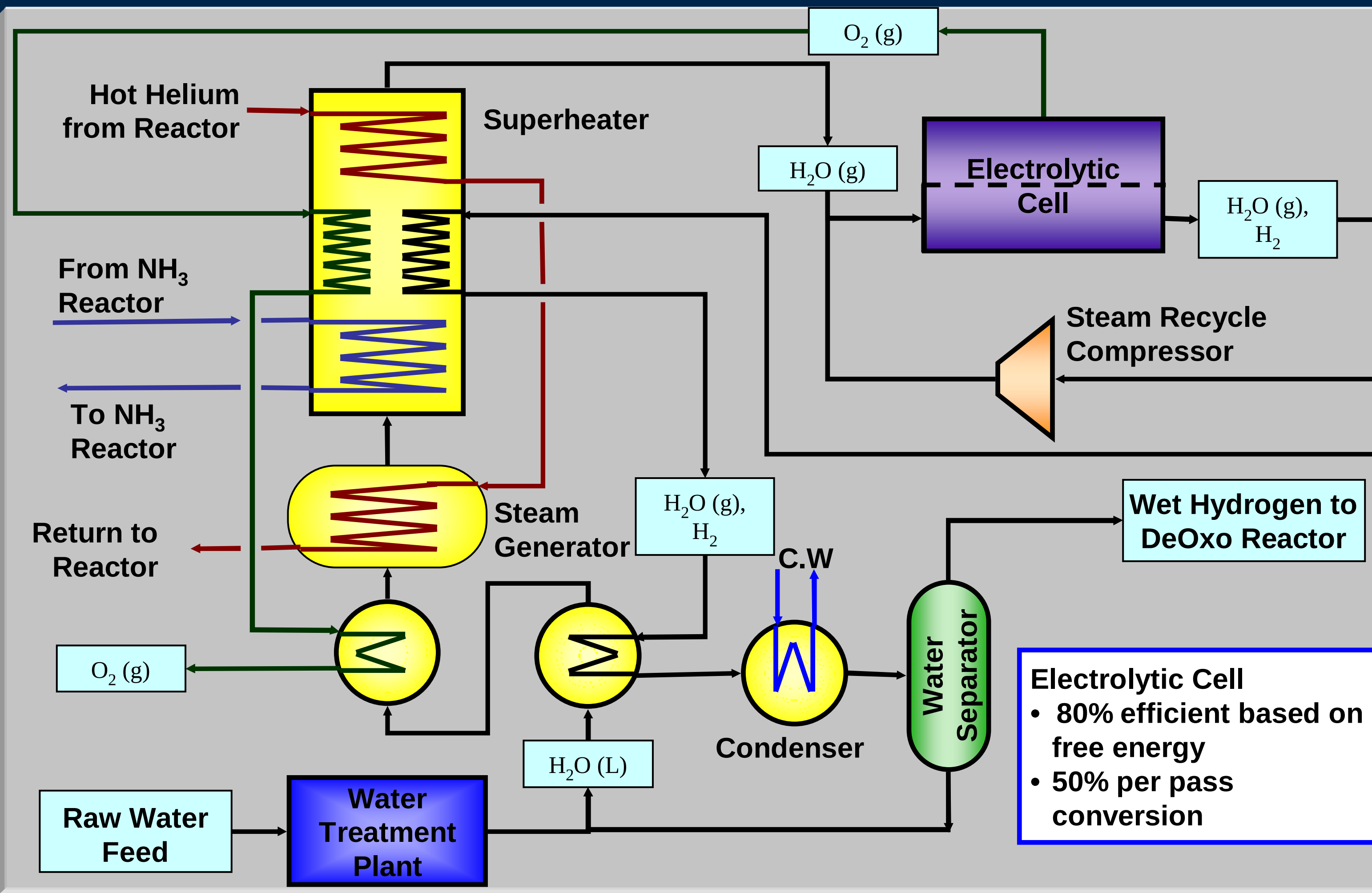
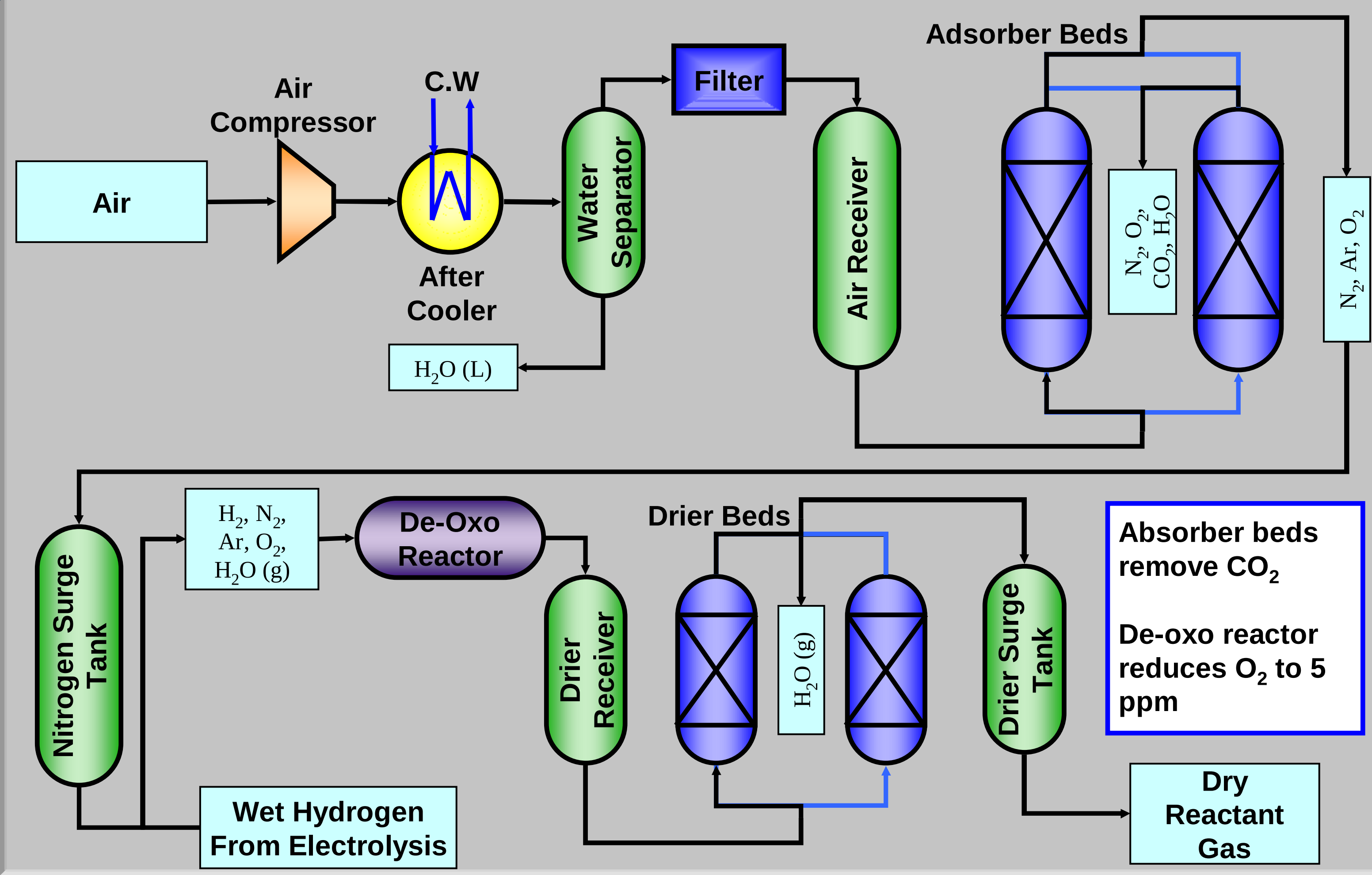
Baseline Process Design: Steam Electrolysis Flowsheet



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

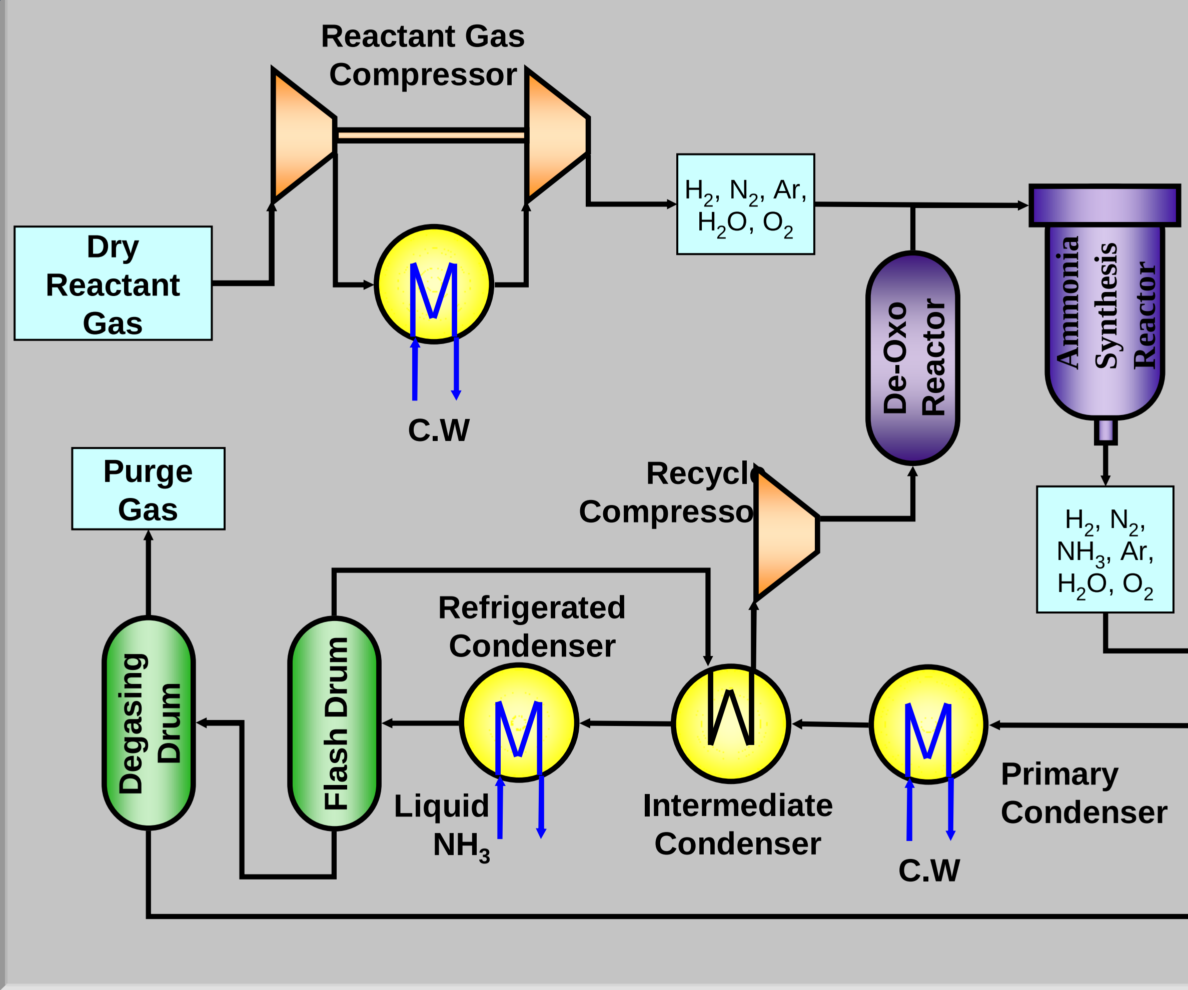
Baseline Process Design: Pressure Swing Adsorption Flowsheet



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

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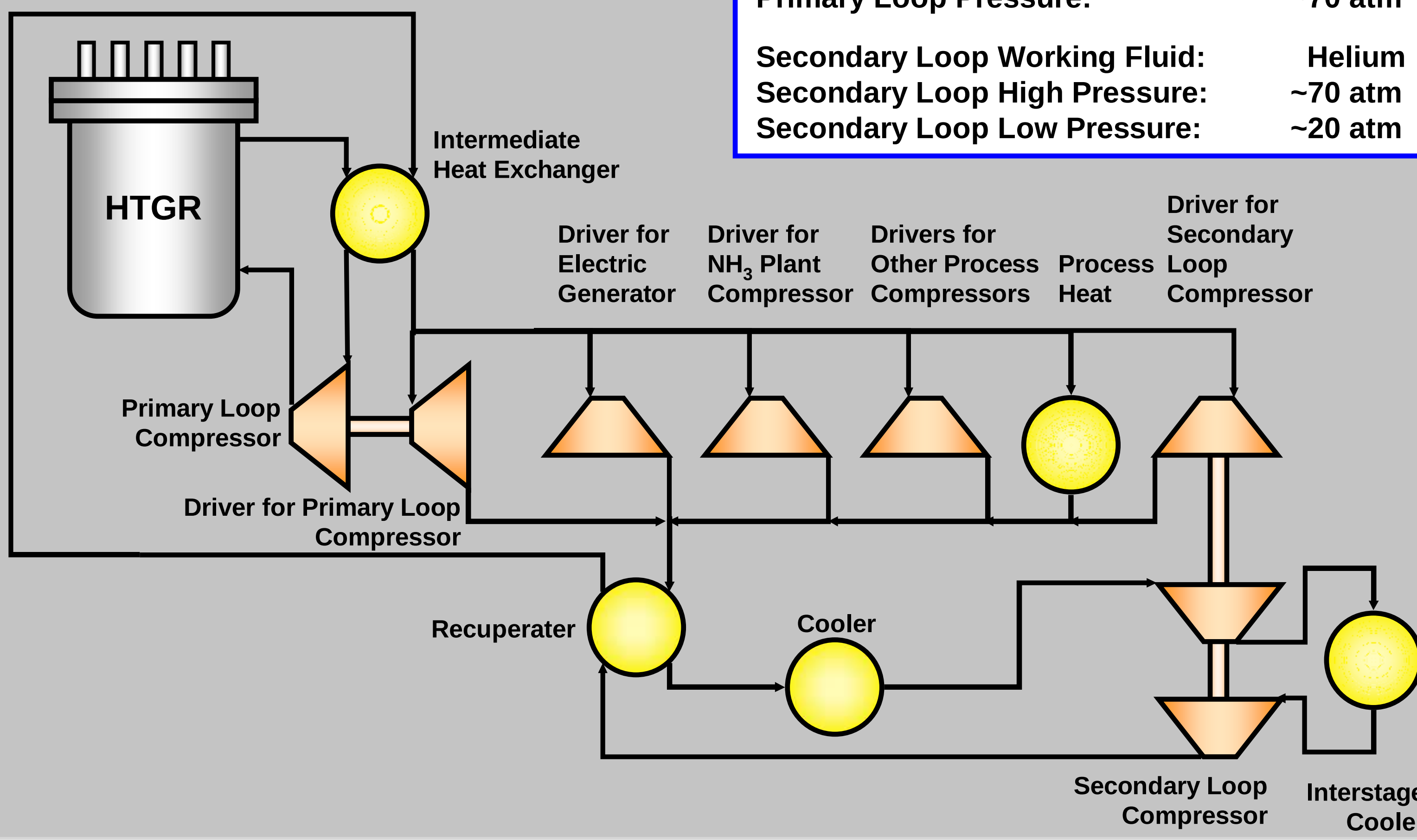
Baseline Process Design: Brayton Cycle Power System

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

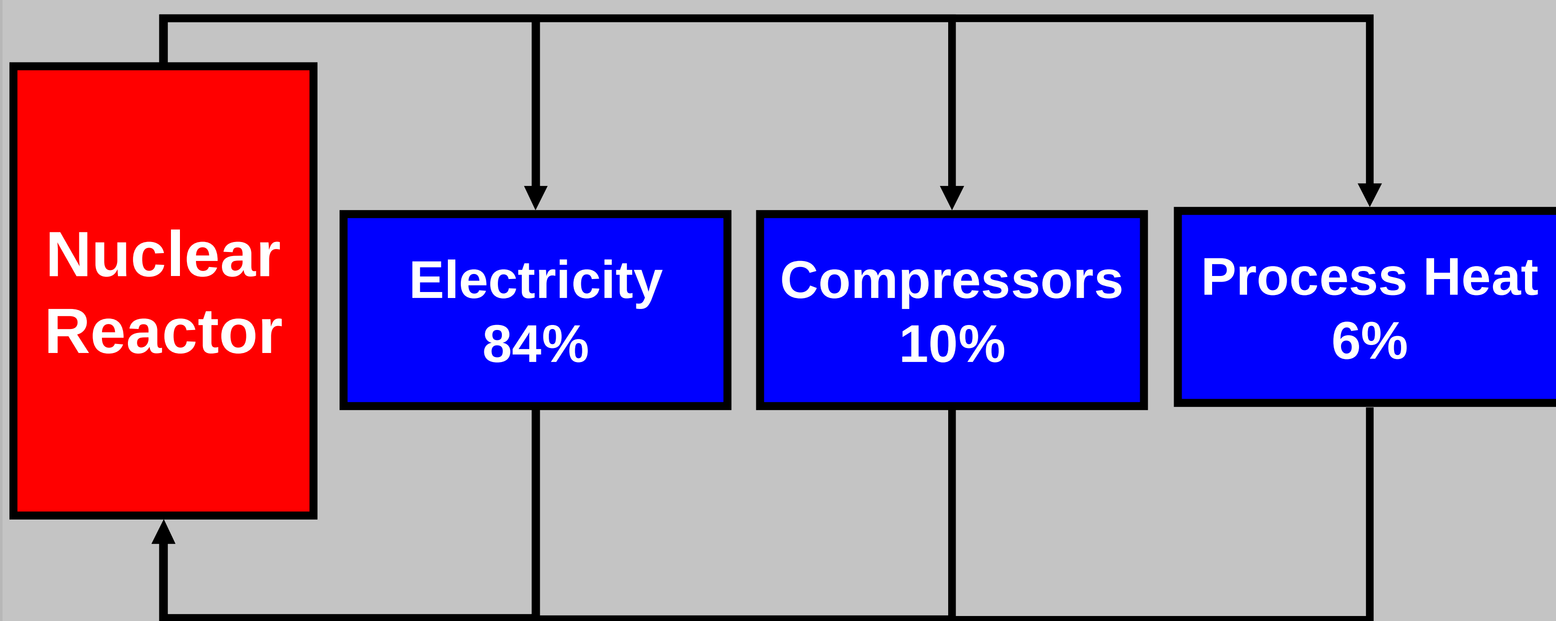


Comparison of Nuclear Options

Reactor Type	Hydrogen Process	Energy Required (kwh_t/tonne)	Efficiency (MJ Fuel / MJ Thermal)
HTGR* with Heat Integration (baseline)	**Steam Electrolysis**	**12,600**	**0.40**
HTGR*	**Water Electrolysis**	**14,200**	**0.35**
HTGR* with no Heat Integration	**Steam Electrolysis**	**14,700**	**0.34**
PWR	**Water Electrolysis**	**23,900**	**0.21**

*Based on a reactor exit temperature of 900℃

Power Consumption for the Baseline Process Design with Optimum Heat Integration



ECONOMIC ANALYSIS

Assumptions for Estimating Costs - Ammonia Unit

- **Capital Costs**
  - **Based on 2000 tonne / day plant**
  - **Estimates based on major equipment costs (±30%)**
  - **Single parameter models used to estimate equipment costs**
- **Operating Costs**
  - **Energy costs are the reactor operating costs**
  - **Other operating costs assumed to be equivalent to convention ammonia plant**
  - **Assume 30-yr depreciation period (**based on nuclear reactor life**)**
  - **Assume periodic major overhauls (**needed to achieve 30-year plant life**)**

Assumptions for Estimating Costs - Nuclear Reactor

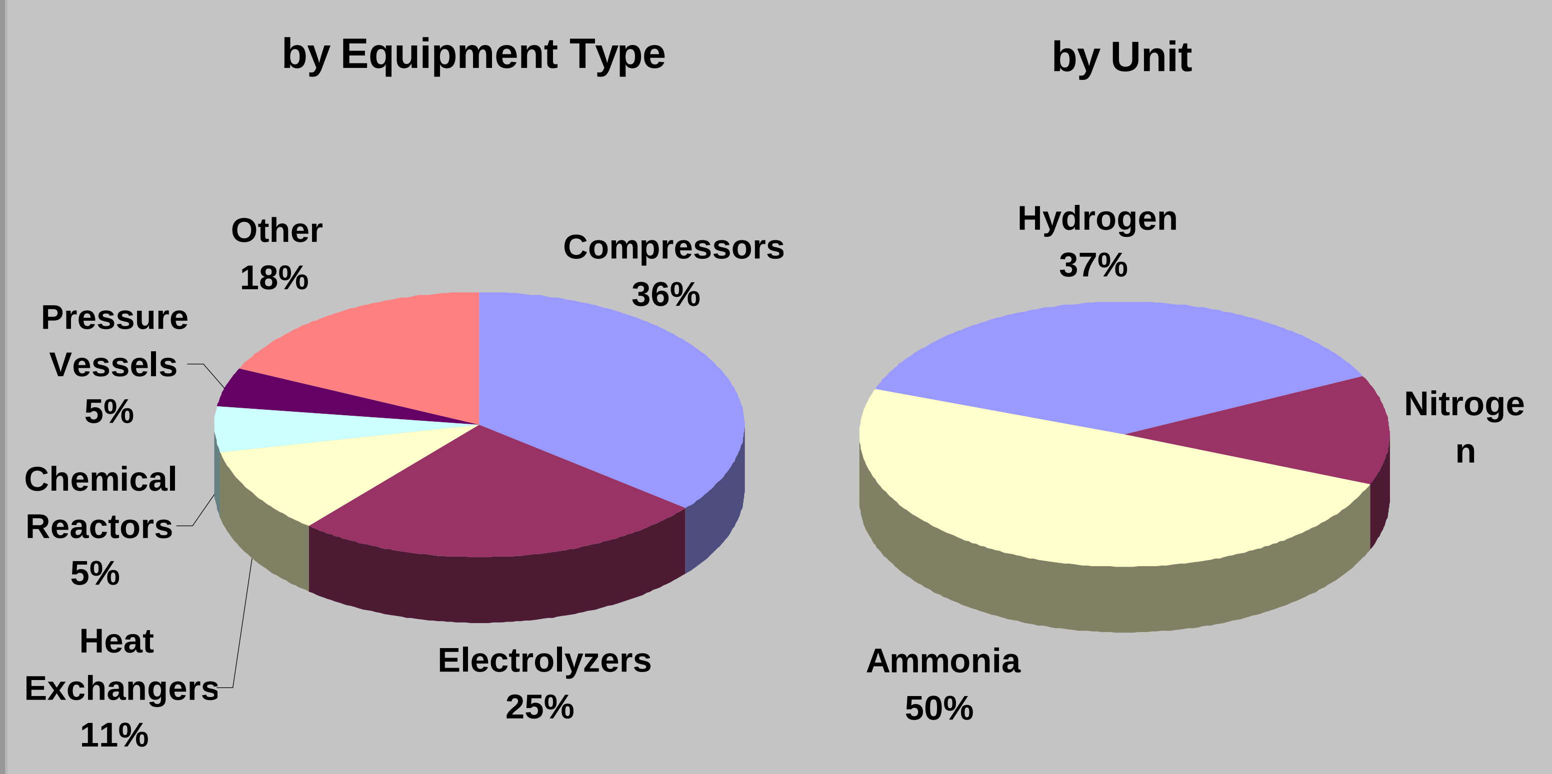
- Capital Costs
  - HTGR capital cost based on General Atomics study of a modular helium reactor (D. Alberstein, 1996)
  - PWR capital cost based on Palo Verde nuclear power station in Arizona
- HTGR operating cost assumed to be 0.55 ¢/kwh_t
  - Average for commercial nuclear power station
  - Comparable to estimated operating costs for modular helium reactor (D. Alberstein, 1996)
- PWR operating costs based on Palo Verde nuclear power station

Capital Costs for Alternatives

Reactor Type	Hydrogen Process	Ammonia Plant Cost (MM$)	Reactor Cost (MM$)	Total Cost (MM$)
HTGR* with Heat Integration (baseline)	Steam Electrolysis	270	1169	1439
HTGR*	Water Electrolysis	245	1274	1519
HTGR* with no Heat Integration	Steam Electrolysis	270	1303	1573
PWR	Water Electrolysis	245	2010	2255

*Based on a reactor exit temperature of 900℃

Capital Cost Breakdown of the Ammonia Unit for the Nominal Design

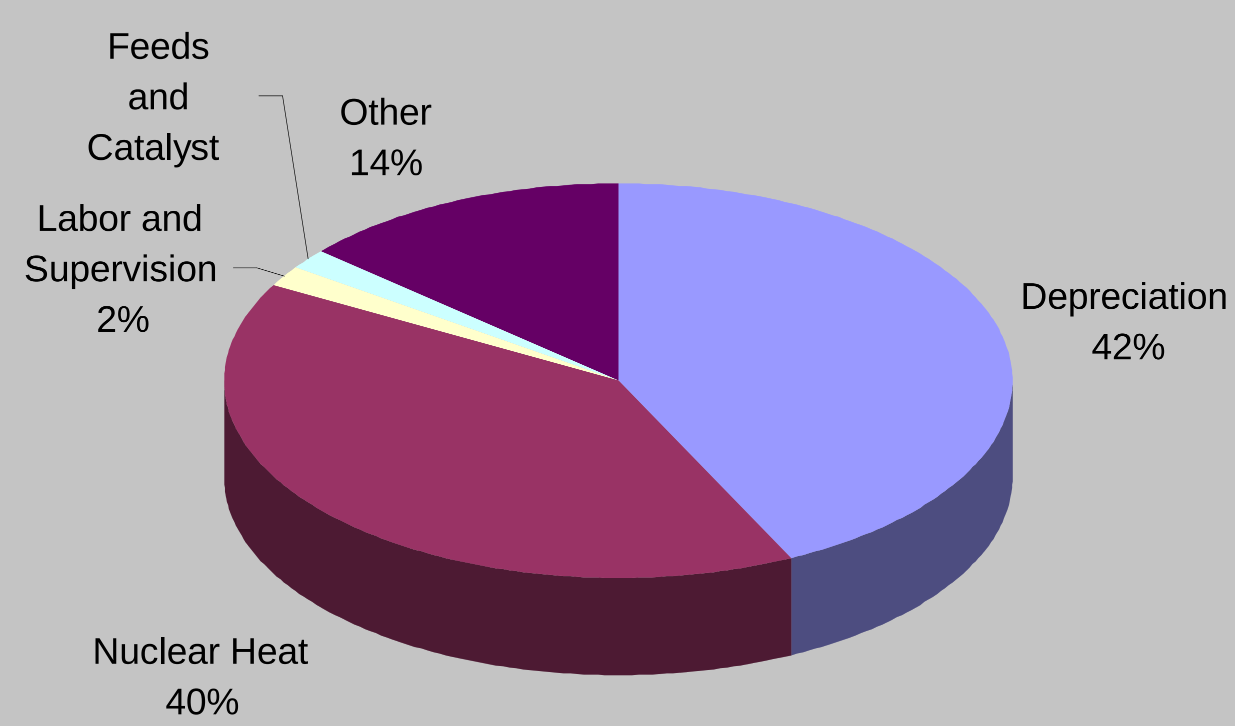


Operating Costs for Alternatives

Reactor Type	Hydrogen Process	Nuclear Heat ($/tonne)	Other Costs ($/tonne)	Total Cost ($/tonne)
HTGR* with Heat Integration (baseline)	**Steam Electrolysis**	**69**	**104**	**173**
HTGR*	**Water Electrolysis**	**78**	**103**	**181**
HTGR* with no Heat Integration	**Steam Electrolysis**	**81**	**108**	**189**
PWR	**Water Electrolysis**	**131**	**132**	**263**

*Based on a reactor exit temperature of 900℃

Breakdown of Operating Costs for the Nominal Design



Coal and Natural Gas Ammonia Plants Consider for Comparisons

- **Coal**
  - Most economic alternative to natural gas for ammonia production given current prices
  - Estimates based on 45.5 MMBtu of coal per short ton of ammonia
  - Production cost based on a coal price of $36 / short ton
- **Natural Gas**
  - Most common raw material for ammonia production
  - Estimates based on 28.5 GJ of natural gas per tonne of ammonia
  - Production costs based on a natural gas price of $8.00 / 1000 scf

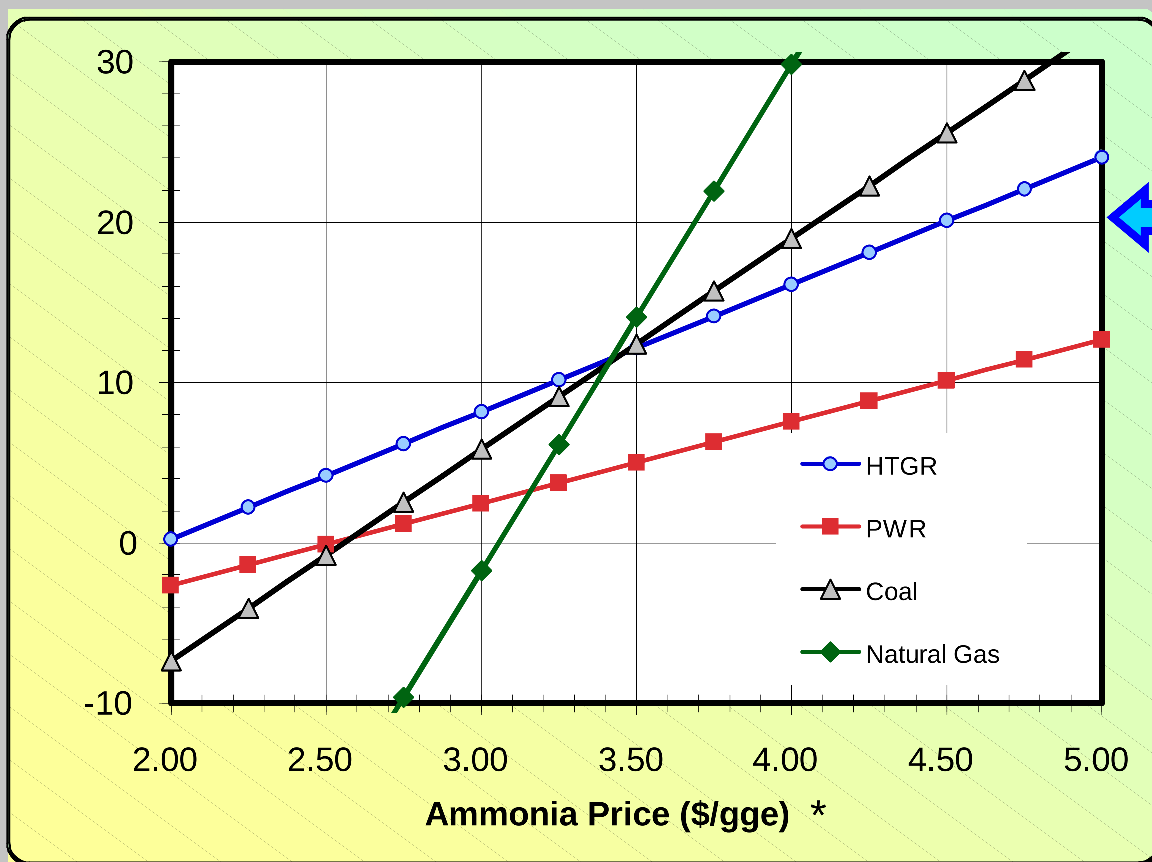
A Nuclear Powered Ammonia Plant Releases No Carbon Dioxide

- **Natural gas and coal plants release significant amounts of carbon dioxide**
  - **A natural gas plant releases 1.6 tonnes CO_2 / tonne NH_3**
  - **A coal plant releases 4.2 tonnes CO_2 / tonne NH_3**
- **Capital cost of carbon sequestration**
  - **Carbon dioxide separation is already part of the process**
  - **Carbon dioxide compressor and condenser required**
  - **Pipeline required (200 km pipeline at $310,000 / km)**
- **Operating costs**
  - **Compressor (0.44 GJ / tonne CO_2)**
  - **Pipeline ($0.02 / tonne CO_2 / km)**
  - **Disposal ($5.00 / tonne CO_2)**

Estimated Costs for a 2000 ton/day Ammonia Plant

Type of Plant	Efficiency (%)	Captial Cost (MM$)	Operating Cost ($/tonne)
Historic Average NH_3 Price	-	-	165
HTGR Powered Plant	40	1439	173
Jan 2005 Tampa Barge Price	-	-	260
PWR Powered Plant	21	2255	263
Coal Plant	39	868	265
Coal Plant with CO_2 Sequestration	38	996	311
Natural Gas Plant	65	362	343
Natural Gas with CO_2 Sequestration	63	452	369
Jan 2006 Tampa Barge Price	-	-	374

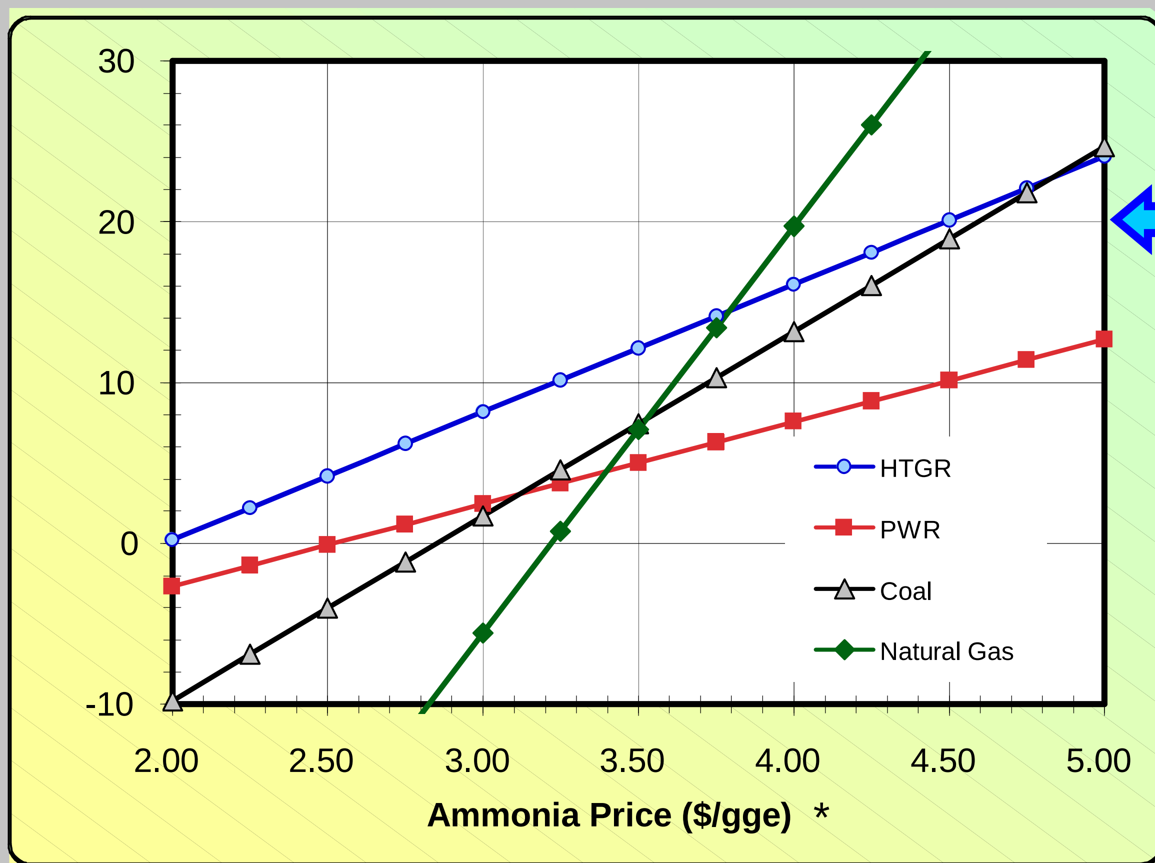
Natural Gas and Coal Plants Provide an Adequate Rate of Return at a Lower Retail Price than Nuclear Power



20% rate of return desired value for typical chemical plant

* Price to consumer at the pump including distribution costs and taxes

Nuclear is Competitive with Natural Gas and Coal with Carbon Sequestration



20% rate of return desired value for typical chemical plant

* Price to consumer at the pump including distribution costs and taxes

Summary

Process Economics

- **A HTGR-powered ammonia plant has the lowest production costs of the options considered in this study**
  - The estimated production cost is $1.10 / gge
- **High capital costs are the biggest economic obstacle to a viable nuclear-powered ammonia plant**
  - Capital cost is ~4X a conventional natural gas plant and ~1.7X a coal plant
  - A retail ammonia price of about $4.50 / gge is needed to earn an adequate return on investment
- **A nuclear-powered plant may be best means of ammonia production without carbon dioxide emissions**
  - ROR less sensitive to price fluctuations than natural gas
  - Better than a coal plant with carbon sequestration

Technological Obstacles

- **Achieving high cycle efficiency is the key to an economically viable nuclear-powered process for producing ammonia**
  - A HTGR or other high-temperature reactor needed to obtain the high cycle efficiency
  - The hydrogen processes is a lesser issue because steam electrolysis does not have a big economic advantage over conventional water electrolysis
- **The major technological obstacle achieving the necessary cycle efficiency is developing a commercial-scale high-temperature reactor**
  - R&D costs for an HTGR are on the order of $800 million
  - Safety regulations appropriate for a nuclear-powered chemical plant are needed