Concept and technology status of HTR for industrial nuclear cogeneration

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AREVA NP

NC2I Workshop, Brussels, 18/03/2015
Process heat needs from industry

### Steam networks

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- **Iron Manufacturing**
  - (Direction Reduction Methods)
  - (with a Blast Furnace)
- **Electricity Generation**
- **Gasification of Coal**
- **Hydrogen (Steam Reforming)**
- **Ethylene (naphtha, ethane)**
- **Styrene (ethylbenzene)**
- **Town Gas**
- **Petroleum Refineries**
- **De-sulfurization of Heavy Oil**
- **Wood Pulp Manufacture**
- **Urea Synthesis**
- **Desalination, District Heating**

### In situ heating

- **Glass Manufacturing**
- **Cement Manufacturing**

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Process heat needs from industry

Steam network

In situ heating

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HTR > 550°C

MSR → 600°C

SFR, LFR, SCWR → 500°C

LWR, HWR → 250°C

VHTR > 800°C

Nuclear Heat

Still to be developed Materials and fuel are challenging Industrial ~ 2050

Still to be developed Industrial ~ 2050 Competitiveness?

Mature technology Large scope Industrial demonstration required First deployment possible within 10 years

Ready to be used (already industrial experience) but limited scope
Process heat market per temperature range

Distribution of the heat market by temperature class and sector

Heat consumption by year (GWh/y)

Temperature class and type of market

- 100-250°C
- 250-550°C
- 550-700°C
- 700-1000°C
- > 1000°C

- Iron and steel (including coke)
- Gypsum
- Mineral wool insulation materials
- Non-ferrous metals
- Cement
- Ceramics
- Glass
- Primary aluminium
- Lime, dolomite and magnesite
- Ferrous metals
- Refinery
- Secondary aluminium
- Industrial gases
- Non-metallic minerals
- Metal ore
- Soda ash and sodium bicarbonate
- Chemical industry
- Steam and hot water supply
- Electricity, gas, steam and hot water supply
The modular HTR concept

- High temperature > 600°C
  - Need of
    - Refractory materials
    - Chemically inert coolant
    - Robust fuel for high temperature operation
  - Moderator: graphite
  - Coolant: helium
  - TRISO particle fuel

- Additional favourable safety features
  - Huge thermal inertia
  - Strongly negative temperature coef.
  - No void effect

- The modular concept

Intrinsic passive safety
Core melting excluded
No exclusion zone required
The industrial concept for process heat applications: nuclear cogeneration

- Main constraints for nuclear energy
  - The power of nuclear reactors cannot vary very quickly
  - To be competitive, nuclear industry needs standardized designs built in series

- Requirements of industrial energy users
  - Process heat / steam needs vary from one site to the other
  - Some processes may induce fast heat / steam load transients
  - Most of the industrial sites need both process heat / steam and electricity

⇒ The solution for supplying process heat / steam with a nuclear reactor is cogeneration, with a possibility of variable share between electricity and heat / steam supply

+ Using as much as possible existing technology for first application ASAP
  - Reactor temperature < 750°C to be able to use existing industrial materials
  - Use of steam generator(s) to transfer heat from the primary circuit to heat and power applications
The HTR cogeneration concept

2 barriers between primary helium and process steam

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HTR technology maturity: the worldwide experience

- First developments of HTRs in the 1950’s

- The two major innovations
  - TRISO coated particles in the early 1960s’, improved in the following decades
  - The modular concept developed in the 1980s’ in Germany and in the US

- Several high temperature test reactors & industrial prototypes built

- High temperature opened a large scope of process heat applications: the coupling of reactors with industrial processes has been explored in Germany since the 1970s’ (PNP project)

- Recent international industrial prototype designs
  - USA: the NGNP project launched by DOE in the 2000s’ initially for H₂ production at ~ 1000° C, then oriented towards lower temperature process heat applications
    - Important achievements in technology (fuel and materials for high temperature)
    - Limited design work
  - South Africa: PBMR project designed an industrial prototype; stopped in 2009
  - China: HTR-PM
HTR technology maturity: the European experience

- The legacy of the German HTR development mostly recovered through FP4 to FP7 projects

- AREVA developed the conceptual design of a combined cycle cogeneration HTR (ANTARES programme)

- Several European organizations have been involved in international design projects (PBMR, NGNP, HTR-PM)

- Mastering of key HTR technologies from FP 5 to 7 (RAPHAEL, ARCHER, etc)
  - Recovery of the main achievements of the German programme
  - Selection and qualification of materials for high temperature (graphite, vessel steel, Ni base alloys…)
  - Manufacturing of fuel
  - Development of a European safety approach for modular reactors
  - Development and performance assessment of a key component: the plate IHX
Recent achievements in Europe

- **ANTARES**
  - UO₂ kernel fabrication
  - UO₂ kernel coating
  - Manufacturing of compacts

- **Plate IHX mock-up**, manufactured by ALFA-LAVAL and tested in the ARCHER project

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Main assets of HTRs for application to industrial cogeneration

- **High temperature**
  - With present technology
    - Reactor operating temp. < 750°C
    - Applications with steam heat carrier < 550°C
  - In the longer term reactor operating temp. > 800°C
    - Depending on the availability of advanced materials and fuel
  - Fits with the energy needs of industrial processes

- **Modular concept**
  - Medium size depending on reactor technology
    - Block type core (600 MWth)
    - Pebble bed core (300 MWth)
    - Intrinsic passive safety
  - Risk of core melt excluded
  - No need of exclusion zone
  - Siting on existing industrial platforms acceptable
  - Flexibility required for industrial application

- **Cogeneration**
  - Mature technology
  - Beginning of deployment possible ~ 10 years
  - Complies with European objectives of CO₂ emission decrease
What is still needed for deployment of cogeneration HTRs?

- Demonstration of industrial operation of HTR cogeneration

For that purpose the technology for designing a HTR is mainly available, but we still need:

1. A viable funding scheme
   - Public support for the first phase of the project (design and licensing)
     - Bridge the gap for too long term ROI for private investors
     - De-risk the demonstration project (mainly licensing risk)
   - A convincing business model to attract investors for the construction phase

2. A partnership between the suppliers of the nuclear cogeneration plant, the future operators and the industrial energy end-users
   - In particular a long term commitment of end-users to buy the steam / electricity produced by the HTR
What is still needed for deployment of cogeneration HTRs?

- Demonstration of industrial operation of HTR cogeneration

For that purpose the technology for designing a HTR is mainly available, but we still need:

3. An optimized design (competitive, complying with the operators’ and end-users’ requirements, reliable, easily maintainable, etc.)

4. A robust and convincing safety demonstration
   - The basis of the modular concept: to be able to rely on physical properties of the reactor, as a substitute for redundant engineered safety systems to demonstrate the safety of the nuclear system
   - The possibility to take into account the outstanding robustness of TRISO fuel as 1st safety barrier and possibility to benefit from it to relax the requirements on the 3rd safety barrier (containment)
   - The behavior of graphite internals in accident conditions
What is still needed for deployment of cogeneration HTRs?

- Demonstration of industrial operation of HTR cogeneration

*For that purpose the technology for designing a HTR is mainly available, but we still need:*

5. An industrial infrastructure for manufacturing
   - Components: no major technical challenge for manufacturing HTR components, but
     - Difficulty to find manufacturers for prototype components without commitments for a series
     - Very few possible suppliers for the heaviest components ⇒ large procurement delays
   - Fuel
     - No HTR fuel industrial manufacturing capability in Europe. Taking into account the large delays needed for qualifying the industrial fuel, a non-European HTR fuel supply should be considered for the demonstration (e.g. US supply)

6. An available test facility infrastructure for qualification of components
   - In particular large scale helium loops
Conclusion

- High Temperature Gas Cooled Reactors can contribute in time to the European objectives of CO$_2$ emission reduction, if available secondary steam cycle technology is selected, at least in a first phase.

- This is a mature technology, of which Europe got a significant experience.

- What is needed for initiating the industrial deployment of nuclear cogeneration is an industrial scale demonstration of operation of a cogeneration HTR.

- The key factors of success of such a demonstration are
  - To get a sound funding scheme, with an essential role of public support, at least in the design and licensing phase of the project,
  - To develop the industrial and test facility basis required for manufacturing and qualifying components, including possible international partnerships (e.g. for fuel)
The TRISO fuel

- No significant fission product release from TRISO particles
  - In normal operation
    - HFR-EU1bis:
      - 11% FIMA,
      - 1250° C in pebble centre
  - In accident condition, up to at least 1600° C
The TRISO fuel

TRISO particle

KERNEL
BUFFER LAYER
SiC-LAYER
INNER PyC-LAYER
OUTER PyC LAYER

1mm

Compact
Block
Block type core

6 cm

Sphere

Pebble bed

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In a HTR, when the temperature increases, the fission stops. Nevertheless the decay heat is still to be released.

If the decay heat is not too high, a balance between
- The generation of decay heat
- The release of heat by conduction and radiative heat transfer

can be reached below a temperature at which the integrity of particles would be jeopardized (> 1600°C), with consequently significant radioactive releases.

Depending on the reactor design, the limit of power is between 300 and 600 MWth

⇒ No need of engineered safety system with high reliability and high redundancy for extracting decay heat, based on simple physics
  ⇒ Simplification in the safety design
  ⇒ Investment savings

⇒ Modular HTRs are based on this simplified safety design. All present projects use this concept.
The HTRs built and operated in the world

Test reactors

- DRAGON, U.K. (20 MW, operated 1963-76)
- Peach Bottom, US (200 MWth, operated 1967-74)
- AVR, Germany (15 MWe, operated 1967-88)
- HTR-10, China (10 MWth, operated since 2000)
- HTTR, Japan (30 MWth, operated since 1998)

Industrial prototypes

- Fort Saint-Vrain, US (300 MWe, operated 1976-89)
- THTR, Germany (300 MWe, operated 1986-89)
- HTR-PM, China (2 x 106 MWe)
The experience of nuclear process heat applications

- Several industrial experiences at relatively low temperature

- The German demonstration programme for HTR process heat applications at high temperature (PNP)

Coal to Liquid with nuclear simulated steam generation

Conversion of coal into liquid transport fuel with nuclear heat source demonstrated at the level of industrial pilot plant

- Lab scale testing, 1973-1980 with 5.0 kg/h
- Semi-technical scale testing, 1976-1984 with 0.5 t/h
- Gasification at 750-850°C and 2-4 MPa
- Total coal gasified: 2413 t
- Operation time of ~26,600 h with ~13,600h under gasification conditions

10 MW steam CH₄ reformer mock-up for nuclear application