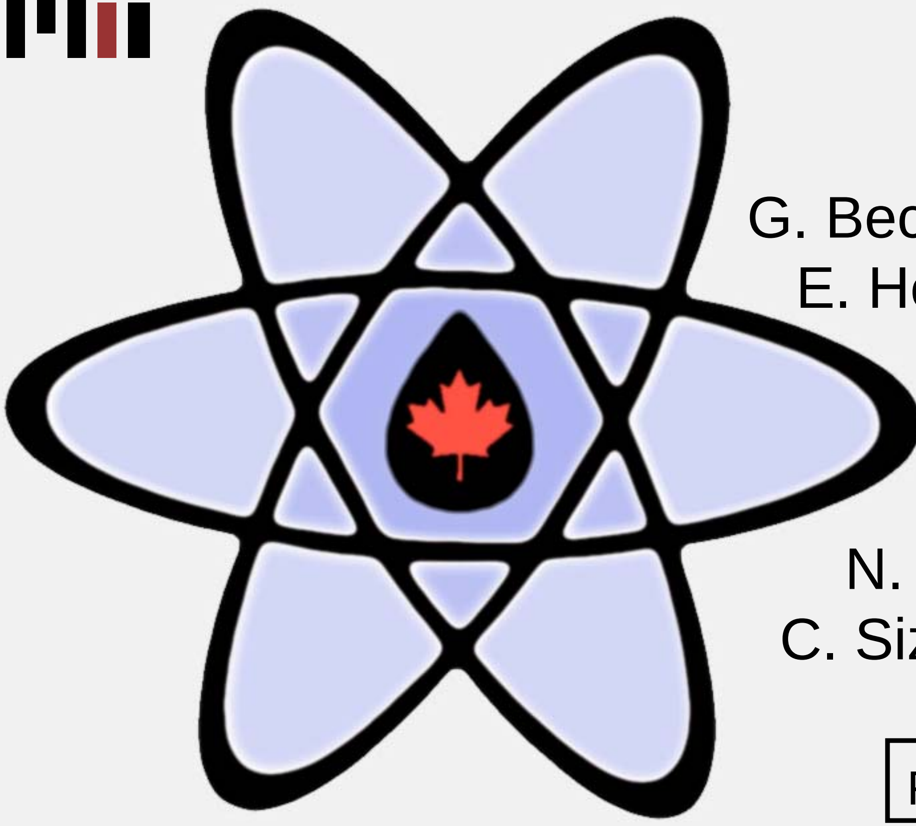


G. Becerra, E. Esparza, A. Finan,
E. Helvenston, S. Hembrador,
K. Hohnholt, T. Khan,
D. Legault, M. Lyttle,
K. Miu, C. Murray,
N. Parmar, S. Sheppard,
C. Sizer, L. Zakszewski, K. Zeller

Friday December 9th, 2005

Integration of Nuclear Power with Canadian Oil Sands

Purpose

- To analyze the feasibility of integrating a nuclear power plant with Steam-Assisted Gravity Drainage (SAGD), an oil extraction technology currently used in Canadian oil sands projects

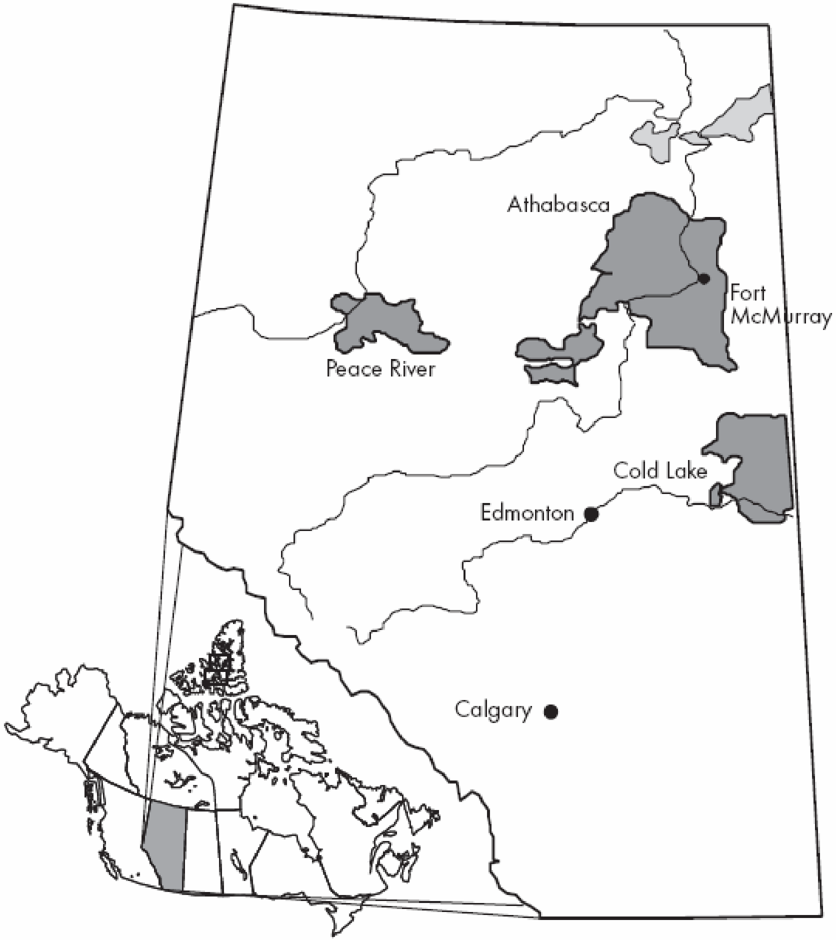
Outline

- Canadian Oil Sands
- Extraction Methods
- Natural Gas Usage
- Energy Requirements
- Nuclear Plant Designs
- Economics
- Nuclear Reactor Licensing
- Nuclear Waste Management
- Obstacles to Nuclear
- Opportunities
- Conclusion
- Questions

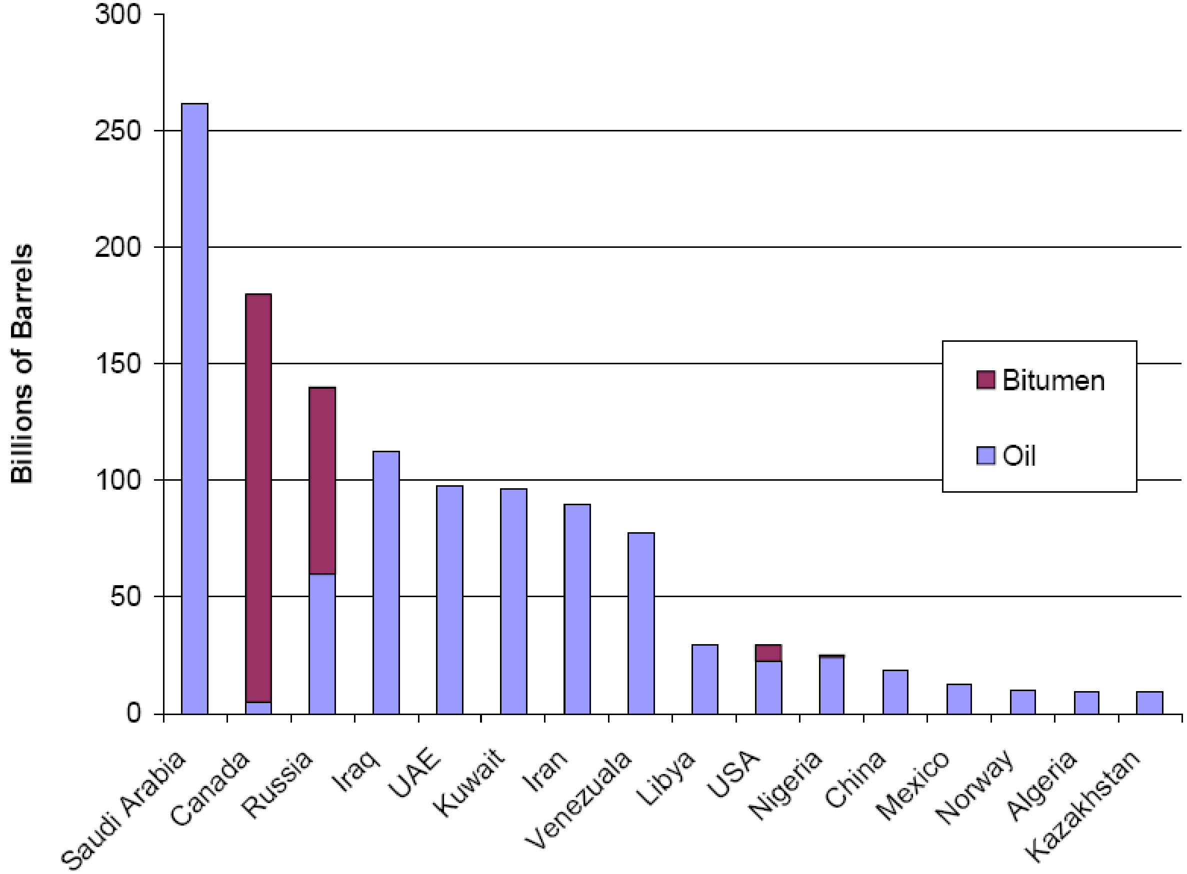
Canadian Oil Sands

Canadian Oil Sands

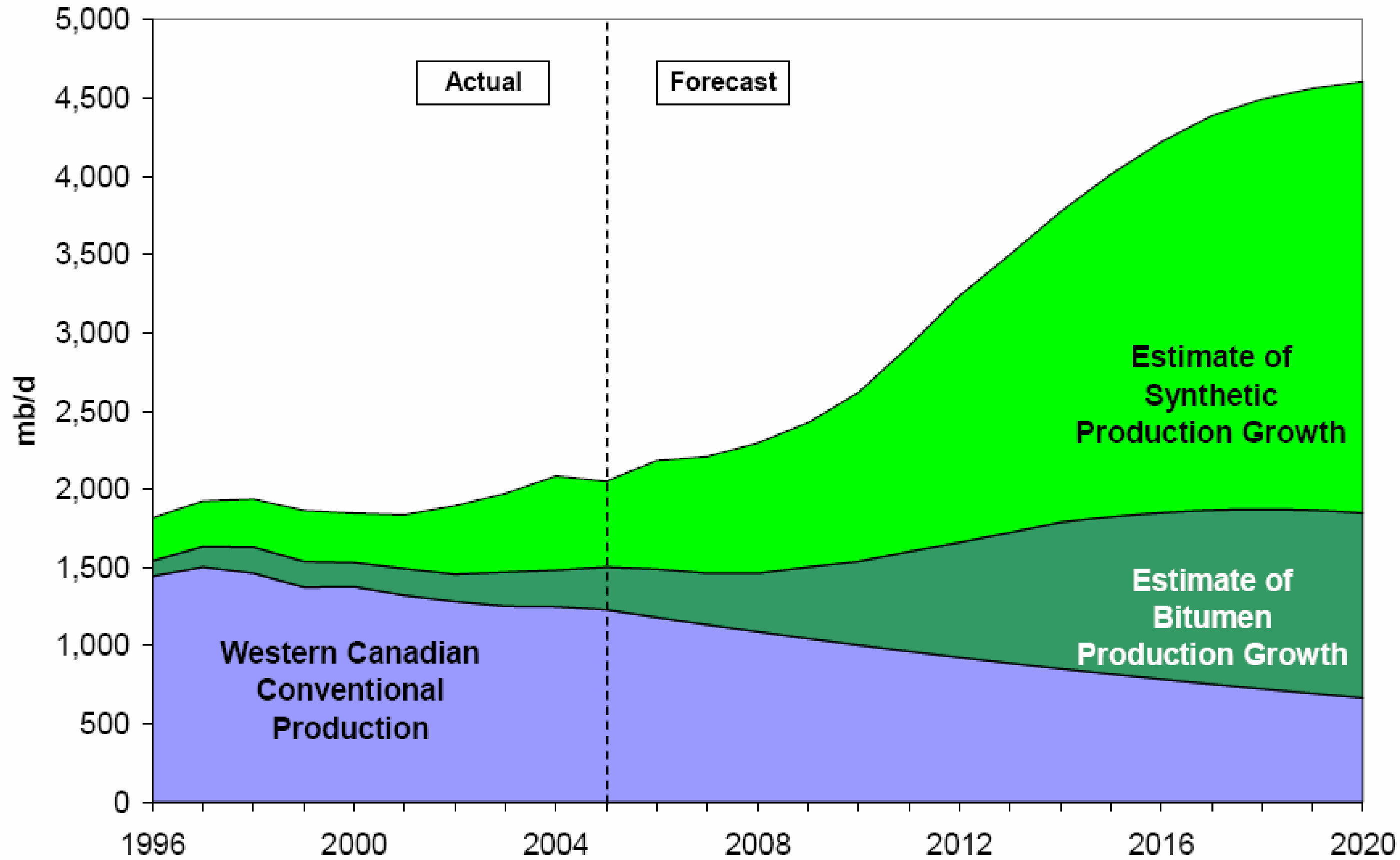
- Composition—oil in the form of bitumen
- Proven reserves in Canada contain 178 billion barrels
- Satisfies Canadian crude oil demand for for over 200 years



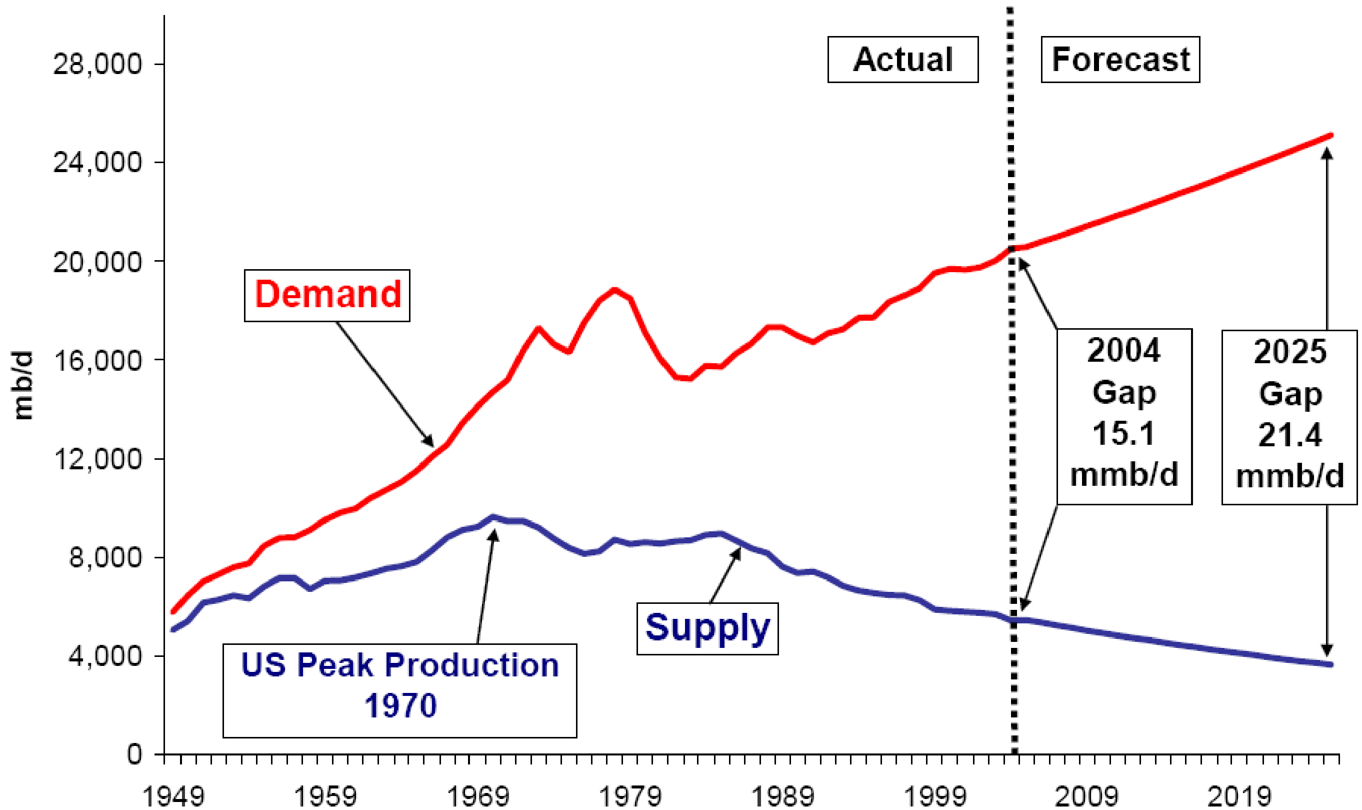
Recoverable Oil Reserves



Canadian Oil Forecast



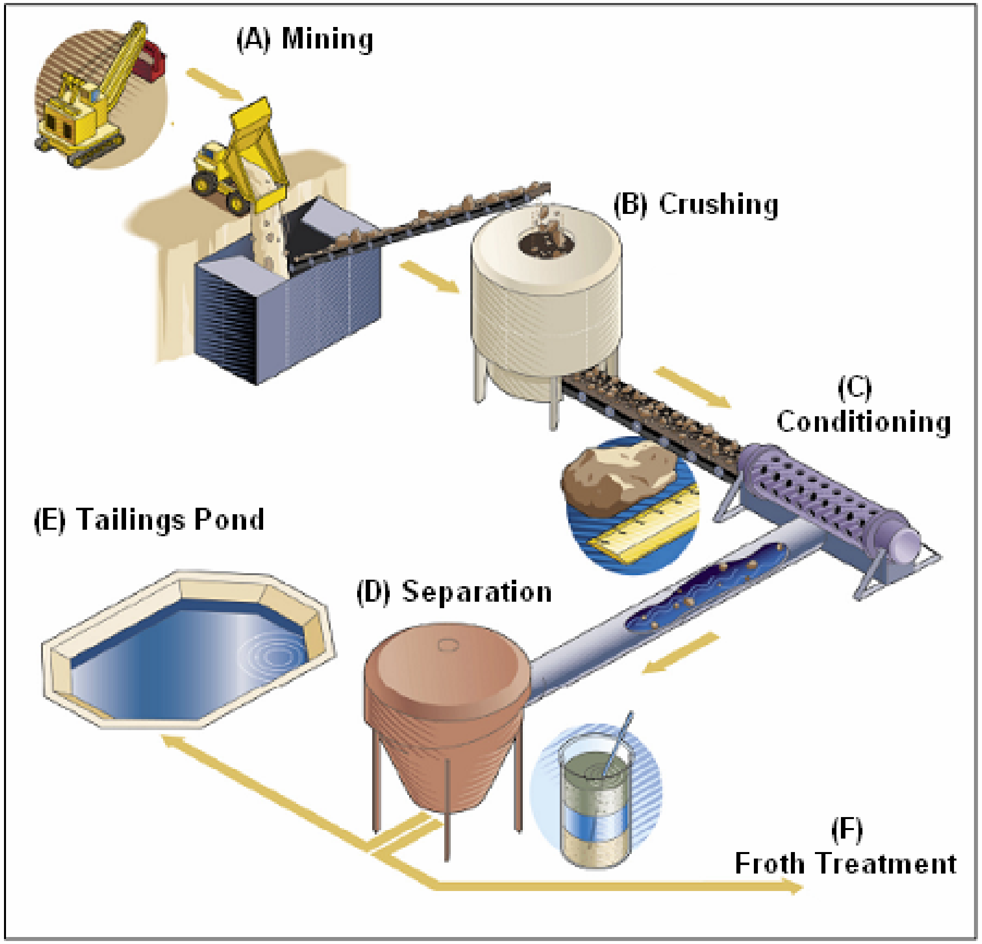
U.S. Oil Production



Extraction Methods

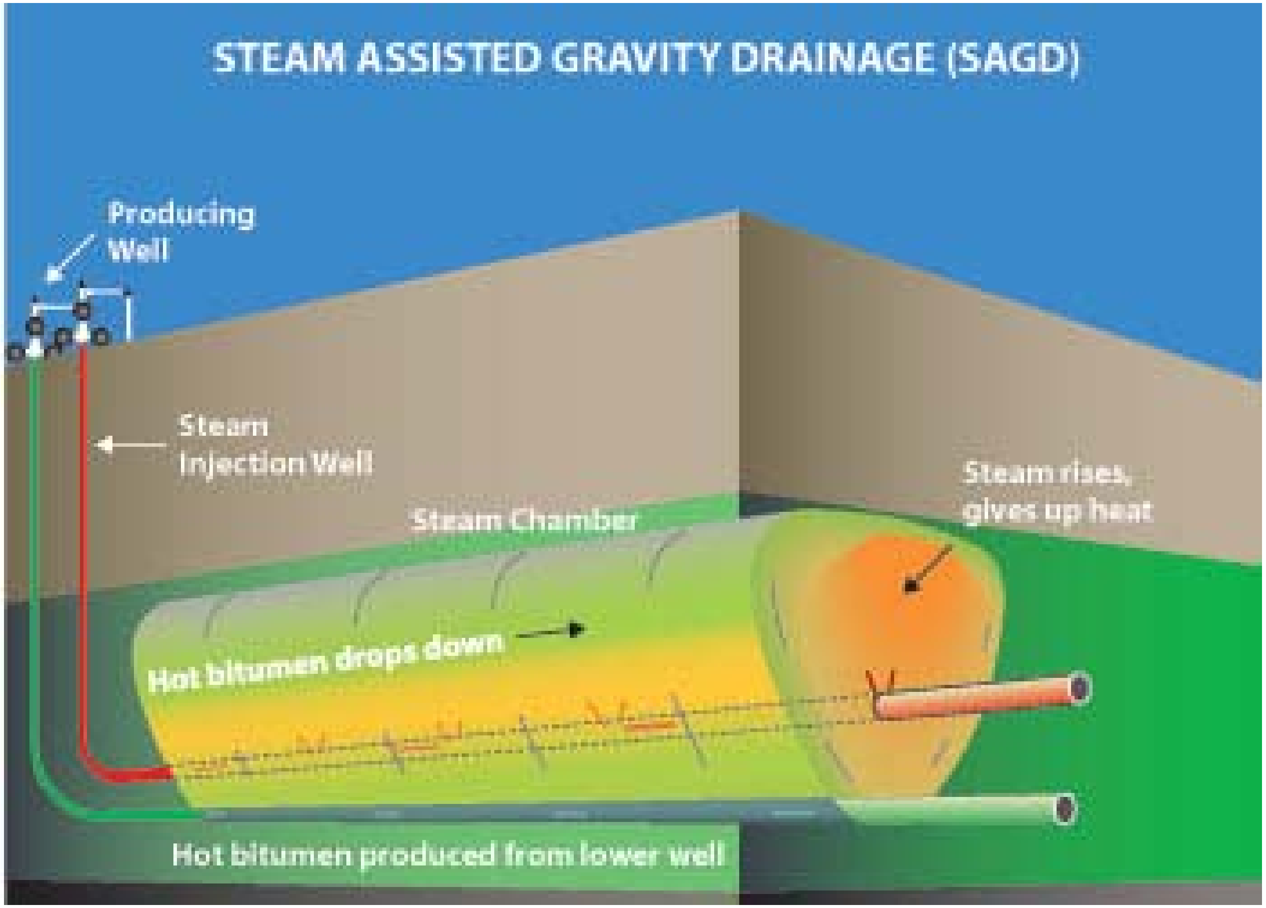
Surface Mining

Surface Mining Process



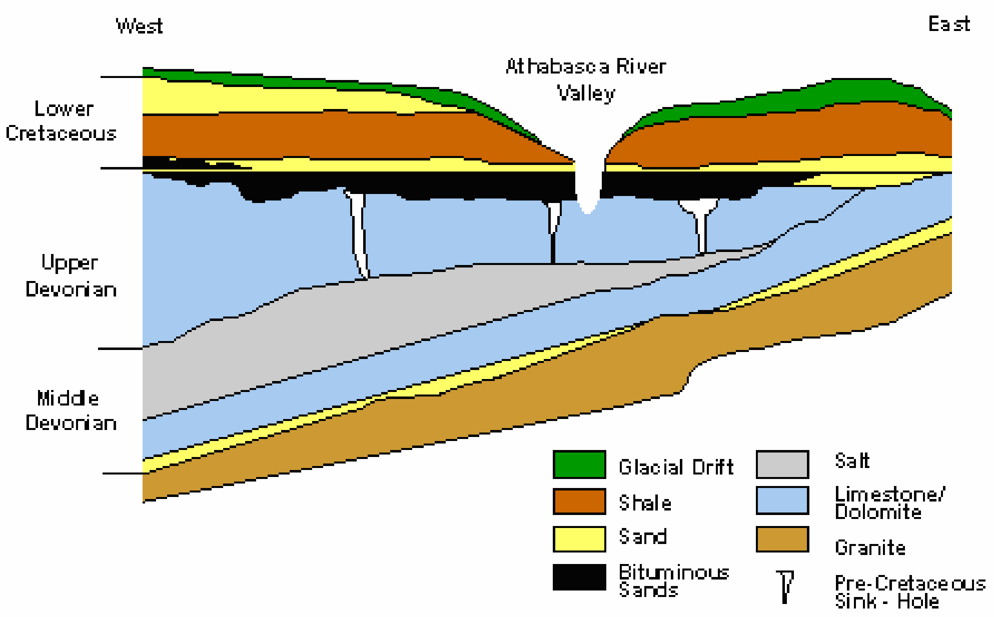
→ Diluted bitumen to upgrader

In-situ SAGD

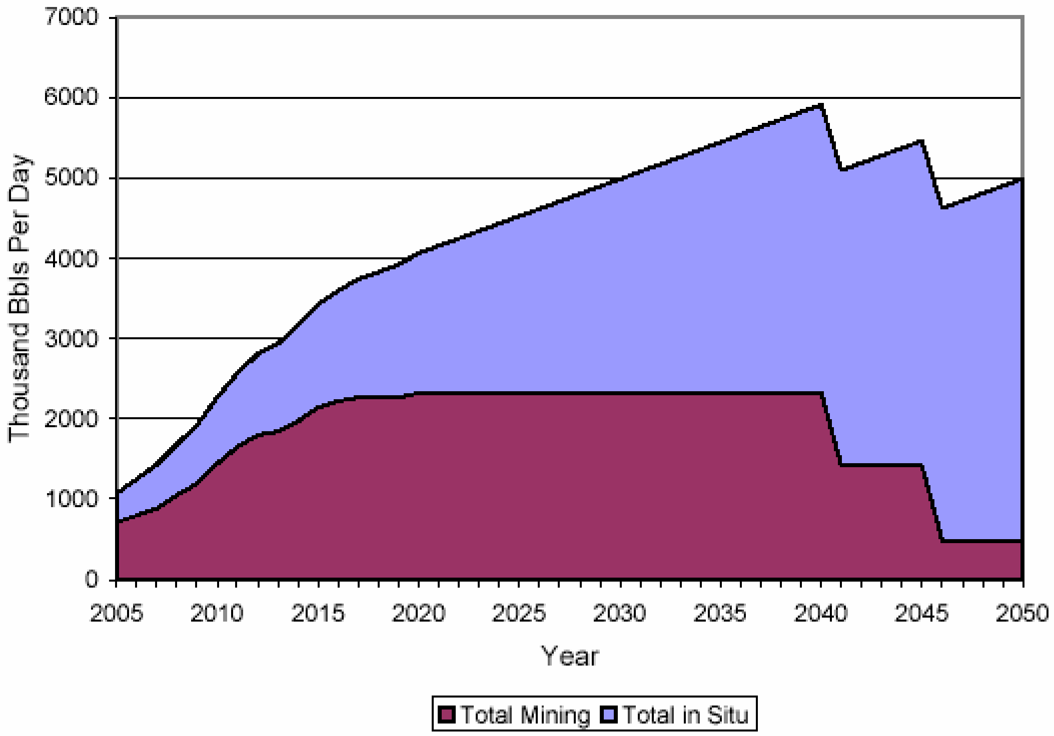

STEAM ASSISTED GRAVITY DRAINAGE (SAGD)
Producing Well
Steam Injection Well
Steam Chamber
Steam rises, gives up heat
Hot bitumen drops down
Hot bitumen produced from lower well

Resources

- Surface mining dominant oil sands industry today
- ~80% of the deposits in Canada are too deep for surface mining



Mining/In-situ Production Forecast



Surface Mining

Pros

- High established production rates
- Field lifetime of about 30 years

Cons

- Higher environmental impact
- 80% of bitumen too deep for surface mining
- Production to level off around 2020

SAGD

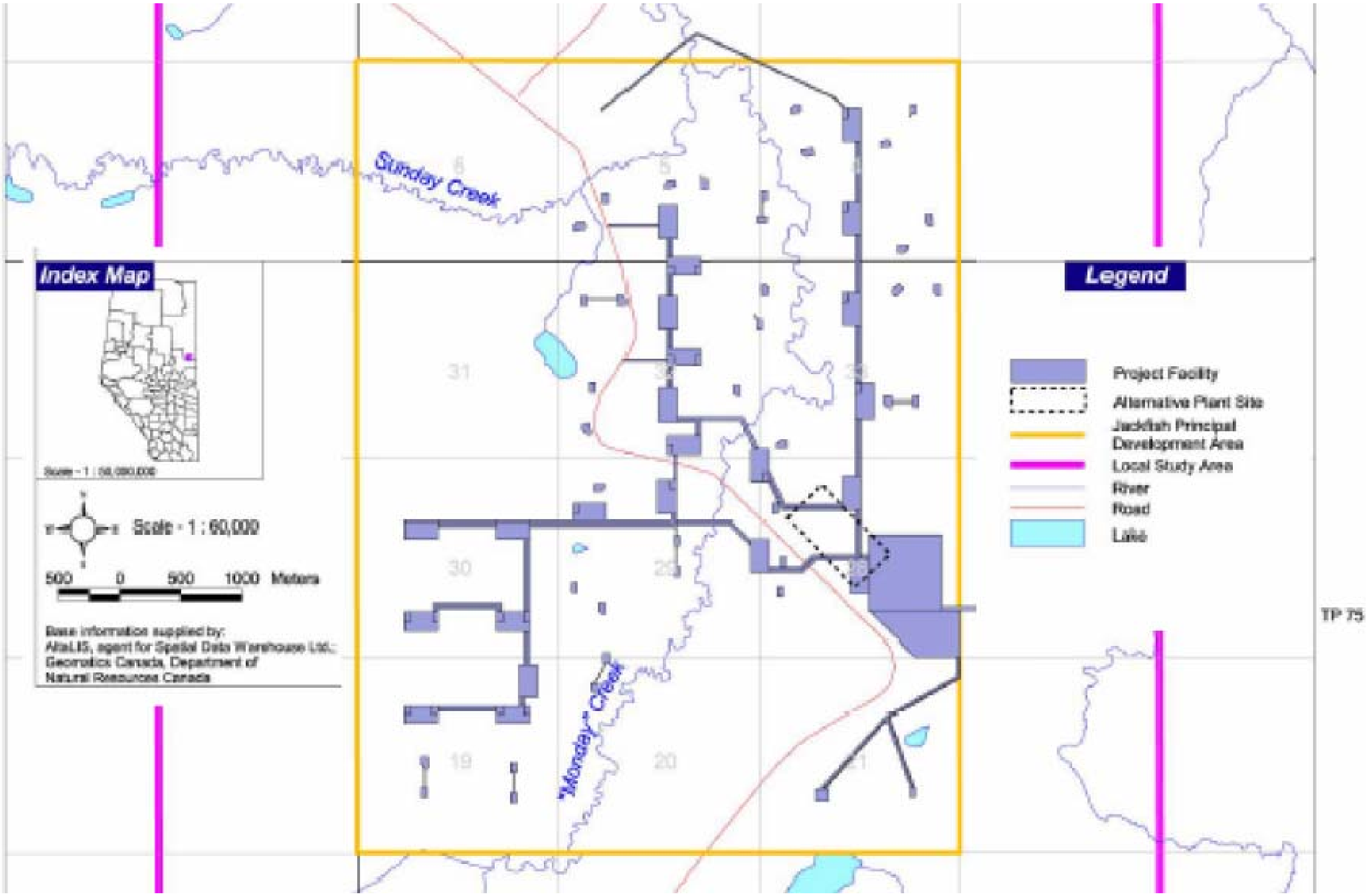
Pros

- Phased project designs
- Some planned production rates at 100,000 Bbl/day

Cons

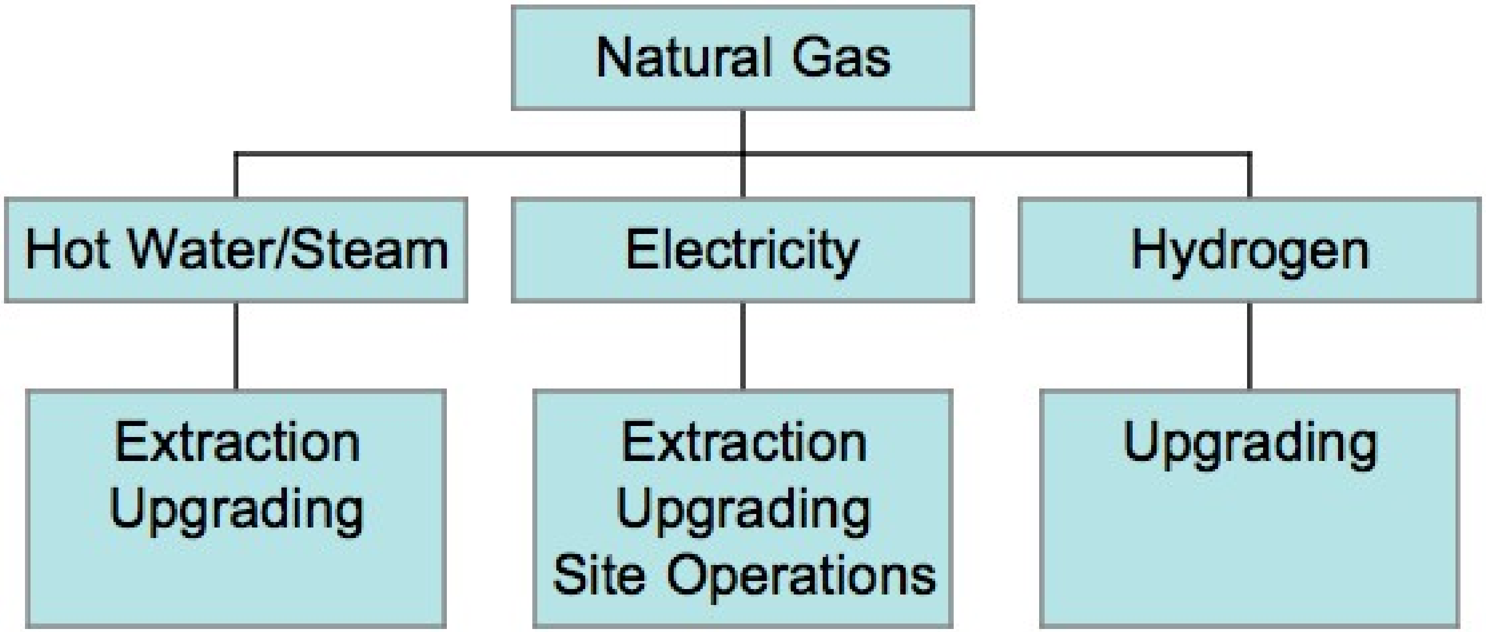
- Demands more natural gas
- Limitations on piping steam
- Well lifetimes are 10-15 years, but phased projects can last >25 years

Reference Plant

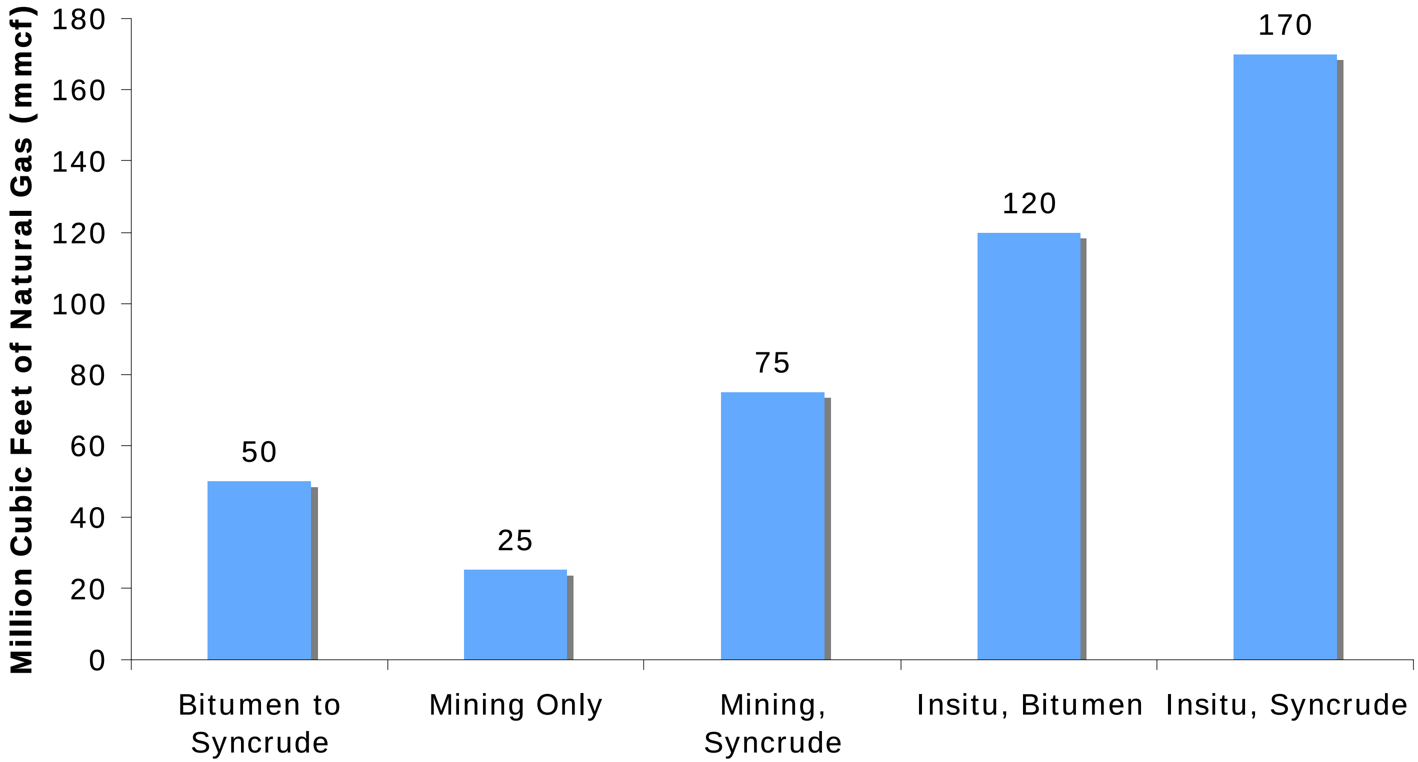


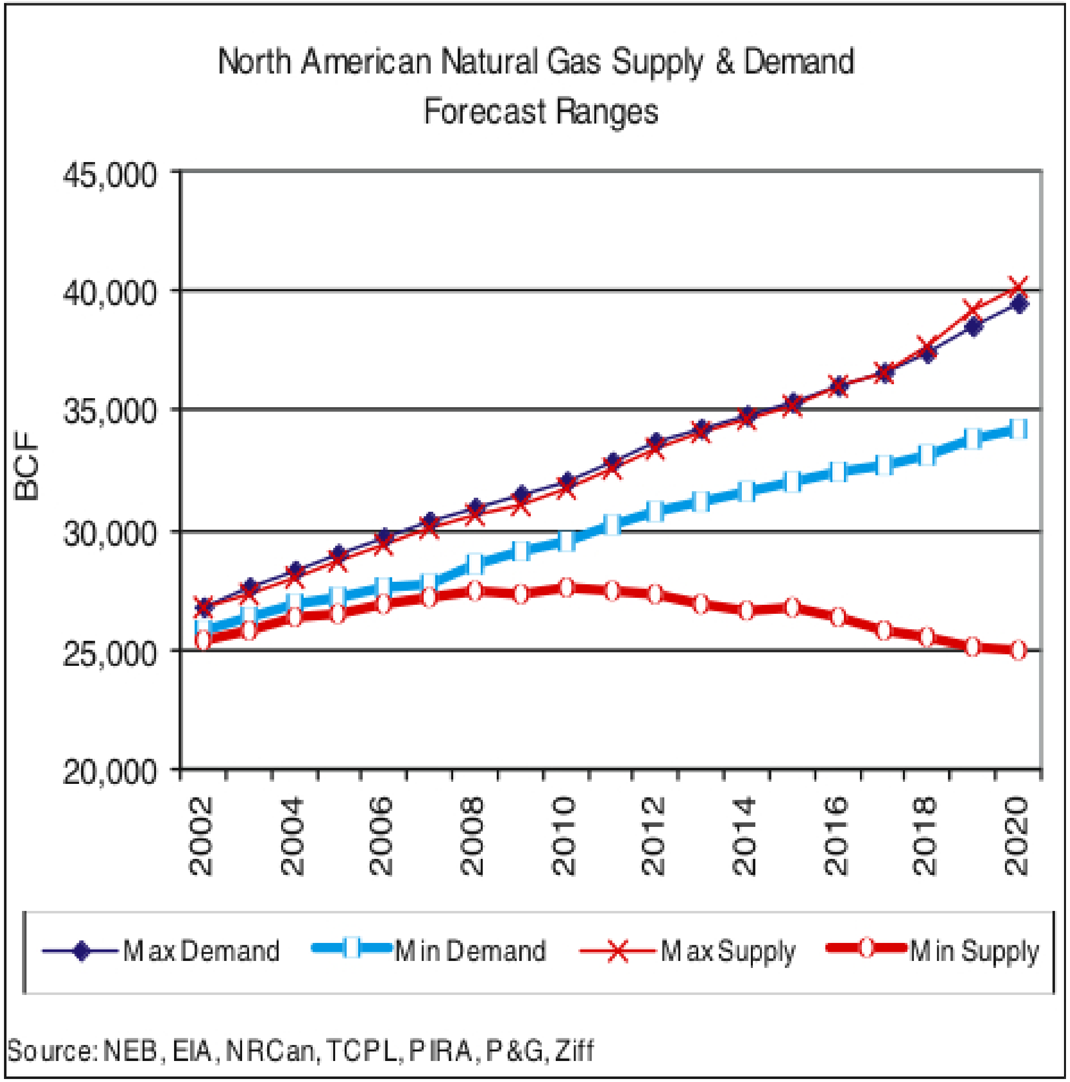
Natural Gas Usage in Oil Sands Facilities

Natural Gas Usage in Oil Sands Facilities

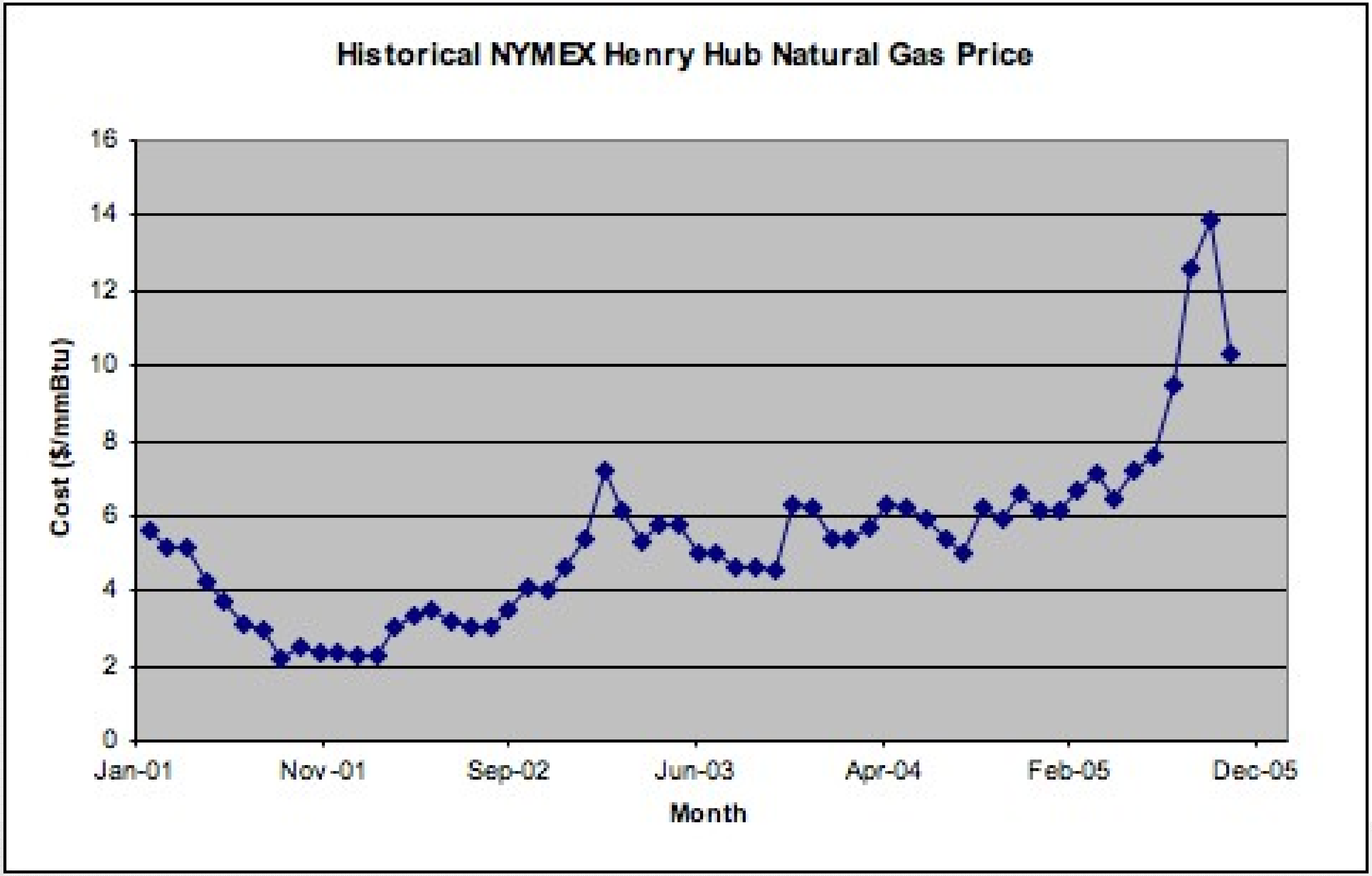


Natural Gas Requirements
(In mmcf/100,000 bbl)



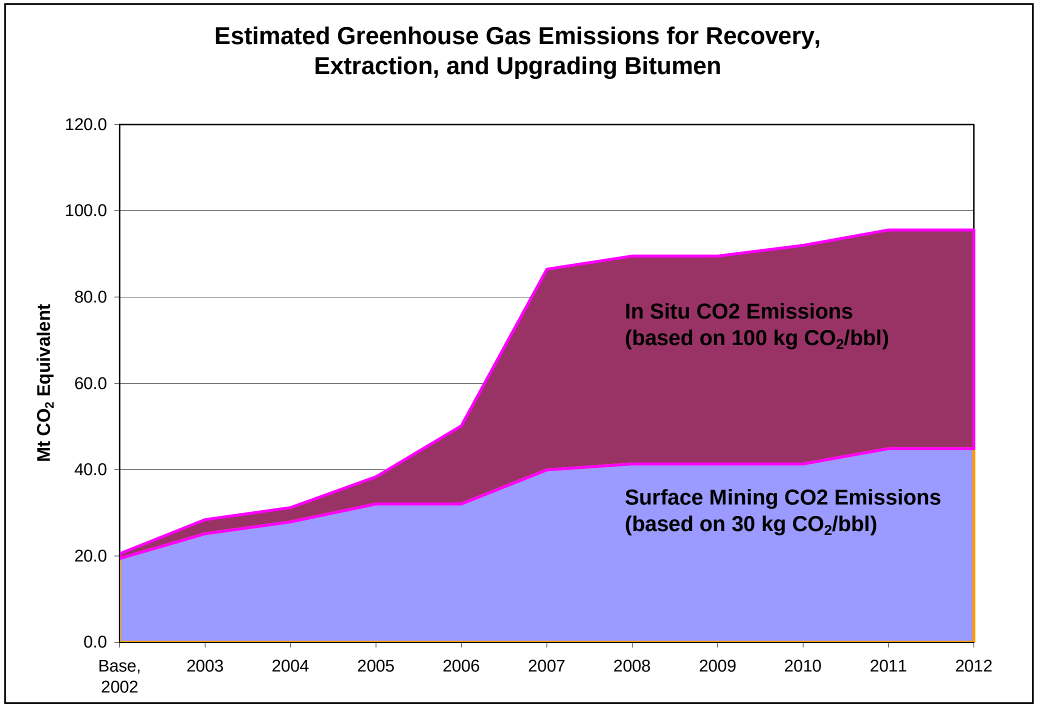

North American Natural Gas Supply & Demand
Forecast Ranges
45,000
40,000
35,000
30,000
25,000
20,000
BCF
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Max Demand
Min Demand
Max Supply
Min Supply
Source: NEB, EIA, NRCan, TCPL, PIRA, P&G, Ziff

Historical Trend of Natural Gas Prices



Greenhouse Gas Emissions from Oil Sands Facilities

- Greenhouse gases: NO_2 & NO, SO_2, CO_2
- 2002: ~20 Mt CO_2/year, 2012 ~100 Mt CO_2/year
- Making oil from oil sands produces 3x more greenhouse gases than producing conventional oil



Kyoto Protocol

- Canada agrees to reduce greenhouse gas emissions by 6% relative to the 1990 level of 612 Mt by 2008-2012 to 575Mt
- Canada's Climate Change Plan (2002/2005)
  - Would like to reduce emissions to 305 Mt
  - In 2012 (at 100Mt CO_2) 17% of total Kyoto target (575 Mt), 29% of Climate Change Plan target (305 Mt)

Natural Gas Usage Conclusions

- Price of natural gas is increasing, due to decreasing supply and increasing demand
- The desire to decrease emissions in Canada
- Must look for another source of energy to fuel oil sands facilities

Energy Requirements

Scenario One:

- Production – SAGD Process Heat Only
- Electricity from off-site source
- Product – Diluted bitumen

Scenario Two:

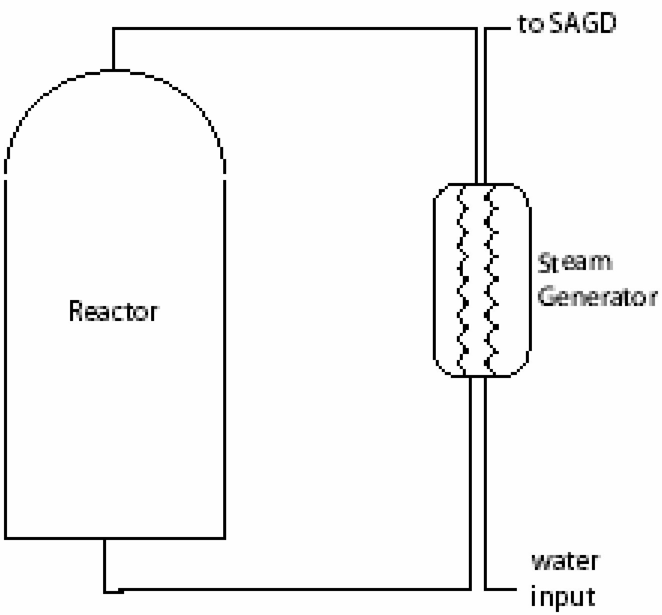
- Production – SAGD Process Heat and Electricity for on-site needs
- Product – Diluted bitumen

Scenario Three:

- Production – SAGD Process Heat, Electricity for on-site needs, and Hydrogen for upgrading needs
- SynCrude

Scenario One: Process Heat Only

- 100,000 bbl/day

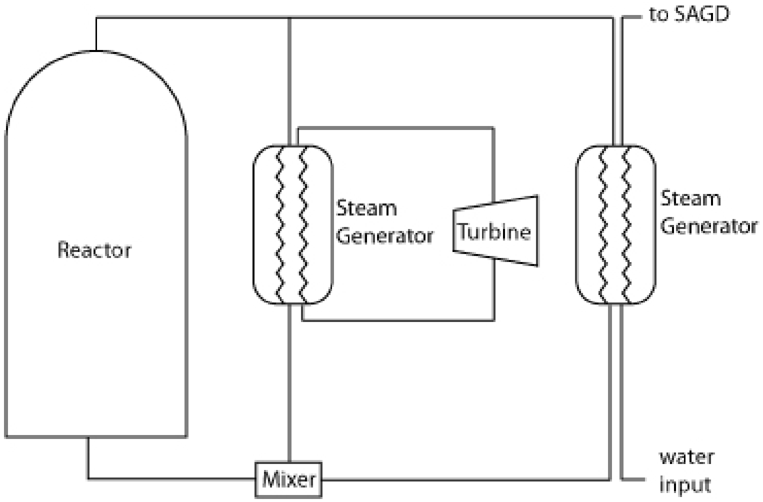


	2 MPa	6 MPa
Low performance	1,230 MWth	1,264 MWth
High performance	820 MWth	843 MWth

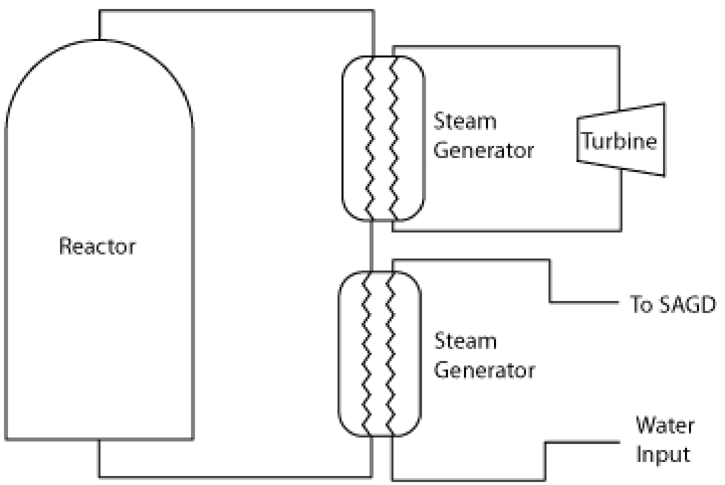
Second Scenario: Process Heat and Electricity

- In addition to SAGD process heat requirements, 250 MWe is required for the on-site requirements of a 100,000 bbl/day facility
- Total needs for electricity and process heat will be 1,400 to 1,600 MWth

Reactor/Steam Generator Configurations for Scenario 2



Split Flow



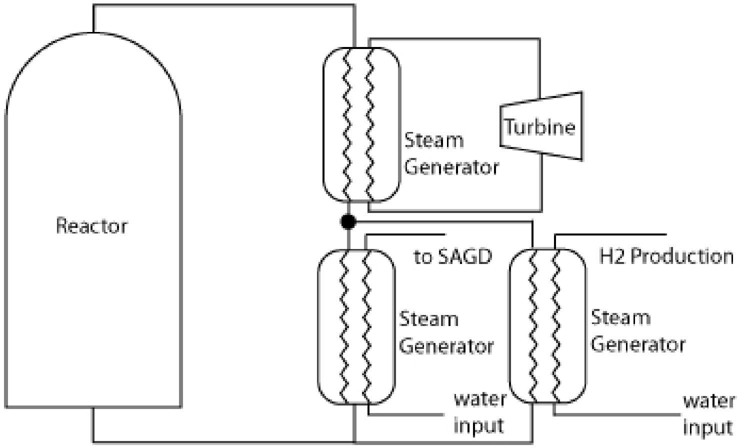
In Series

Scenario Three: Process Heat, Electricity, and Hydrogen

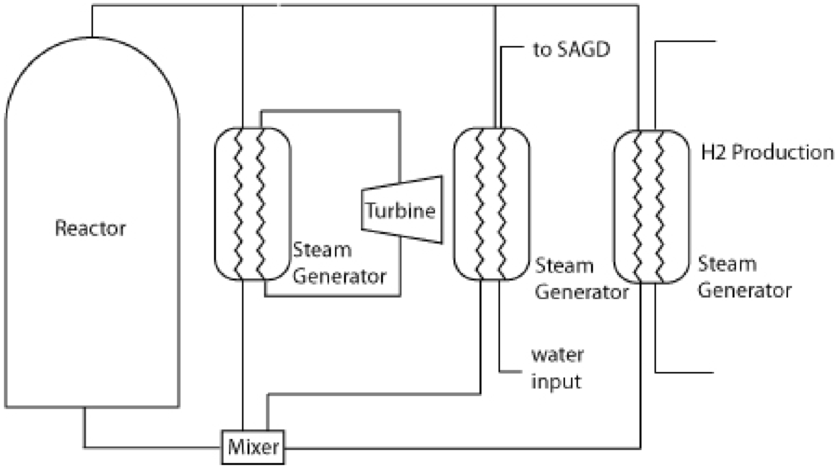
- Process heat and electricity requirements remain the same
- A further 100 MWe will be needed to supply the upgrading facility
- High Temperature Steam Electrolysis was chosen as the hydrogen production method
- When on-site upgrading is performed, an additional 310 MWe and 80 MWth will be required for hydrogen production
- Total needs for electricity and process heat will be 2,495 to 2,800 MWth

Reactor/Steam Generator Configuration for Scenario Three

- Two possible reactor/steam generator configurations
- Split flow system is ideal as it allows a low temperature reactor to be used if desired



Partially Split Flow

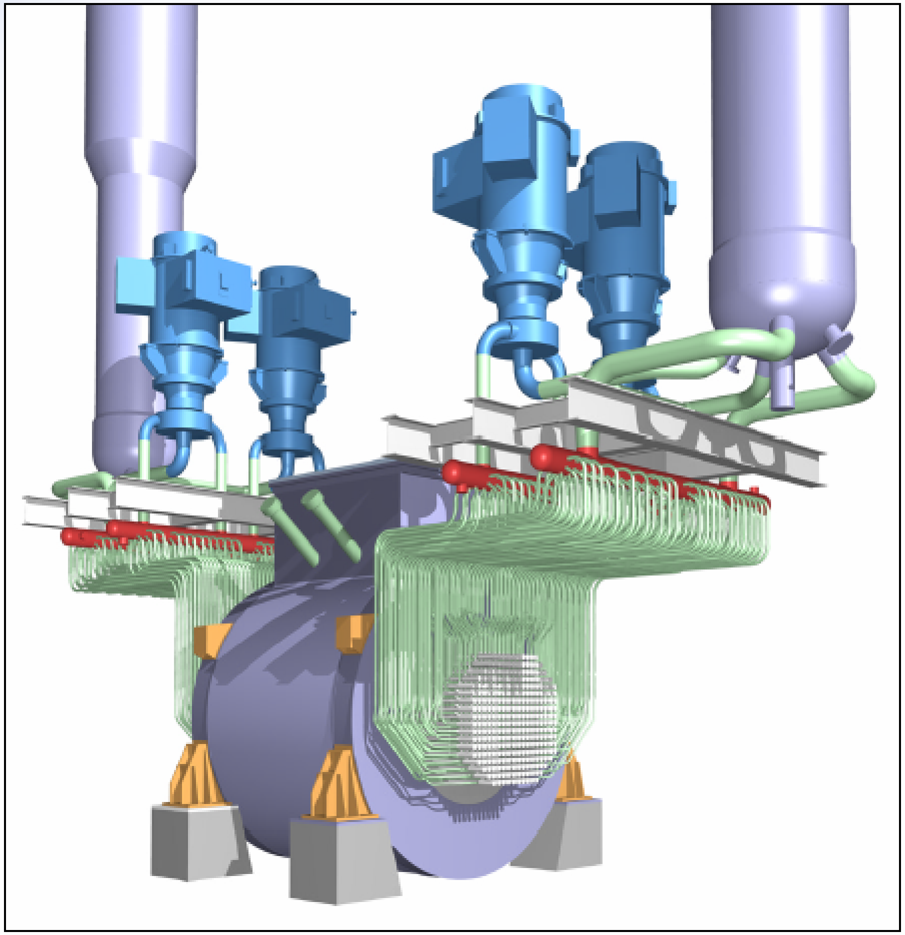


Split Flow

Nuclear Reactor Design Options

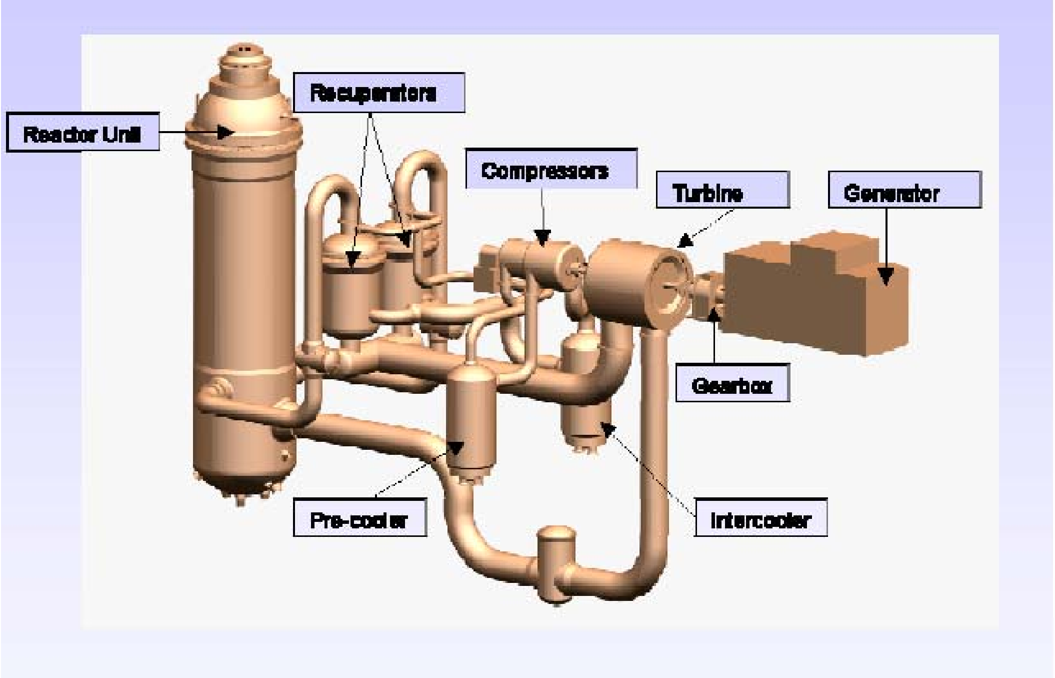
ACR-700

- Thermal Power: 1983MWth
- Electrical Power: 731MWe
- Primary coolant: Light Water
- Moderator: Heavy Water
- Primary Outlet: 326°C
- Fuel: Canflex bundle; SEU(slightly enriched Uranium) ~2%
- Most accepted in Canada because it is Canadian technology



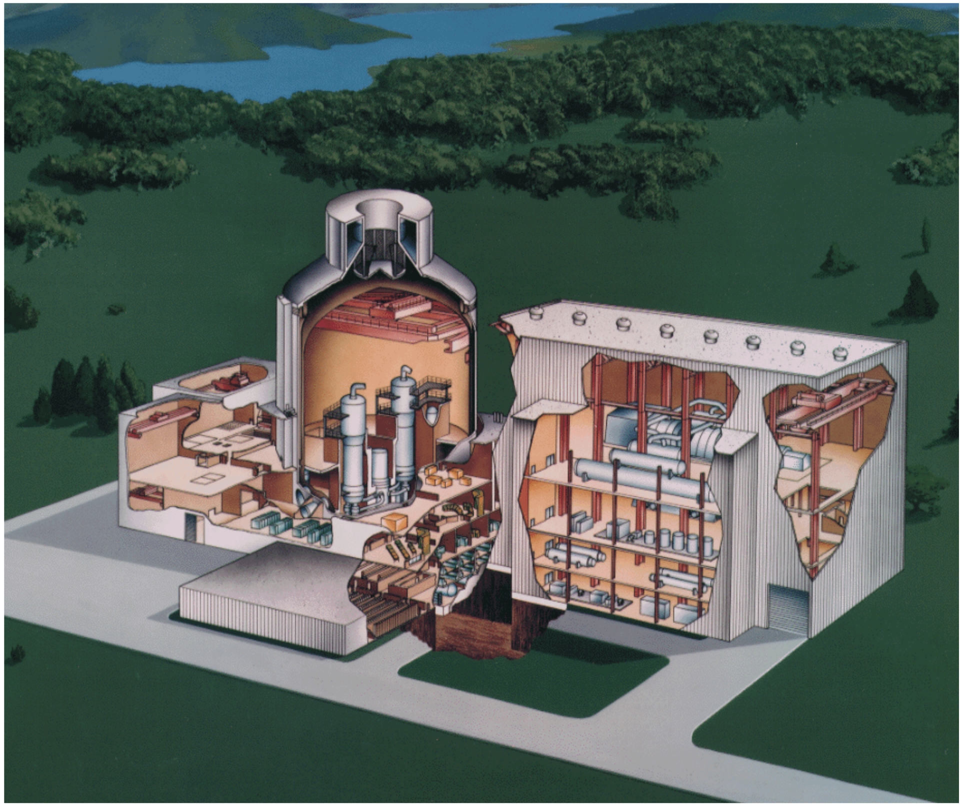
PBMR(1 unit)

- Thermal Power: 400MWth
- Electrical Power: 165MWe
- Primary coolant: Helium
- Moderator: Graphite
- Primary outlet: 900°C
- Fuel Pebbles: 60mm, outer dia., encloses ~11,000 C/SiC coated fuel microspheres of UO_2
- May be difficult to license; it has many technological innovations



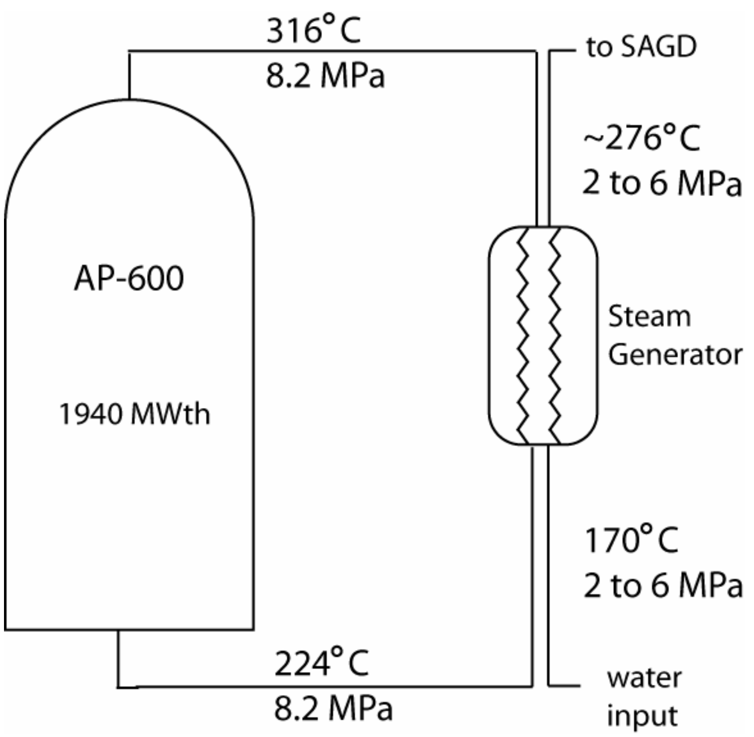
AP600

- Thermal Power: 1940MWth
- Electric Power: 600MWe
- Primary Coolant and Moderator: Light Water
- Primary Outlet: 316°C
- Fuel: 4.20 wt % ^{235}U , sometimes MOX (mixed oxide) fuel
- Prides its passive safety, USNRC completed final design approval, but Canadians are still relatively unfamiliar with PWRs



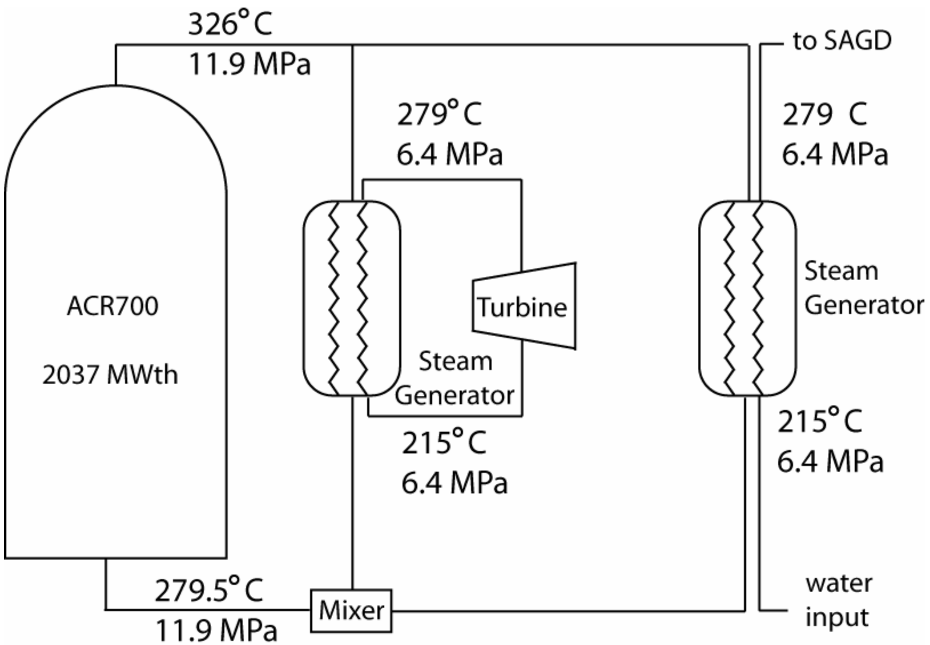
Optimal reactors for Scenario One

- A reactor needs to be able to provide up to 1,264 MWth at peak load
- Either one AP600 or four PBMRs would meet this energy requirement



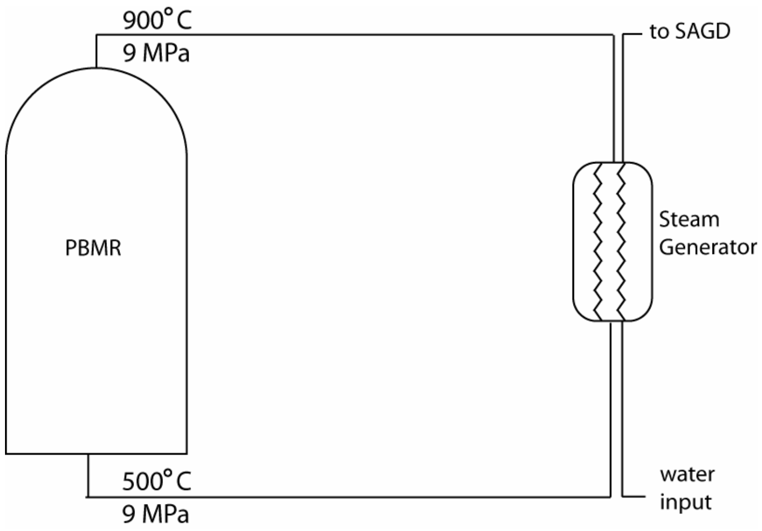
Optimal Reactors for Scenario Two

- A reactor needs to provide up to 1400 - 1600 MWth at peak
- One ACR-700 could be used by modifying its conventional configuration
- Configuration could also use the split flow from five PBMRs in parallel

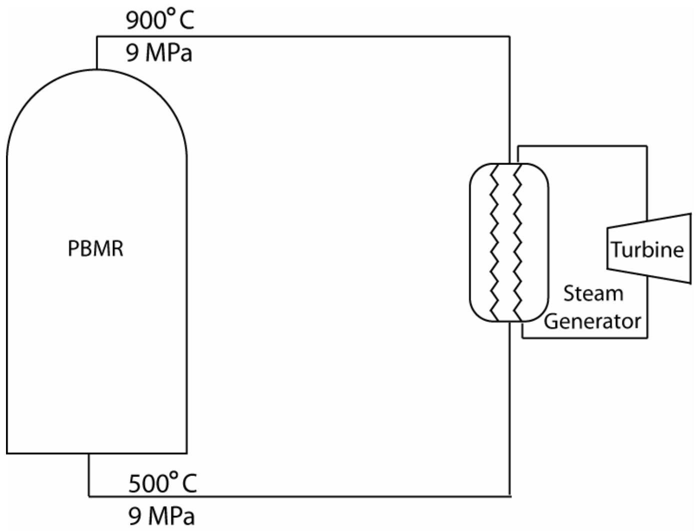


Dedicated Reactors

- Alternatively process heat and electricity can also be provided with dedicated reactors to meet each requirement



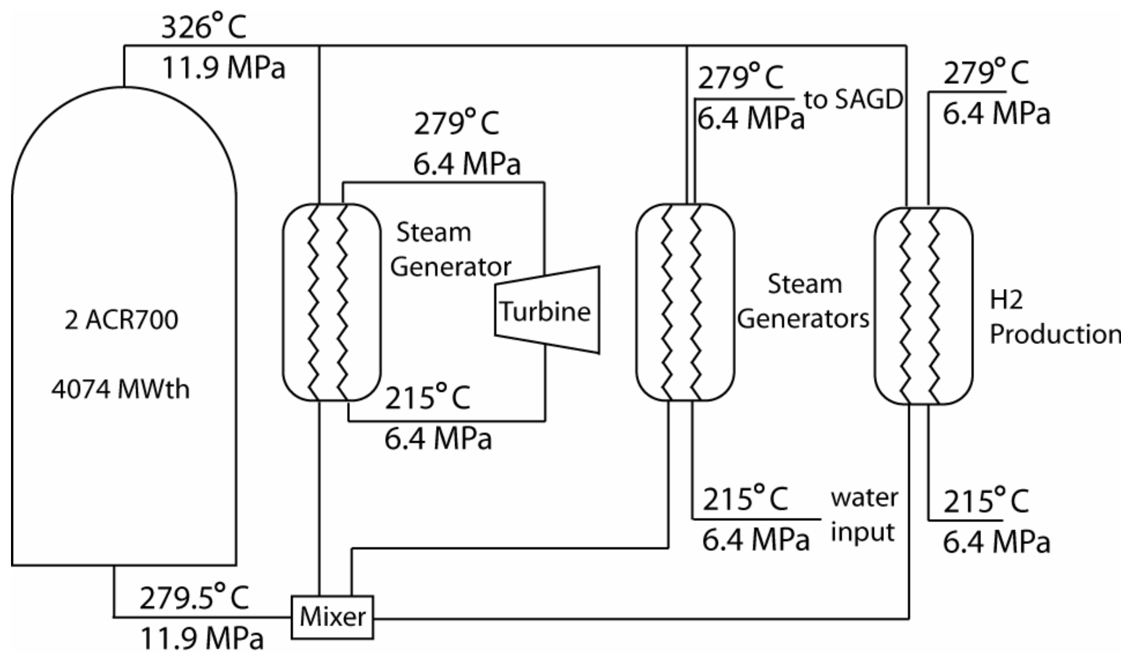
Process Heat Plant
(3 PBMR Units)



Electricity Generation Plant
(2 PBMR Units)

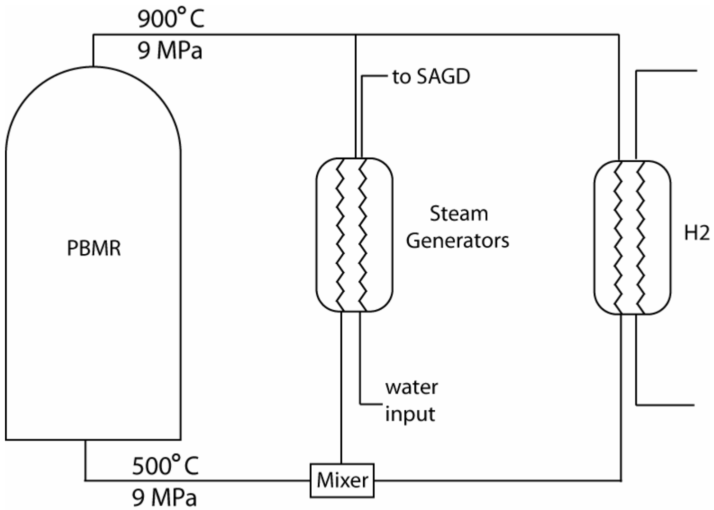
Optimal Reactors for Scenario Three

- Either two ACR-700s or two AP600s in parallel would be acceptable for this scenario
- Configuration could use the split flow from eight PBMRs in parallel

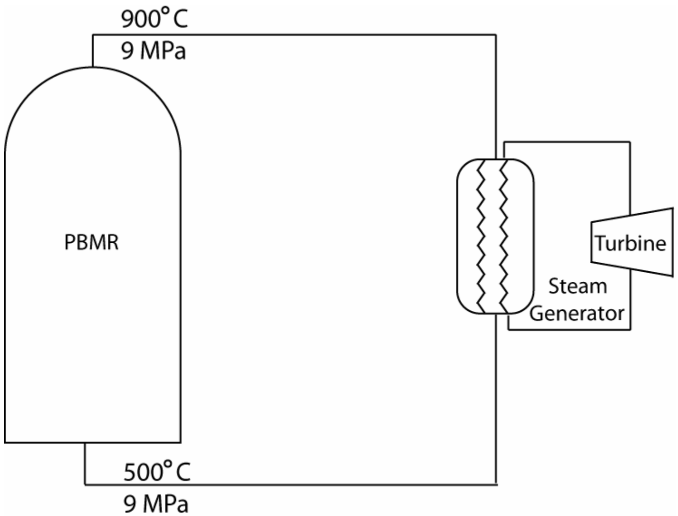


Dedicated Reactors

- Alternatively, process heat and electricity can also be provided with dedicated reactors to meet each requirement



Process Heat Plant
(3 PBMR Units)



Electricity Generation Plant
(5 PBMR Units)

Economics

Purpose of economic analysis

1. Should natural gas or nuclear be used for the SAGD extraction process?

2. Should the electricity requirements of the plant be fulfilled by buying electricity off the power grids, or by making it at the plant?

3. Should the hydrogen required for the bitumen upgrading process be bought from private suppliers, or produced at the plant?

Economic Assumptions

- All costs are in US dollars (US$)
- The lifetime for the plants are assumed to be 30 years, and the Net Present Value (NPV) is calculated for a 10% discount rate
- No inflation is assumed
- Easy access to Alberta electricity power grid is assumed, price is ~US$0.05/kWhr
- Buying price of hydrogen is assumed to be ~US$2.50/kg of H_2
- Costs do not include that of processing and upgrading plants as these are held constant and independent of heat source used
- 4 categories of cost: capital, O&M, fuel and decommissioning
- 3 final types of costs looked at: Cost of Process Heat, Cost of Electricity, and Cost of Hydrogen Production

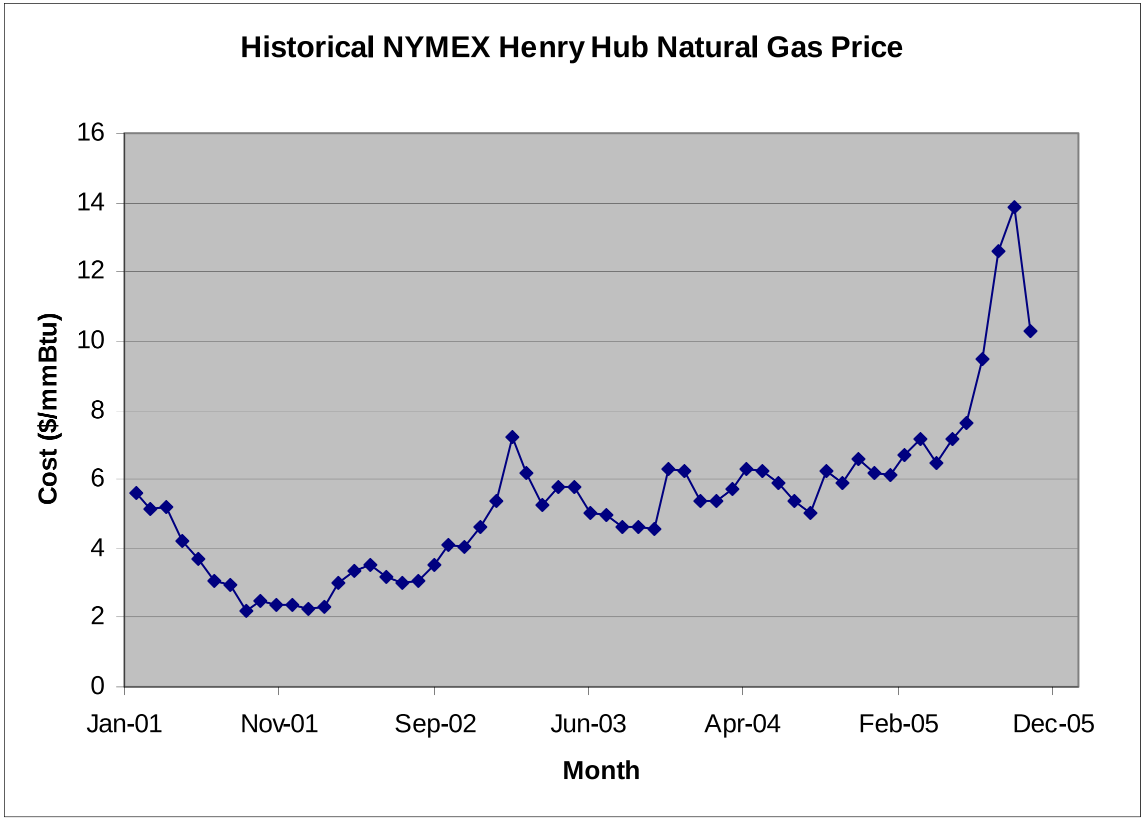
Additional Natural Gas-specific Assumptions

- Natural gas price is assumed to be $8.00/mmBtu
- Kyoto protocol costs were not included in the calculations and would have resulted in an increase in the total cost for natural gas plants since they produce large quantities of CO_2
- No natural gas price escalation over time is assumed

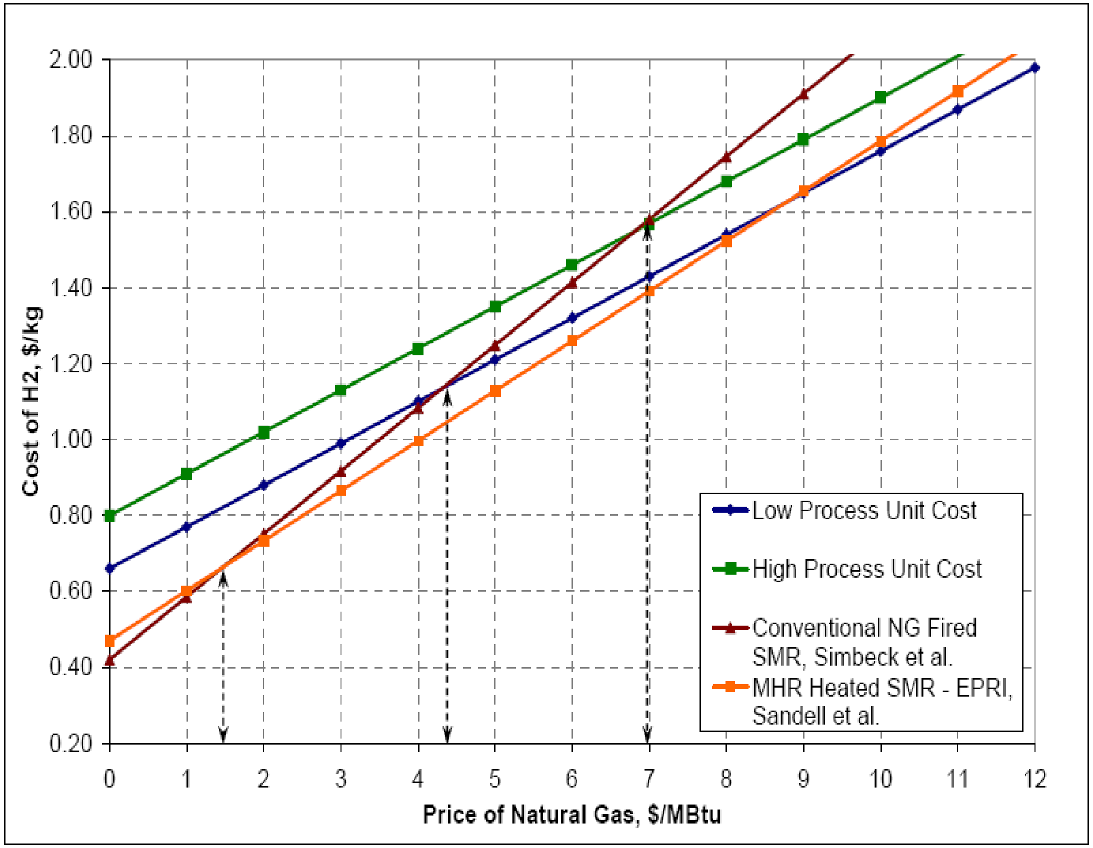
Natural Gas Lifetime Cost

Type of Cost	Lifetime Cost ($M over 30 years)		
	Scenario 1	Scenario 2	Scenario 3
Process Heat	2976.9	2976.9	2976.9
Electricity	1053	1178.4	1178.4
Hydrogen	-	-	Buy - 2744.2
			Make - 1920.3
Total	***4029.9***	***4155.3***	***6075.6***

Volatility of Natural Gas Price and Effect on Gas-Fired Facilities



Volatility of Natural Gas Price & Effect on Gas-Fired Facilities



- 25% change in natural gas price raises the steam production facility and hydrogen production cost by 17.8%

Number of Reactors Required for Each Scenario

Type of Reactor	Number of Reactors		
	Scenario 1	Scenario 2	Scenario 3
PBMR	4	5	8
ACR-700	1	1	2
AP600	1	1	2

Additional Nuclear-specific Assumptions

- A conservative estimate of 90% is assumed to be the learning curve for building additional reactors – some studies such as one by Westinghouse assume the learning curve to reduce costs as low as 70%
- No nuclear fuel escalation cost is assumed

Nuclear Technology Lifetime Cost

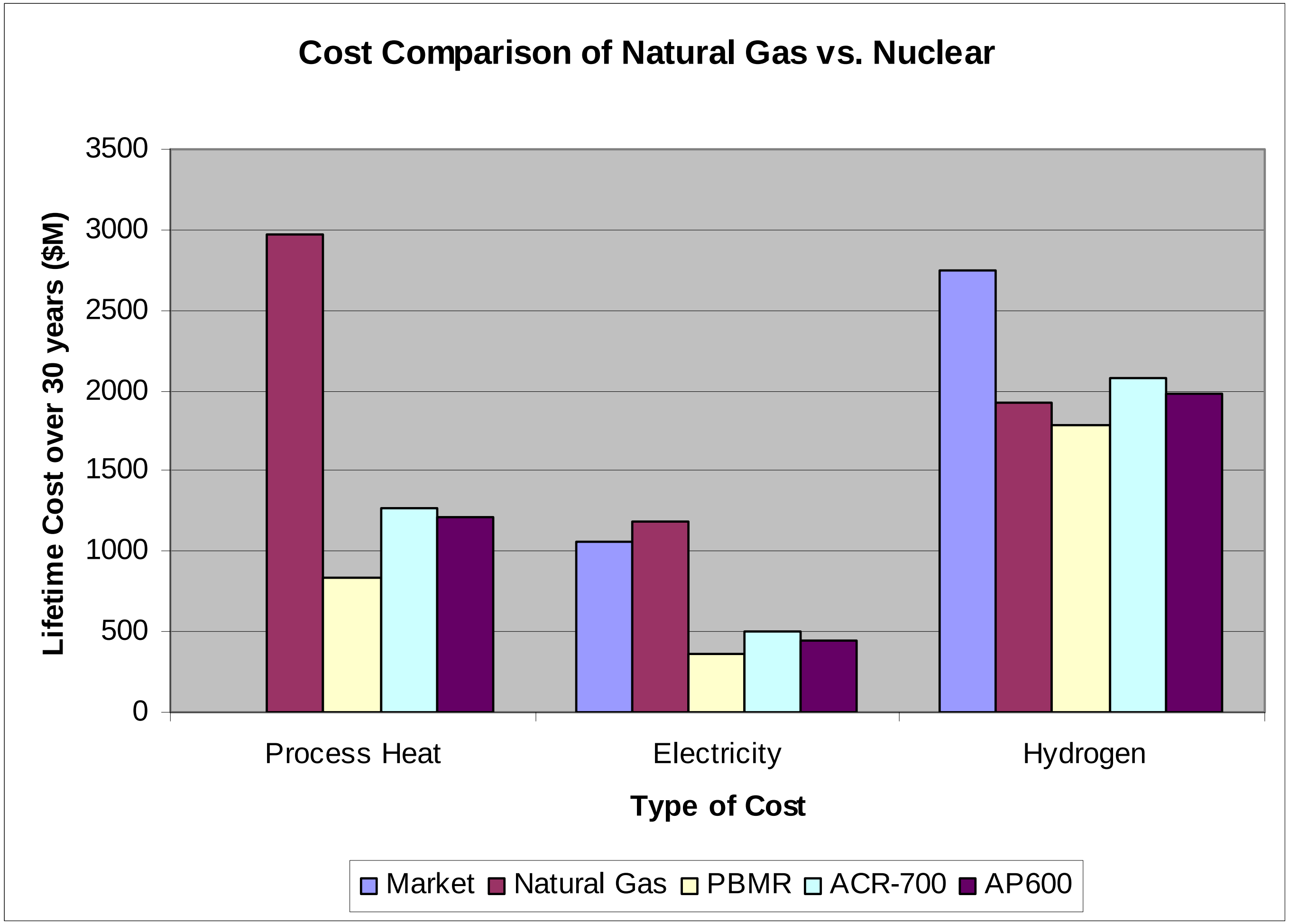
		Lifetime Costs ($M over 30 years)		
		PBMR	ACR-700	AP600
Scenario 1	Process Heat	829.9	1271.7	1218.8
	Electricity	1053	1053	1053
	Total	***1882.9***	***2324.7***	***2271.8***
Scenario 2	Process Heat	829.9	1271.7	1218.8
	Electricity	355.7	499.8	444.5
	Total	***1185.6***	***1771.5***	***1663.3***
Scenario 3	Process Heat	829.9	1271.7	1218.8
	Electricity	355.7	499.8	444.5
	Hydrogen - Buy	2744.2	2744.2	2744.2
	- Make	1791.7	2082.1	1983.4
	Total	***2977.3***	***3853.6***	***3646.7***

Sensitivity of Total Cost to Changes in Capital Cost

	PBMR	ACR-700	AP600
Change in Total Cost for a 25% increase in Capital Cost	11.3%	13.9%	12.5%

Capital cost is an initial fixed cost, unlike natural gas cost which is a recurring cost over the lifetime, i.e. capital cost has no future volatility

Cost Comparison of Natural Gas v. Nuclear



Economic Conclusions

- Given current natural gas costs, nuclear is a much cheaper alternative for producing process heat for SAGD.
- Producing electricity using nuclear power is more cost-effective than buying it off the Alberta power grid or producing it using natural gas.
- While Steam-Methane Reforming has historically been a cheaper process than High Temperature Steam Electrolysis, the cost of HTSE with nuclear power is now comparable to SMR due to high natural gas cost.
- Overall, using nuclear power is a much more economically viable alternative to using natural gas due to high prices and volatility of natural gas, and new compliance regulations of the Kyoto protocol

Reactor Licensing

Licensing

• New application of nuclear: licensing challenge.

•CNSC: less prescriptive than the US NRC

• Requirements are site-specific.

• 3 license applications before operation:
  • license to prepare site; to construct; to operate.

• ACR-700 at an advantage in CNSC's familiarity and Canadian politics.

•Due to the less prescriptive requirements of the CNSC, it is feasible to license a new reactor design like the PBMR or the AP600.

Canada’s Disposal Plan for Nuclear Waste

Nuclear Waste

- Intrusion Resistant Underground Structure
  - LLW, long-term, 500 year solution
- Deep geological repository
  - Spent fuel, long term disposal, to be completed in 20 yrs
- Canada will have a HLW site regardless of use of nuclear systems in oil sands

Obstacles for Nuclear Energy Use in the Canadian Oil Sands

Key Obstacles

- Public perception of nuclear power
  - Public education campaign required
- Constructability
- Oil Companies' Unfamiliarity with Nuclear Power
  - Have utility companies operate the nuclear power station for the oil companies
- Use of non-CANDU designs
  - Would be more costly to license, due to unfamiliarity to CNSC.
  - Would face more public/political opposition for non-Canadian design.

Opportunities

Constraints to Expanding Oil Sands Production with Natural gas

- Dependence on water
- Shortage of diluent
- Increasing price of natural gas
- Greenhouse gas emissions

Integration of oil sands with nuclear power addresses 3 out of 4

Conclusion

- Large projected growth in oil sands industry
- Energy needs can be met by nuclear power
- Constraints to expanding production
- Nuclear addresses most of these concerns
- Nuclear systems can compete economically with natural gas-fired plants

Questions?