COUPLING A HYDROGEN PRODUCTION PROCESS TO A NUCLEAR REACTOR

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Basic Options (1/2)

• Co-generation is often proposed, but:
  – Operation of a co-generation plant seems to be difficult
  – Relative power of H2 and electricity production is an open parameter
  – Detailed coupling circuit is complicated

• A dedicated VHTR is studied to deliver heat to a Sulfur/Iodine chemical process
  – It reduces the number of difficulties
  – Outlet temperature of the VHTR is adapted to the needed temperature of the process
  – Electricity comes from the grid
  – A detailed scheme for the coupled plant should be obtained
  – Optimization can be done
Basic Options (2/2)

- A dedicated 600 MWth VHTR
- Temperature is above 900°C
- $\text{H}_2$ production is around 1 kmol/s
Towards a Hydrogen Production Plant

• A reference flow-sheet
  – With present thermodynamic data
  – Using chemical engineering techniques
  – Assessed by expert judgment
• Very detailed flow-sheet based on a conceptual design for an experiment
• Thermo-chemical analysis of each component
• Design of each main component
  – Heat exchangers
  – Reactive columns
• Finally a plant layout is drawn
A reference flow-sheet

- Each section is clearly defined in detail
- Example: Section I (Bunsen)
  - Excess of water and iodine (to be optimized in the future)
  - Elimination of outlet sulfur dioxide
Component design: Bunsen reactor

Scaling for a 1 mol/s unit

- Diameter: 300 mm
- Total Height: 2,100 mm
- Reactive zone: 1,350 mm
- Thermal Power: 95 kW
- Liquid-liquid heat exchange
- Degraded heat transfer coef.: 540 W.m⁻².K⁻¹
- Water Coolant: 15 °C – 0.2 MPa (E = 140 °C)
- Log Pinch Temp.: 98 °C, S = 2.1 m²
- Serpentins: 38 spires - DN 25 – D = 0.25m – Pinch 30mm
- 9 compartments of 150 mm in the reactor
- Residence time: 180 s.
- Enlarged reactor bottom diameter: 450 mm
- DI-Iodine loading: ~ 550 kg
Component design: H$_2$SO$_4$ / SO$_3$ convertor

Scaling 1 mol/s

2 Evaporators (KESTNER type)

- Bundle: 9 tubes DN38/34 mm
- Height: 7,000 mm
- Thermal Power: 105 kW
- Operating temperature: 250 to 370 °C
- Operating pressure: 0.4 MPa

- Bundle: 18 tubes DN38/34 mm
- Height: 7,000 mm
- Thermal Power: 270 kW
- Operating temperature: 370 to 800 °C
- Operating pressure: 0.4 MPa
Hydrogen Production Plant layout

- 1 kmol/s = 80 000 m³/h
- 599 MWth + 100 MWe from the grid
- 10 shops
Coupling the HYPP with a VHTR

- Heat is delivered to High Temperature stage
- Then to Medium Temperature stage
- The intermediate circuit includes 1 IHX and 1 Process HX
- Heat Exchanger temperature pinch must be at least 30°C
Transferring heat

- Optimization of the heat transfer piping
  - Heat loss less than 0.001°C/m (1kW/m)
  - Pressure drop = 400 Pa/m
  - Steel tube no more than 400°C
- Allows several 100 m length of circuit

- Finally the needed minimum temperature from the VHTR is calculated
  - 870°C in the process
  - 2 X 30°C temperature drop in IHX
  - > 930°C at the outlet of the core
Safety Rules for Coupling

• Plants Safety Classing

VHTR = Regulated Nuclear Plant          HYPP = Seveso II Regulations
Safety Approach ...  

Safety of the Coupling = Regulated NP Rules

• 4 levels of states are studied

1. Normal operation
   • Respect operating constraints, Master dangerous materials
     ➢ Heat transfer stability, Hydrogen transfer limitation (T, H₂)

2. Abnormal operation
   • Control, to limit deviations, Protection, to come back to a safe state
     ➢ Rapid decrease of thermal exchanges, Chemical burst, Abnormal Tritium concentrate, IHX leakage, Isolation valve default

3. Accidents
   • Uncoupled the facilities, Emergency shutdown systems, Heat removal systems
      ➢ Loss of elec. Supply, coupling failure, limited HYPP leakages

4. Severe accidents
   • Impact from one plant on the other, Safety arrangements
      ➢ Hydrogen risk
VHTR-HYPP Coupling : Operation

Verify compatibility of VHTR and HYPP states

- During normal operation, start up, shut down

• Heat transfer stability
  1. Hot towards HYPP
  2. Cold back to VHTR

• Hydrogen transfer limitation
  3. Respect Tritium regulations
    - Limit $H_2$ permeation

• 1 et 2 : Procedure & system for coupling/decoupling when nominal $T^\circ$ is achieved :
  - Isolation valves
  - VHTR heat removal systems : Self Operating System
  - Possibly, auxiliary heating system on HYPP

• 3 : Tritium/$H_2$ management
  - Purification of primary and intermediate circuits
  - Low IHX permeation

Achievable 0.05% transferred = respect 10 pCi/g $H_2$ produced
VHTR-HYPP Coupling - Incidents

Objectives :

• Avoid significant impact from one on the other
• Maintain each plant under safe state

Incidents to be studied

– Rapid decrease of thermal exchanges
– Chemical burst (Bunsen)
– Abnormal Tritium concentrate
– IHX leakage
– Intermediate circuit leakage
– Isolation valve default : shut-off - rejection

• Introduce a tank for heat transfer inertia
  – Stabilizing SG on intermediate circuit, coupled to HYPP through steam pre-heating
VHTR-HYPP Coupling - Accidents

- Analysis of each plant: internal hazard + coupling
- Probability/consequences approach: scenario evaluation, acceptance
- Only concern in a first step:
  - HYPP Accident Products release Explosion - Fire cumulative with VHTR Fission Products release

Provisions
- Reduce $\text{H}_2$ risk on HYPP + Protect VHTR
- Prevention
  - Detection on production column
  - Cut off incoming flow in various sections
    - Back stream on HI distillation column - Stop electrolysis
  - Continuous evacuation of $\text{H}_2$ production
  - Non explosive production of $\text{H}_2 + \text{H}_2\text{O}$
  - Leakage dilution: HYPP at open air
- Protection
  - Separating hill
  - VHTR underground
  - Distance
    - Distant $\text{H}_2$ production zone, located in the HI section. Far from the high temperature zone.
Hydrogen Risk Mitigation

- Separating hill
- Reactor building underground
- Safe Distance
- Flow regulation
- Distant storage
- Leak detection on producing tank
Coupling a HYPP to a VHTR: Conclusion

- Work is underway to determine the layout of a first S/I chemical facility coupled to a VHTR
- Using a dedicated plant simplifies the study
- One needs to iterate between
  - Basic data
  - Detailed Flow-sheet
  - Component design
  - Safety needs
- For the chemical facility
- For the coupling circuit
  - That are new complex systems
- Key points are progressively identified
- Economic evaluation will end the study

Comparative work on other processes is scheduled