ANTARES Application for Cogeneration

Oil Recovery from Bitumen and Upgrading

Michel Lecomte
Houria Younsi (ENSEM) – Jérome Gosset (ENSMP)
Presentation Outline

- Introduction
- Description of main ANTARES features
- Positioning nuclear heat source for combined heat and power production
- Example: Bitumen recovery and upgrading
- Conclusion
Introduction

- A fast evolving context:
  - Fossil fuels are becoming more expensive
  - Price volatility of conventional fuels is high
  - Environmental concerns are growing

- Incentives for:
  - Improved efficiency
  - Strict limitations or control of GreenHouse gases releases

- HTRs are a non GHG producing heat source able to deliver both power and heat in a significant temperature range

- ANTARES design with a combined cycle power production system is readily adapted to most combined heat and power applications.
Description of ANTARES Features

- The project started in 2003 based on an extensive legacy of experience with the German MODUL and the GT-MHR

- Presently in its conceptual design phase.

- Basic technical choices:
  - Prismatic type fuel
  - Annular core
  - Combined cycle power conversion system using mostly conventional components
  - The thermal power is 600 MW

- The design should be adaptable to combined heat and power configuration without any major redesign: have a standardized heat source as much as possible
The Case for Nuclear Combined Heat and Power (1/3)

- Nuclear power cost has a weak dependence on nuclear fuel cost
  - A doubling of uranium cost only increases power cost by 5%, therefore it is predictable and reasonably stable for the medium term
  - In contrast, fossil fuel power cost is very dependent on fuel cost
  - A doubling of natural gas price increases power cost by 75%. Therefore fossil fuel power cost is very sensitive to fuel cost and volatile. It is unpredictable on a medium term basis. (The Henry Hub natural gas price moved from 2.5 $/mmbtu in 2002 to over 13 $/mmbtu recently, it was 1$/mmbtu in 1978)

- For those applications that are big consumers of heat and power, power cost stability and predictability is essential on a medium term basis since an industrial basis is rarely established for less than 20 years
The Case for Nuclear Combined Heat and Power (2/3)

- To be cost effective, the nuclear heat source must be standardized but a process heat power requirement will probably never match the nuclear plant power. Combined heat and power design allows excess power to be distributed as electricity.

- Bulk process heat is used in large amount in some industries.

- Combined heat and power production is very efficient, in some applications up to 80% of the heat source is used.

- Combined heat and power is a commonly used technique in the conventional fossil fuel field.

- In the present and probable future energy environment, the HTR used as a heat source to a combined heat and power application brings the well-known efficiency advantage together with long term price stability and no greenhouse gases release.
The Case for Nuclear Combined Heat and Power (3/3)

- Because of its capability to supply heat up to 800°C in the near term, maybe up to 1000°C in the longer term, the HTR concept is the only near term nuclear concept able to replace fossil fuel heat sources.

- By design ANTARES is able to supply heat and power to a variety of applications with only minor adaptation.

- Optimization of the plant configuration and performance is accomplished with a computer code named “THERMOPTIM” and a methodology developed at the Ecole des Mines of Paris. As a function of the heat needs, it helps identify where to get it from the power cycle to have the best overall electricity+heat performance.
Example of application: Bitumen recovery and upgrading

- We assume bitumen is recovered with the SAGD (Steam Assisted Gravity Drainage) process.
- If the heat source is a nuclear unit it should be able to provide steam to the field for 30 years at least. Steam must have a sufficient range, say up to 10 km from the steam generator ➔ pressure at the source must be sufficient, about 100 bars.
- Steam can be dry or up to 20 % wet
- Steam to oil (SOR) of 2.5 to 3 are required
- A field producing 100000 barrels per day (bpd) needs about 120 Mwe for its operation, mostly for pumping
- When a field has been treated with steam for several months, steam injection interruption for up to a month does not affect production due to soil thermal inertia. Plant refueling can take place without losses.
Bitumen Recovery results

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>100000</td>
<td>bpd</td>
</tr>
<tr>
<td>SOR</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Steam quality</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>Steam Temperature at the generator</td>
<td>310</td>
<td>°C</td>
</tr>
<tr>
<td>Steam pressure at the Generator</td>
<td>100</td>
<td>bar</td>
</tr>
<tr>
<td>Steam flowrate</td>
<td>460</td>
<td>Kg/s</td>
</tr>
<tr>
<td>Thermal heat to steam</td>
<td>912</td>
<td>MWth</td>
</tr>
<tr>
<td>Number of HTR modules</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Electricity production</td>
<td>186</td>
<td>MWe</td>
</tr>
<tr>
<td>Net electricity export after SAGD consumption</td>
<td>66</td>
<td>MWe</td>
</tr>
</tbody>
</table>
Bitumen upgrading

- The recovered bitumen is too viscous for long distance pumping
- It is not adequate for feedstock in refinery
- Therefore, it is upgraded meaning basically enriched with hydrogen
- H2 need is about 3.5 kg per barrel (depends somewhat on the bitumen)
- This is usually produced with steam reforming of natural gas but several problems are expected in the future:
  - Natural gas availability if many SAGD operations are running
  - Natural gas price impacts strongly H2 cost
  - Extensive CO2 production. Either CO2 sequestration is required (expensive and not necessarily practical) or a CO2 tax is levied in a country abiding by the Kyoto agreement
- From nuclear electricity, hydrogen can be produced today from conventional electrolysis of water (about 52 kwhe per kg) and in the future from advanced electrolysis (hoped for 34 kwhe per kg)
## H2 supply

<table>
<thead>
<tr>
<th></th>
<th>Conventional Electrolysis</th>
<th>Advanced Electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 need for 100000 bpd</td>
<td>350 ton/day</td>
<td>350 ton/day</td>
</tr>
<tr>
<td>Need Electric power</td>
<td>773 Mwe</td>
<td>496 Mwe</td>
</tr>
<tr>
<td>Number of reactor modules</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Available power for export</td>
<td>82 Mwe</td>
<td>74 Mwe</td>
</tr>
</tbody>
</table>
### Total Heat and Electricity Needs for recovery and upgrading

<table>
<thead>
<tr>
<th>Number of modules For 100000 bpd</th>
<th>With conventional electrolysis</th>
<th>With advanced electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Net electric power for export or other internal use</th>
<th>148 MWe</th>
<th>140 MWe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Nuclear Thermal Power</td>
<td>3000 MWTh</td>
<td>2400 MWTh</td>
</tr>
<tr>
<td>- 1051 for SAGD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1627 for H2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 312 for Export</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 release avoidance</td>
<td>12 000 to 15000 tons/day (compared to natural gas use)</td>
<td>12 000 to 15000 tons/day (compared to natural gas use)</td>
</tr>
</tbody>
</table>

Sharing the unit output both for electricity and heat brings a very good level of redundancy ensuring high H2 availability, while steam production can be cut partially or totally, as mentioned before without impacting production.
Conclusions

- Nuclear combined heat and power production becomes more and more attractive in the context of volatile fossil fuel prices.
- Such combined production has a very high efficiency, over 80% depending on usage.
- There is no greenhouse gases releases.
- ANTARES is, by design, ready for such combined production without any modification of the nuclear heat source.
- Many industrial applications could potentially benefit from this concept.
- Bitumen recovery and upgrading illustrates such a good match.
A Specific Fuel Design

- TRISO Particles
- Graphite
- Helium

Double heterogeneity
- Particle
- Compact

Particles
Compact
Block
ANTARES design
Realizing Benefits of Modular HTRs Involves Development and Risk

▶ Advanced modular HTRs promise significant benefits
  ◆ Passive safety
  ◆ High temperature for process heat and efficient power generation
  ◆ Incremental deployment

▶ Key development areas
  ◆ Fuel
  ◆ Reactor technology
  ◆ Materials
  ◆ Power generating system

▶ This development entails risk for each project phase
  ◆ R&D may overrun cost/schedule
  ◆ Selected design approaches may not be feasible
  ◆ Completed facility may not perform as planned

Minimizing these risks is a priority for AREVA’s HTR design approach
Genesis of the AREVA HTR Concept

Modular prismatic HTR (e.g., GT-MHR reactor)
- Economical heat source
- Enhanced passive safety

Indirect cycle configuration
- Simplifies nuclear heat source
- Provides versatility

CCGT generating systems (e.g., natural gas-fired)
- Very high efficiency
- Reliable operation
- High fuel costs

AREVA HTR Concept
- Flexible heat source
- Passive safety
- Economical power
- Non-emitting process heat

Need for non-emitting high temperature process heat (e.g., for H₂ production)
- Scarcity and price of oil
- Environmental impact of carbon-based fuels
AREVA Commercial HTR
Combined Cycle Electric Power Generation

Primary Loop
850°C
600 MWe Rx core
355°C
Circulator

HT isolation valve
800°C
625 kg/s

IHX
233 kg/s
5.5 MPa
300°C

Gas Cycle

Gas turbine

S.G

Steam Cycle

Condenser

Steam turbine

Generator ~ 300 MWe

He
N₂/He mixture
Water/steam
AREVA HTR Concept Can Also Serve Variety of Process Heat Markets

- **Primary Loop**
  - 600 MWt Rx core
  - IHX
  - Circulator

- **Gas Cycle**
  - Gas turbine
  - S.G.
  - Steam Cycle
  - Condenser
  - Generator
  - Water/steam

- **He**
  - He or N₂/He

- **Heats**
  - **High Temp. Process Heat**
    - ~550 to 800°C
  - **Med. Temp. Process Heat**
    - ~250 to 550°C
  - **Low Temp. Process Heat**
    - ~30 to 250°C
VHTR ANTARES Nuclear Heat Source

Plant design for one primary hot gas duct and one IHX-vessel with plate IHX
# Approximate Plant Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power</td>
<td>600 MWt</td>
</tr>
<tr>
<td>Reactor Outlet Temperature</td>
<td>850°C</td>
</tr>
<tr>
<td>Reactor Inlet Temperature</td>
<td>355°C</td>
</tr>
<tr>
<td>Primary Coolant Flow Rate</td>
<td>240 kg/s</td>
</tr>
<tr>
<td>Primary Coolant Pressure</td>
<td>5.5 MPa</td>
</tr>
<tr>
<td>Reactor Vessel Material</td>
<td>9 Cr – 1 Mo or SA 508</td>
</tr>
<tr>
<td>Core Configuration</td>
<td>102 Columns, 10 blocks high.</td>
</tr>
<tr>
<td>Fuel Particle Type</td>
<td>SiC Coating</td>
</tr>
<tr>
<td></td>
<td>UCO or UO$_2$ kernel</td>
</tr>
<tr>
<td>Operating Max Fuel Temp. Guideline</td>
<td>1300°C</td>
</tr>
<tr>
<td>Accident Peak Fuel Temp. Guideline</td>
<td>1600°C</td>
</tr>
<tr>
<td>IHX Design</td>
<td>Compact</td>
</tr>
<tr>
<td>IHX Nominal Heat Load</td>
<td>608 MWt</td>
</tr>
<tr>
<td>IHX Effectiveness</td>
<td>90 %</td>
</tr>
<tr>
<td>IHX Primary Tin</td>
<td>850°C</td>
</tr>
<tr>
<td>IHX Tout</td>
<td>350°C</td>
</tr>
<tr>
<td>Secondary Fluid</td>
<td>Nitrogen/helium Mixture</td>
</tr>
<tr>
<td>IHX Secondary Tout</td>
<td>800°C</td>
</tr>
<tr>
<td>IHX Secondary Tin</td>
<td>300°C</td>
</tr>
<tr>
<td>Secondary Flow Rate</td>
<td>614 kg/s</td>
</tr>
<tr>
<td>Secondary Coolant Pressure</td>
<td>5.5 MPa</td>
</tr>
</tbody>
</table>
SAGD
Steam at 310°C, 100 bar
SAGD Principle of bitumen recovery
Temperature Range of Industrial Heat Uses

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
</tr>
<tr>
<td>Glass Manufacturing</td>
</tr>
<tr>
<td>Cement Manufacturing</td>
</tr>
<tr>
<td>Iron Manufacturing (Direction Reduction Methods)</td>
</tr>
<tr>
<td>(with a Blast Furnace)</td>
</tr>
<tr>
<td>Electricity Generation (Gas Turbine)</td>
</tr>
<tr>
<td>Gasification of Coal</td>
</tr>
<tr>
<td>Hydrogen (IS Process)</td>
</tr>
<tr>
<td>Hydrogen (Steam Reforming)</td>
</tr>
<tr>
<td>Ethylene (naphtha, ethane)</td>
</tr>
<tr>
<td>Styrene (ethylbenzene)</td>
</tr>
<tr>
<td>Town Gas</td>
</tr>
<tr>
<td>Petroleum Refineries</td>
</tr>
<tr>
<td>De-sulfurization of Heavy Oil</td>
</tr>
<tr>
<td>Wood Pulp Manufacture</td>
</tr>
<tr>
<td>Urea Synthesis</td>
</tr>
<tr>
<td>Desalination, District Heating</td>
</tr>
</tbody>
</table>

Reactor Temperature: 725°C – 1200°C

Figure 2. Potential uses of nuclear heat from Generation IV Systems.
Natural gas price volatility

U. S. Wellhead Natural Gas Price

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