ARE THE LESSONS OF THE TECHNO-ECONOMIC STUDIES ON THE SULPHUR-IODINE CYCLE APPLICABLE TO THE OTHER CYCLES?

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On the potentiality of the S-I cycle

$SO_2 + I_2 + 2\,H_2O \rightarrow H_2SO_4 + 2\,HI$

$H_2SO_4 \rightarrow H_2O + SO_3$ then $SO_3 \rightarrow SO_2 + \frac{1}{2}O_2$

$2\,HI \rightarrow H_2 + I_2$

- **The temperature at which O_2 is created is high ($T \geq 850°C$)$\rightarrow$ the energy efficiency η_T could be high.**

- **In the case where the work (W) and the heat (Q) necessary for the process are produced from a Very High Temperature Reactor**

$$\eta_T = HHV / [Q + (W/\eta_{el})]$$

Where the electricity is produced with an energy efficiency η_{el}

And HHV is the high heating value of hydrogen

Limits for the competitiveness of the S-I Cycle (1)

It is necessary at first, to compare with a reference chain:

Heat from the reactor→electricity→hydrogen from alkaline electrolysis.

η_T the net efficiency the S-I cycle will have to be higher than that of the reference chain defined by:

$$\eta_{Ref} = \eta_{el} \times \eta_{electrolyzer}$$

- Where $\eta_{electrolyzer}$ is the efficiency of the transformation electricity→hydrogen
- NorskHydro company has developed devices with $\eta_{electrolyzer}$= 73 %
- it is generally assumed that for a VHTR η_{el} # 47 % $\Rightarrow$ η_{Ref} = 34 %.

Due to the complexity of the S-I cycle, the investment and maintenance costs would be higher than those of the reference chain

A first limit to the competitiveness : $\eta_T > \eta_{Ref}$ = 34 %.

Limits for the competitiveness of the S-I Cycle (2)

- **Different studies, from France and USA**

  which assess the long term evolution of the Steam Methane Reforming , as well as the progressive implementation of 3rd Generation nuclear reactors coupled with large alkaline electrolysis plants

- **estimated that in the future, the new processes for producing hydrogen should reach**

a target between 2 to 3 $/kg of H_2 .

- **This provided a second limit for the competitiveness of the S-I cycle coupled with a HTR**

On the present knowledge of the S-I cycle

- **Chemical reactions are usually not complete; as a matter of fact, the consumption of energy needed for the decomposition of HI is higher than expected.**
- **Excess of H_2O and I_2 at the outlet of the Bunsen reactor are needed to avoid miscibility of HI and H_2SO_4 acids. These lead to high material circulation and heat needs.**
- **Heat management will be optimised in order to reach a correct balance between the recovery of the heat and the size of the apparatus.**

Generic improvements of the basic operations are currently studied by CEA

Alternative thermochemical cycles and compatibilities with Generation IV nuclear reactors

- **The Generation IV International forum (GIF) has retained six innovative concepts of nuclear reactors.**
- **M.A Lewis (Argonne) selected four promising alternative pure thermochemical cycles.**

Innovative concepts of nuclear reactors

1. **the Gas Fast Reactor (GFR) $T_{oc} \in$ [550-850℃],**
2. **the Molten Salt Reactor (MSR) $T_{oc} \in$ [640-850℃],**
3. **the Lead Fast Reactor (PbFR) $T_{oc} \in$ [520-620℃],**
4. **the Sodium Fast Reactor (SFR) $T_{oc} \in$ [500-640℃],**
5. **the Supercritical Water Reactor (SCWR) $T_{oc} \in$ [380-500℃],**
6. **the Very High Temperature Reactor (VHTR) $T_{oc} \in$ [880-1000℃].**

T_{oc} *is the temperature at the outlet of the reactor core*

Promising alternative thermochemical cycles

I. **Cerium-Chlorine (Ce-Cl) T_h =850℃,**
II. **Magnesium-Iodine (Mg-I) T_h =600℃,**
III. **Iron-Chlorine (Fe-Cl) T_h =739℃,**
IV. **Vanadium-Chlorine (V-Cl) T_h = 770℃.**

T_h is the temperature of the hotter point for each cycle:
i.e. the temperature at which O_2 is produced

Compatibility between reactors and cycles (1)

	Ce-Cl	Mg-I	Fe-Cl	V-Cl
GFR	No	Yes [+]	Yes [+]	Yes [+]
MSR	No	Yes [- +]	Yes [+]	Yes [+]
PbFR	No	No	No	No
SFR	No	Yes [+]	No	No
SCWR	No	No	No	No
VHTR	Yes [+]	Yes [- +]	Yes [- +]	Yes [- +]

+ *corresponds to the upper bound among the studied values for the outlet core temperature,*
- to the lower bound.

Compatibility between reactors and cycles (2)

It appears that, at the present stage of knowledge:

- **all the four alternative cycles selected, would be compatible with the VHTR,**
- **none of them with the PbFR and the SCWR.**
- **the Magnesium-iodine (Mg-I) is compatible with the SFR, the GFR and the MSR,**
- **the chlorine based cycles: Iron-Chlorine (Fe-Cl) and Vanadium-Chlorine (V-Cl) are both compatible with the GFR and MSR,**

The alternative cycle and the first limit of competitiveness

considering a NorskHydro alkaline electrolyser with η_{el} = 73 %,

And the efficiencies η_{el} for producing electricity from the reactors

$$\eta_{Ref} = \eta_{el} \times \eta_{electrolyzer}$$

- **it is possible to define values of the net efficiency (η_T) that an alternative cycle coupled with a given reactor will have to exceed**

Due to the complexity of all the thermochemical cycles, they would lead to investment and maintenance costs higher than those of the reference chain of the selected reactor

	η_{el} [%]	η_T[%]
GFR	42	> 31
MSR	29	> 21
PbFR	44	> 32
SFR	40	> 29
VHTR	47	> 34

The alternative cycle and the second limit of competitiveness

Somewhat more complex to express than the first limit.

- **The energy consumption must be very carefully estimated, particularly for the reactions which produce H_2. These reactions are not spontaneous. Heat management will be optimised in order to reach a correct balance between the recovery of the heat and the size of the apparatus.**

- **The cost of electricity must be precisely assessed. For Generation IV reactors, the cost of electricity and the total failure probability could be greater than for Generation III reactors.**

- **The cost of the coupling between the reactor and the thermochemical cycle must be investigated in terms of investment, additional energy consumption and safety consideration.**

Conclusions

- **Among the promising thermochemical cycles studied with a view to produce hydrogen from nuclear reactors, and given the present state of knowledge, most of them would only be compatible with VHTRs.**

The future of these cycles should strongly depend on the VHTRs.

And conversely the future of the VHTRs will depend on their interest for producing hydrogen

- **In any cases, the sets reactor + thermochemical cycles will be confronted with limits of competitiveness.**

- **Critical points have been identified, which are currently examined by CEA.**

CEA will realize a deeper assessment of the thermochemical cycles at the end of 2008.