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Nuclear Hydrogen Production

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- Economics
- Considerations & Safety Aspects
- Environmental Impact
- IAEA Research Collaborative Activities on Nuclear Hydrogen Production
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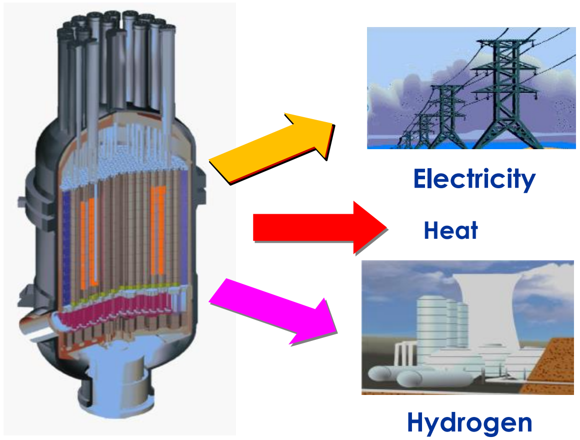
Introduction

Need for Nuclear Hydrogen Production

- **Increased interest in hydrogen.**
- **Demand is large and keeps growing (at rate of 6-10 % /year).**
- **96% of current annual hydrogen production is by steam reforming**
- **Hydrogen as a transportation fuel**

Characteristics

- ✓ Promising
- ✓ Still under R&D
- ✓ Safety of coupling



Future of Hydrogen Demand in Transportation Sector

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- **China:**
  50,000 FCEVs on the road by 2025 & 1 million by 2030
- **Japan:**
  200,000 FCEVs on the road by 2025 & 0.8 million by 2030
- **Korea:**
  replace 27,000 CNG with FCEVs by 2030
- **EU:**
  600 to 1000 FCEV Buses by 2020
  & Double H2 Filling Station biannually
- **Germany:**
  350 Million Euro for 400 refueling stations for FCEVs by 2023
- **USA:**
  California set a goal of 100 station by 2020 & cut petroleum use for cars to half by 2030

Photo from http://mhlnews.com/powered-vehicles/world-hydrogen-market-set-35-percent-annual-growth-through-2018

FCEVs= Fuel cell electric vehicle

Routes of Nuclear for Clean H2 Production

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For Current nuclear reactors:

- Low-temperature electrolysis, efficiency ~ 75%

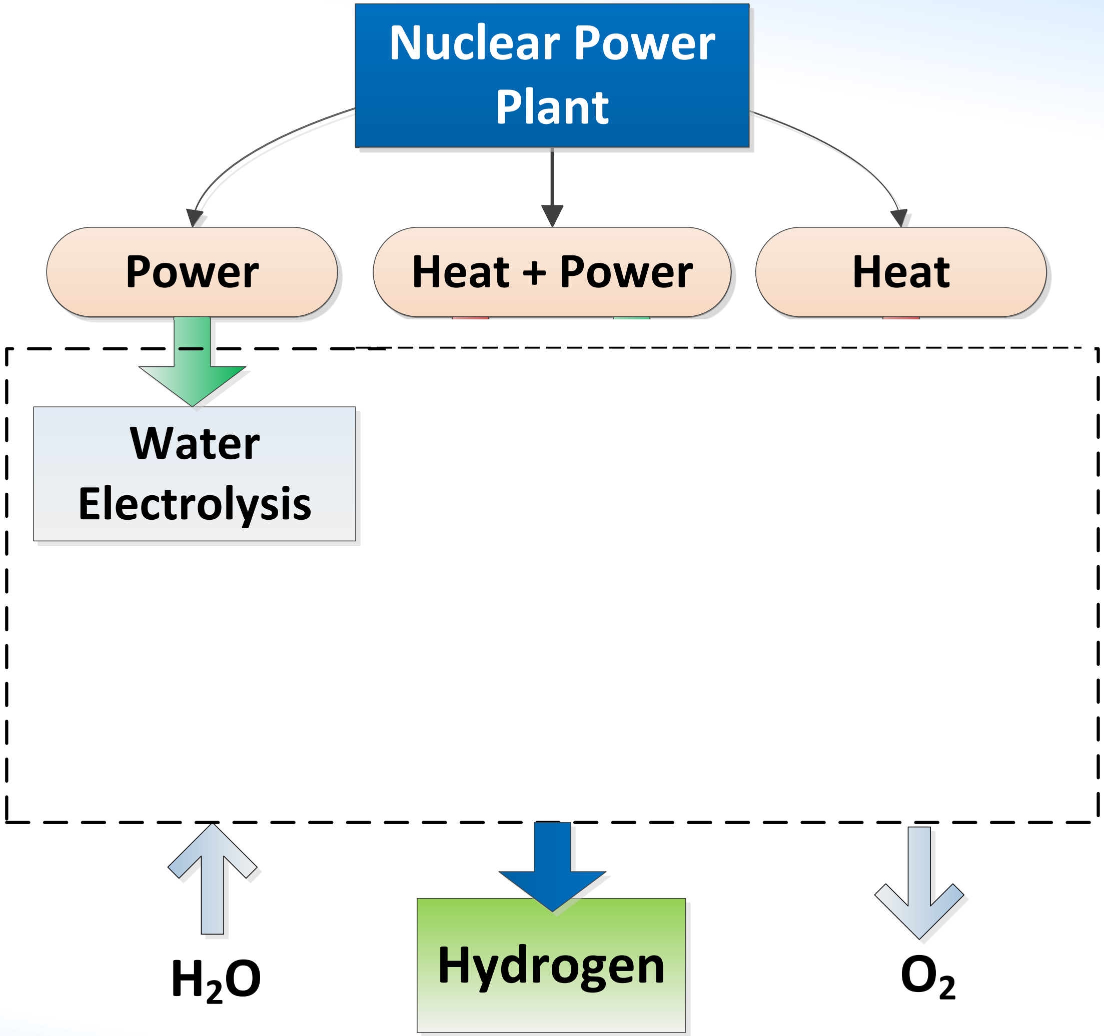
- Off-peak power or intermittent

Future nuclear reactors:

- High-temperature electrolysis, *efficiency ~ 95%*

- Thermochemical/hybrid thermochemical cycles, *efficiency (up to 95%)*

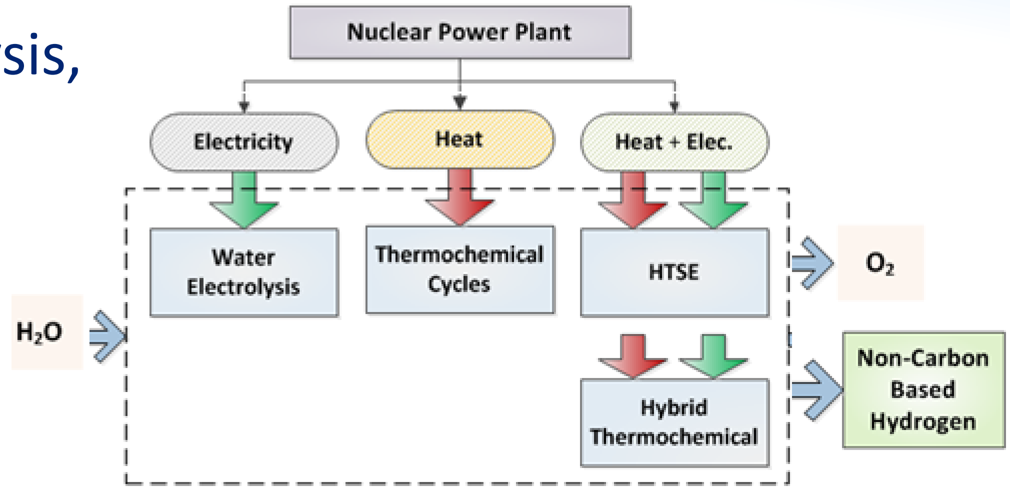
✓ Sulfur- Iodine cycle.
✓ Sulfur-Bromine hybrid Cycle cycle
✓ Copper Chlorine cycle
✓ .... etc



Nuclear Hydrogen Production: Promising Technologies

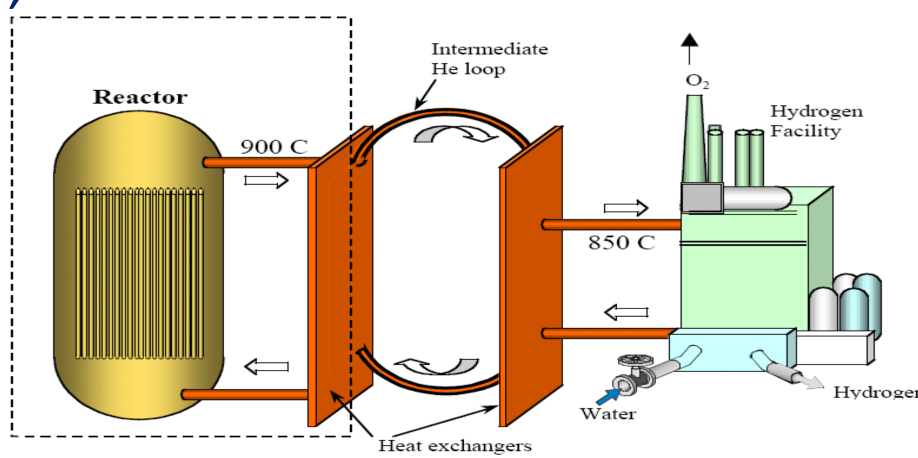
For Current nuclear reactors:

- ❑ Low-temperature electrolysis, efficiency ~ 75%
- ❑ Off-peak power or intermittent



Future nuclear reactors:

- ❑ High-temperature electrolysis, *efficiency ~ 95%*
- ❑ Thermochemical splitting, *efficiency ~ 95%*
  - ❑ Sulfur- Iodine cycle.
  - ❑ Sulfur-Bromine hybrid Cycle cycle
  - ❑ Copper Chlorine cycle .... etc



Major Technologies for Nuclear Hydrogen Production (1)

Conventional Electrolysis

- Ideal for remote and decentralized H2 production
- Off-peak electricity from NPP (if share of nuclear among power plants is large)
- Use of nuclear outside base-load is more attractive, as fossil fuels become more expensive.

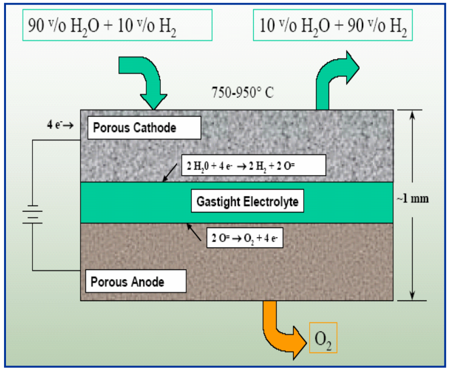
Plant for 200 m^3/h

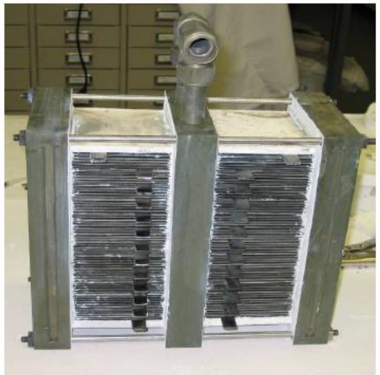
Major Technologies for Nuclear Hydrogen Production (2)

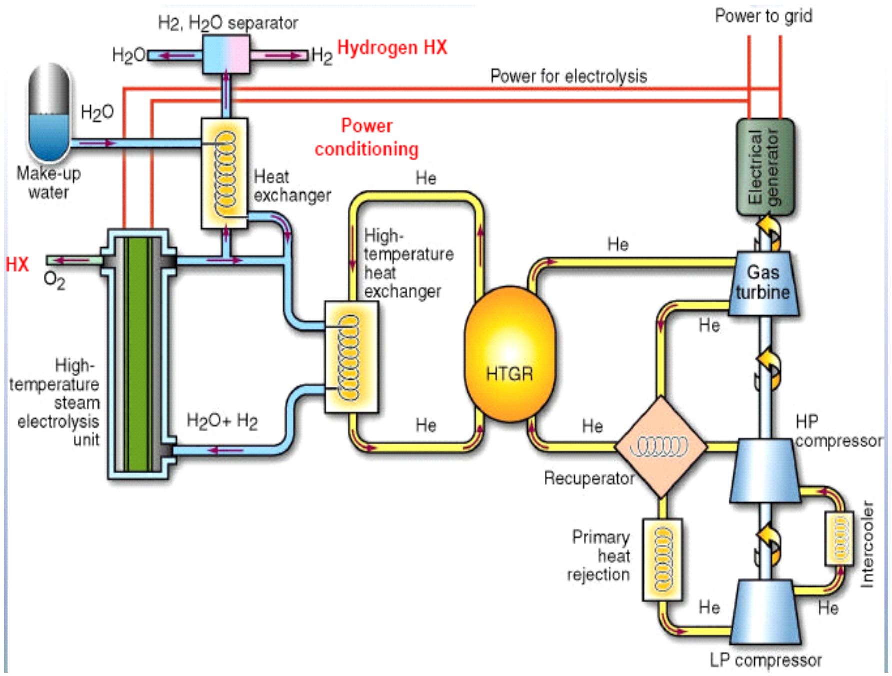
High Temperature Steam Electrolysis

- Higher efficiency;
- Reduced electricity needs;
- Capitalize from SOFC efforts.

(SOFC= ***Solid Oxide Fuel Cell***)







Suitable for integration with HTGR, VHTR and SCWR

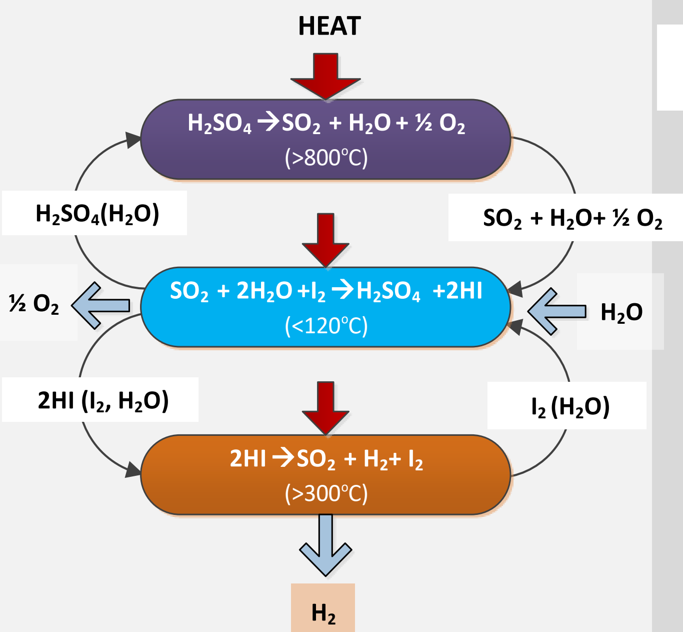
HTGR= high temperature Gas cooled reactors
VHTR= Very high Tempertaure Reactors
SCWR= Supercritical Water Reactors

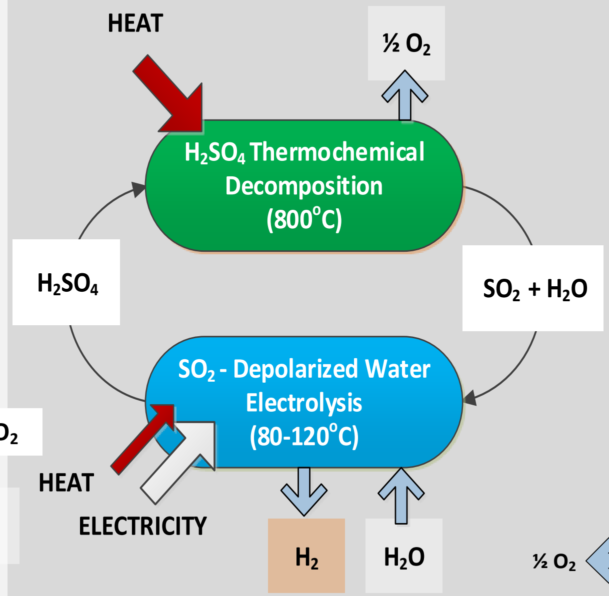
Major Technologies for Nuclear Hydrogen Production (3)

Thermochemical & Hybrid Cycles

Sulphur-Iodine (S-I)

Convenient with Very High Temperature Reactor (VHTR)



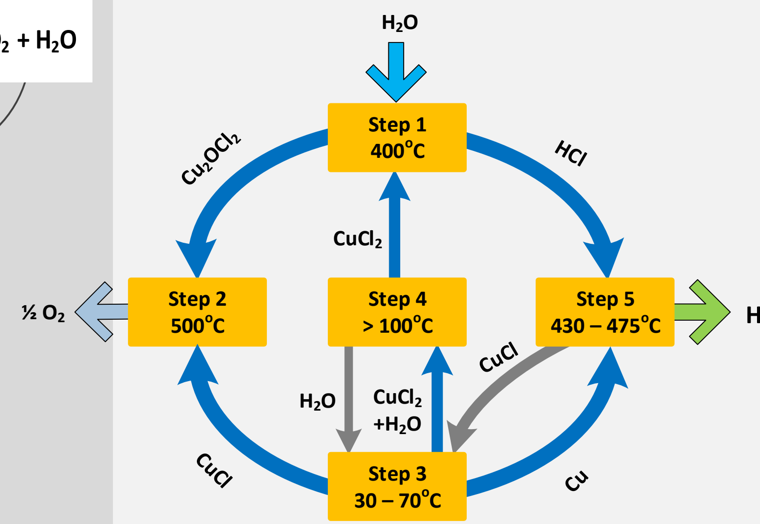


Hybrid Sulphur (HyS)

Convenient with Very High Temperature Reactor (VHTR)

Copper Chlorine Cycle

Considered for coupling with (SCWR)



Insight on Nuclear Hydrogen Production & Global Status on High Temperature Reactors (1)

- **China** developing HTR – start up imminent (SI & HTSE)
- **USA** proceeding on NGNP
- **Japan** is very active with VHTR (SI)
- **France** VHTR was a breeder option (HTSE)
- **Canada** is more focus on SCWR (HTSE & CuCl)
- **India** looking at molten salt option (SI & HTSE)
- **Rep. of Korea** HTR (SI & HTSE)
- **South Africa** suspends PBMR effort
- **Russian Federation** (HTR)

Insight on Nuclear Hydrogen Production & Global Status on High Temperature Reactors (2)

Increasing interest in electrolysis

- Low temperature has potential – but the economics?
- High temperature is 10 to 20 years away!!
- Major efforts in China, US, Canada, Japan, India…

Chemical processes of interest, Yet…

Which reactors – monolithic, pebble bed, molten salt??

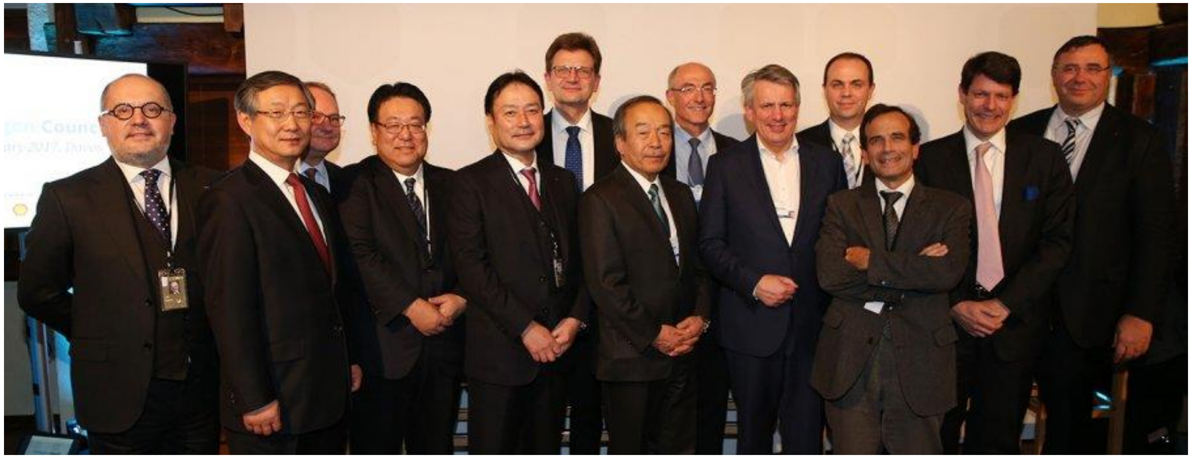
Insight on Nuclear Hydrogen Production & Global Status on High Temperature Reactors (3)

HYDROGEN COUNCIL

Event: World Economic Forum

Venue: Davos

When: 17th January 2017



13 global industry leaders join together in promoting hydrogen to help meet climate goals

http://hydrogencouncil.com/

Specific Considerations for Nuclear Hydrogen Production

- Overcome barriers to economic hydrogen generation.
- Demonstrate large-scale production & storage of hydrogen.
- Develop chemical processes that operate efficiently and reliably.

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Economics

Nuclear Hydrogen Production Cost

GEN-IV reactors for hydrogen production

Country Specific Case Studies (Results of CRP)

	JAPAN	CHINA	GERMANY	CANADA		
Nuclear power plant	GTHTR300	HTR-PM	HTR-SR	SCWR		
H2 production process	S-I	S-I	SR	S-I	HyS	CuCl
Thermal efficiency%	46.98	-	20.34	46.98	-	32.2
Hydrogen production ($kg/MW_{th}h$)	12.28	10.90	102.8	4.16	6.9	7.5
Hydrogen cost ($/kg)	2.46	3.78	3.61	4.1	4.74	5.34

Economic Challenges

- **Demonstrating low Hydrogen production costs on an industrial scale**
- **Exploiting today's needs to move towards a large future market**
- **Building and operating very large number of NPPs with low energy generation costs**

Cost of hydrogen can be reduced by:

- Sell electricity to grid during periods of high demand/high price
- Use electricity for hydrogen production during periods of low demand/low price

Considerations & Safety Aspects

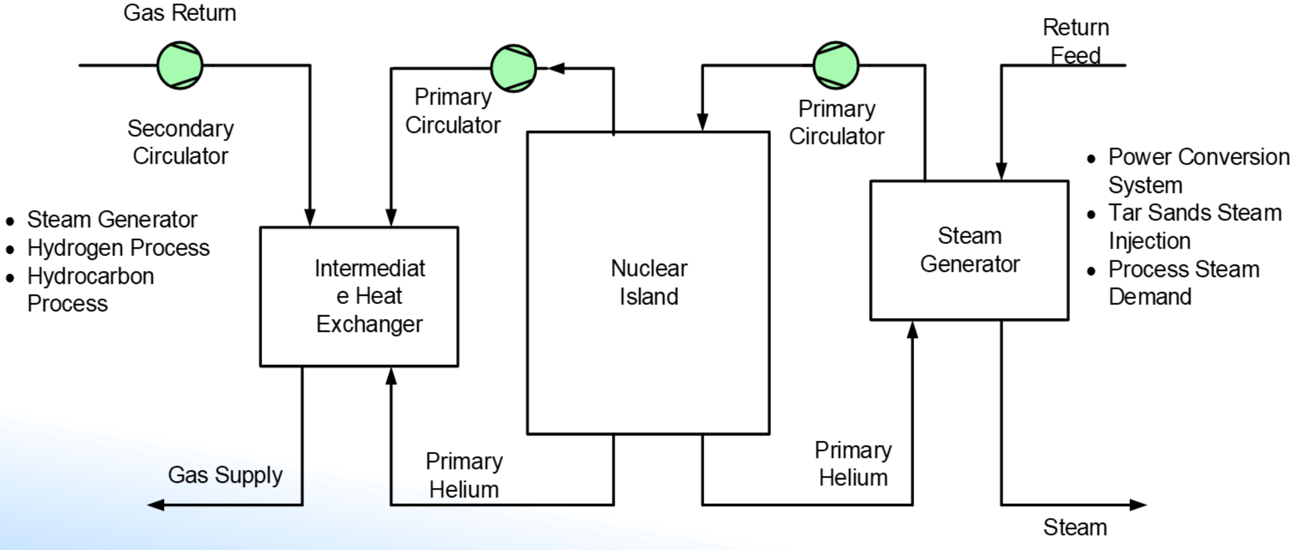
Main Issues of Consideration for Nuclear H2 Plants

Coupling for Nuclear Hydrogen Production

Coupling for *Hydrogen production* or *process heat* applications through heat transfer:

-Via an intermediate helium circuit from the reactor to the process heat plant;

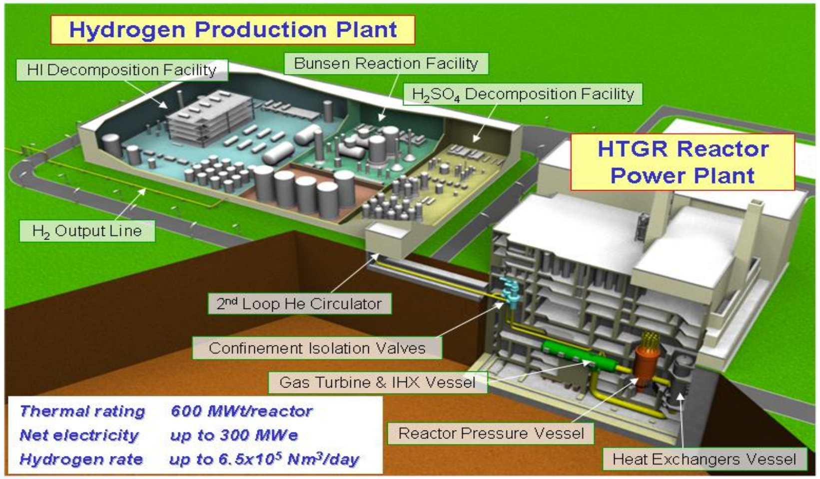
-Directly to the high temperature heat exchanger in the primary circuit.



Specific Safety Considerations for Nuclear Hydrogen Production

Nuclear power reactors should:

- Have inherent/passive safety features
- Constructed with separate containment
- Build underground
- Arranged with a safe distance from the hydrogen plant



Siting for Safety of Nuclear Hydrogen Production (General 1)

The need to locate a nuclear facility near industrial plants, and perhaps population centers, implies additional considerations towards licenseability and public acceptance. **Some potential issues include**:

- Requirements for additional safety features;
- The need of plans for the safe and orderly shutdown of the industrial process and sheltering or evacuation of the industrial facility staff in the event of accidents;
- The need of detailed plans for public notification, sheltering, or evacuation in the event of accidents;
- Increased requirements for public education and programs encouraging public acceptance.

The specific requirements will be determined by such factors as the reactor type, the nature of the industrial process, the distances of the industrial facility and population centers from the nuclear plant, and prevailing public attitudes.

A new generation of smaller reactors with passive safety features may at least partly mitigate the above siting issue.

Siting for Safety of Nuclear Hydrogen Production (General 2)

❖ The supply of steam to an industrial process by a nuclear plant generally implies the need to have the nuclear facility in close proximity to the industrial process. This is due to the technical and economic characteristics of steam transmission.

For the design and the site selection, the following rules of thumbs can be used:

- For a given steam delivery pressure, the unit energy cost of steam transmission increases with distance and decreases with transmission capacity and inlet pressure;
- Steam transmission costs decrease as the steam delivery pressure is decreased;
- The use of compressors in a steam transmission system is generally not economical;
- Heat in the form of hot water can be delivered at a distance of up to about 150 km with a reported loss of 2%.

Siting for Safety of Nuclear Hydrogen Production (Specific)

Coupling of Hydrogen production plant with NPP

- Preventing Hydrogen migration
- Preventing Hydrogen combustion

❖ **Separation distance between the NPP & H2 production system is a key element.**

Factors affecting the safety separation distance:

Air shock wave impact;

Capital costs;

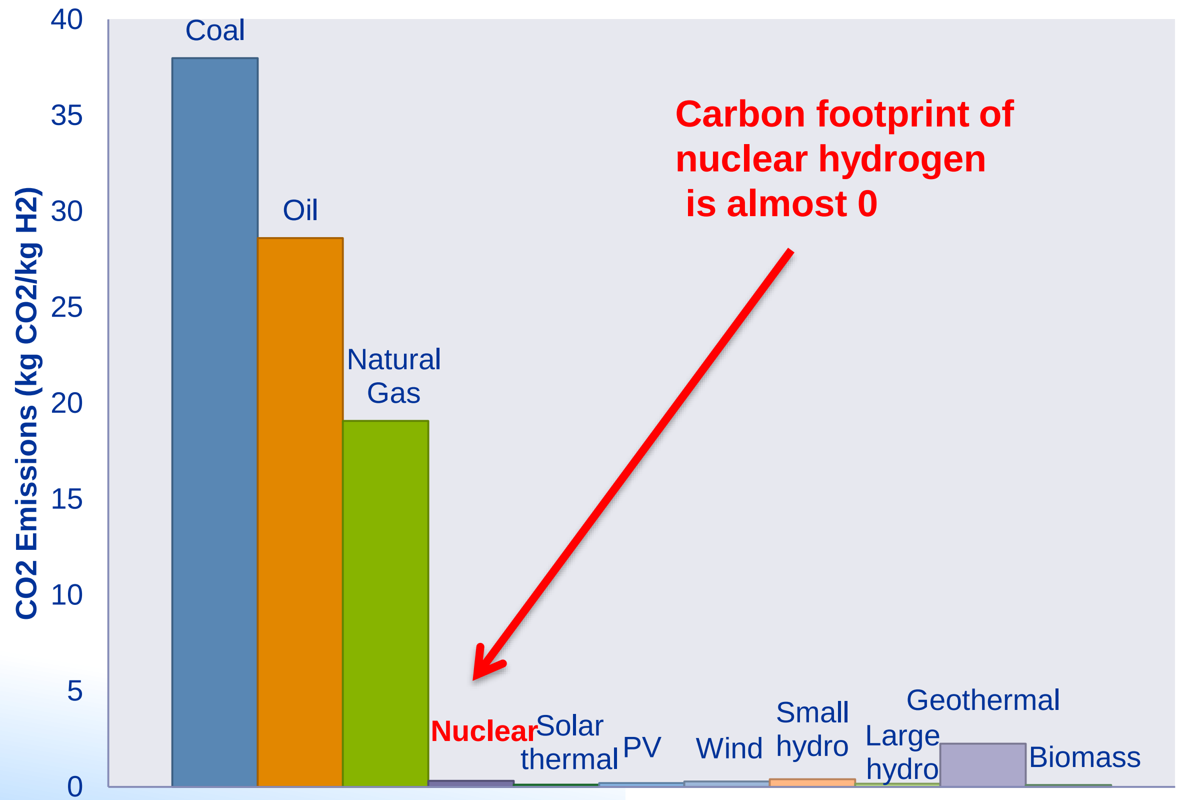
Heat losses;

Coolant pumping power requirements.

Environmental Impact

Environmental Impact of Nuclear H2 Production (1)

- **Replacement of CO_2 emitting fossil fuels**
- **Securing energy supply by reducing dependency on foreign oil uncertainties**
- **Saving of resources by 30-40%**



Environmental Impact of Nuclear H2 Production (2)

Replacement of CO_2 emitting fossil fuels

In the short term, coupling nuclear and hydrogen generation plants would serve in reducing the carbon emissions accompanied with the currently fossil-powered steam methane reforming hydrogen plants.

In the long term, nuclear hydrogen is to be serving as a direct fuel for hybrid hydrogen fuel cell vehicles which are expected to replace currently operating ones as one of the strategies currently adopted by several nations for decarbonisation of the transportation sector.

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IAEA Research Collaborative Activities on Nuclear Hydrogen Production

IAEA Coordinated Research Projects (CRP)

Title: Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software

Duration: 2013-2016

Objectives:

- **Assessment of various hydrogen production technologies and examine the aspects of nuclear hydrogen production.**
- **Validation of HEEP through benchmarking and comparisons with similar available tools.**

11 Member States, 4 RCMs, 86277 Euro Total cost,

- More then 20 research papers in prestigious journals, in international conferences, and in edited books by respected publishers.
- 1 book chapter; and 6 conference papers
- Training more than 10 graduate students (2 PhD students and 6 M Sc. student and 2 B.SC).
- Benchmark of HEEP and the preparation of 4 detailed generic case studies for nuclear hydrogen production.

IAEA Coordinated Research Projects (CRP)

Title: Assessing Technical and Economic Aspects of Nuclear Hydrogen Production For Near-Term Deployment

Duration: 2018-2020

Objective:

- **Assess gained experience from R&D on nuclear hydrogen production in MSs.**
- **Assess potential near-term deployment of nuclear hydrogen production.**

1st RCM Meeting: 03-05 December 2018

Summary

- Nuclear hydrogen production will be an important dimension of the hydrogen economy

- All power cooled reactors can be used for hydrogen production

- Nuclear hydrogen production faces challenges

- Additional safety measures have to be introduced when hydrogen production plant is coupled to nuclear reactors.

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Questions & Discussion!

Thank you!