Gas Cycle testing opportunity with ASTRID, the French SFR prototype

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• **INTRODUCTORY POINTS:**
  – Governmental key decisions in France & corresponding Strategy for Fast Reactor.
  ⇣ Few comments about CEA project for a 1500 MWth prototype, "**ASTRID**".

• **GAS POWER CONVERSION CYCLES STUDIES WITHIN SFR R&D PROGRAM:**
  – The path to the Nitrogen choice made for ASTRID reference gas cycle.
  – sCO$_2$ cycle status & outlines of R&D studies performed.
    (Thermodynamic, Cycle Dynamic, Chemical Interact° with Na, **Material**)

• **CONCLUSION.**
French Fast Reactor strategy & Governmental key decisions

- **2006**, January, French President decision:
  
  « to launch, immediately, the design, within the CEA, of a 4th generation reactor, that shall be commissioned by 2020. We will associate the industrial and international partners which would wish to join »

- Subsequent French parliament act on radioactive waste management in June:
  
  « Transmutation of long-lived radioactive elements: Studies & investigations shall be conducted (...), in order to provide by 2012 an assessment of the industrial prospects of those systems and to commission a pilot facility before Dec 31, 2020 »

- To comply with these objectives, 2 fast neutron systems are studied in parallel
  
  - **As a reference, the Sodium Fast Reactor:**
    Promising potential to reach GENIV criteria & is the most mature option due to gained safety experience on PX/SPX, for a commercial reactor around 2040/2050

  - **As a longer term option, the Gas-cooled Fast Reactor:**
    - A GenIV system that combines advantages of fast neutrons and of high temperatures (cycle efficiency, cogeneration applications).
    - Support to ALLEGRO, 80 MWth React., to be developed in East. Europe.
Few words about ASTRID 1500 MWth prototype

**ASTRID:** Advanced Sodium Technological Reactor for Industrial Demonstration

**CURRENTLY INVESTIGATED AREAS ADDRESS, E.G.:**
- New core design e.g. to reduce fuel reactivity per cycle and void coefficient.
- Implementation of robust safety devices for DHR, an additional defense line for ULOF, a core catcher.
- Development of Improved inspection techniques (US sensors), repair technologies (robotic)
- Optimization of load factor (fuel handling strategy).
- Energy conversion system that minimizes sodium reaction risks:
  - Modular Steam generator
  - More radical alternative: use a gas cycle!

**ORGANISATION, BUDGET & SCHEDULE**
- CEA is project leader; takes advantage of industrial partnerships with AREVA NP (nuclear island) and support to the owner by EDF.
- 650 M€ awarded to CEA by government to conduct design studies of ASTRID prototype & associated R&D facilities
- First & second phases of conceptual design expected for Ends of 2012 & 2014:
Gas PCS : the path to identify $N_2$ for ASTRID ref. gas cycle

> Thermodyn. comparison of Na/Na/gas cycles perf. = $f^o$ ("classical" gas type)

- **Common component performance hypothesis**:
  - Isentropic total-total efficiency = 93% turb., 88-89% comp.
  - HX pinch point : 15°C.

- **Bound. Cond:** TIT = 515°C, Heat sink Temp. = 21°C, Pmax = 180bar & Tin $Na$-vessel = 395°C.

<table>
<thead>
<tr>
<th>Thermo. Dyn</th>
<th>Gas nature</th>
<th>$N_2$</th>
<th>He-$N_2$</th>
<th>He-Ar</th>
<th>Ne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Cycle efficiency, %</td>
<td>38.5</td>
<td>38.9</td>
<td>38.6</td>
<td>39.2</td>
<td></td>
</tr>
<tr>
<td>Tin, °C</td>
<td>351</td>
<td>364</td>
<td>364</td>
<td>364</td>
<td></td>
</tr>
<tr>
<td>Tout, °C</td>
<td>515</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compacity, MW/m³</td>
<td>1.11</td>
<td>1.03</td>
<td>1.07</td>
<td>0.76</td>
<td></td>
</tr>
</tbody>
</table>

← Cycle performance difference < 1 point.

← Compared compactness of Na/gas HX for tubes & shells technology:

- But for Neon, similar compactness.

  - Peculiar point : Poorer intrinsic thermal perf. of pure $N_2$ Vs He-$N_2$ is balanced by a higher HX pinch point. This is due to a Cp light unbalance between repecurator sides for $N_2$ case which limits its – thermodyn. optimized - inlet T in the HX.
  (if bypass + recup. split implemented such as for s$CO_2$ case ← 1 pt would be gained for $\eta$).

← TM : in spite of higher PR (2.1 Vs 1.8), pure $N_2$ found to present 1-2 less stages Vs He-$N_2$ : expected trend due to higher Cp for pure N2 (for a given stage load, a higher PR avail.).
ASTRID gas PCS: the path to N\textsubscript{2} reference cycle

> Most decisive argument for gas selection: PRAGMATISM. N\textsubscript{2} is viewed as the most reliable candidate for the ASTRID tight development schedule. Use of a single gas is expected to significantly ease cycle operation.

> Refined N\textsubscript{2} cycle design by Optim. P\text{max} & Integrat. Press. losses from detailed HX design

\[ \text{\delta} \eta < 0.1 \text{pt if } P > 180 \text{bar} \]

> Next:

- TM: contract for engineering Design studies under advanced discussion
  (preliminary CEA design for Axial turbine: 4-6 stages, $\phi_{\text{tip}} = 1.5 \text{m}$, double flow, $M \leq 0.4$).

- HX: test of compact Na/gas component carried out in Cadarache in 2012
  on DIADEMO-Na facility (Stamped plates & PCHE technologies)

\[ \rightarrow \text{Address: HT perf. (12.6 MW/m}^3 \text{PCHE ?), plugging test (channel } \phi \text{), response to cyclic therm. stress} \]
sCO2 cycle: Status & On-design perf. map at 515°C TIT

> **sCO2 cycle status within SFR strategy:** due to given short project timescales & significant R&D work that remains to be carried out before perf. & safety of this innovative system can be demo. at an industrial scale ↩ developed independently from ASTRID.

> **However, ASTRID is intended to have the ability to test innovative options:**
  - May be part of future test of new techno. on the prototype

> **Thermodynamic:** as an engineering guideline, mapped the relationship between cycle thermodyn. performance & main compressor inlet T- P, for which design choice depends on:
  - Available Heat sink temperature (usually chosen in a 32-35°C range).
  - Feed-back regarding cycle operability-stability studies (which dynamic control technolo. relevant / necessary ?).

![Optimizations of Flow & thermal flux splits between HT&BT recuperators using “simplex” algorithm](image)
TESTCASE: Application of an sCO2 cycle complying with ASTRID

- Starting design choice for “paper-code” studies: 32°C for Comp. inlet T, the optimal P (see thermodyn. Perf. chart) found to be 80.8 bar.

- If one compares to N2 reference gas cycle:
  - Cycle efficiency gain is significant: 6 points (43.6% net)
  - Max. P has been raised to 250 bar instead of 180 bar for N2 to improve η of 1 more point (questionable, see σ)

- A learning lesson from Perf. Chart ↓ Still a large performance gain over N2 case even with more Temp. margin to Tcrit: e.g. +3 points (41%) if Tin ≤ 40°C.
sCO2: simulation of reactor transient studies

- CEA’s CATHARE reference code for transient studies (water, gas, Na) does not comply with sCO₂ thermodyn. specifics → Framework of GEN IV CD-BOP, at present modeling using the Plant Dynamic Code from ANL.

- So far, completed analysis of PDC code. Is implemented:
  - ☺ A convenient approach for various components design using reference correlations (such as “Aungier” methodology for radial turbomachinery)
  - ☺ An appropriate approach to component off-design performance: adequate non-ideal treatment, TM perf. maps depend on Tin, Pin

- Application to ASTRID testcase under progress:
  - ☺ → ☺: Recently “Solved” code numerical instability issue → gave a feed-back to ANL code developer

- Next steps will address:
  - Steady-state simulations of off-design events:
    - HX progressive corrosion of ferritic-martensitic steel: define how to best deal with the drop of HT perf.
    - Seasonal heat sink temperature variation
  - Transient off-design simulations (part-load, break event, etc); Objectives:
    - Gain knowledge on peculiar behavior of sCO₂ cycle operation (Vs N₂ cycle studies with CATHARE)
    - Pay attention to technological realism regarding inputs such as control-command data.

<table>
<thead>
<tr>
<th>ASTRID testcase (750 MWth loop):</th>
<th>main RADIAL compressor design, 50 rev/s using PDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stages</td>
<td>2</td>
</tr>
<tr>
<td>Inlet guide vanes / splitters / shrouded</td>
<td>no / yes / no</td>
</tr>
<tr>
<td>Number of blades per stage</td>
<td>29</td>
</tr>
<tr>
<td>Mean radius of impeller eye, m</td>
<td>0.18</td>
</tr>
<tr>
<td>( \Theta ) of impeller / ( \Theta ) of vaneless diff., m</td>
<td>0.9 / 1.5</td>
</tr>
<tr>
<td>Impeller flow angle at exit, deg</td>
<td>65</td>
</tr>
<tr>
<td>Speed at vaneless diffuser exit, m/s</td>
<td>65</td>
</tr>
<tr>
<td>Maximum Mach number</td>
<td>0.29</td>
</tr>
<tr>
<td>Total to total isentropic ( \eta ), %</td>
<td>89.0</td>
</tr>
</tbody>
</table>
sCO\textsubscript{2} : studies regarding chemical interaction with Na

Experimental facility, "DISCO2", built to study reaction kinetics between a CO\textsubscript{2} jet & Na

**N. Simon, L. Gicquel, CEA-CAD/DTN**

**Online monitoring → data for kinetics model**

**Sonic CO\textsubscript{2} injection:**
- \( P_{\text{CO}_2} \leq 15 \text{ bar, } ~10 \text{ l/min} \)
- 0.3 to 1 mm \( \Phi \) Nozzle

**Driving motor for thermocouples axis translation**

**2 litres of Na, T varied in a 300-600°C range**

**~ 10 cm width**

**NEXT : Mass spectrometry of released gas flow → measure time dependant amount of gaseous products**

**Instrument°: set of radially spaced thermocouples with free axial translation → on line monitoring of jet T field (gain data about exothermic reaction)**

**2 litre Na cylinder, T varied in a 300-600°C range**

**~ 10 cm width**

**Sonic CO\textsubscript{2} injection:**
- \( P_{\text{CO}_2} \leq 15 \text{ bar, } ~10 \text{ l/min} \)
- 0.3 to 1 mm \( \Phi \) Nozzle

**Driving motor for thermocouples axis translation**
sCO₂ : chemical interaction mechanism

> Calorimetric studies: dual phenomenology depending on T range along HX
  - Below 500°C:
    1. \( \text{Na} + \text{CO}_2 \rightarrow (1/4) \text{Na}_2\text{C}_2\text{O}_4 + (1/4) \text{CO} + (1/4) \text{Na}_2\text{CO}_3 \)
    2. \( 4\text{Na} + \text{Na}_2\text{C}_2\text{O}_4 \rightarrow 3\text{Na}_2\text{O} + \text{CO} + \text{C} \)
  - Above 500°C:
    3. \( 4\text{Na} + 3 \text{CO}_2 \rightarrow 2 \text{Na}_2\text{CO}_3 + \text{C} \)
    4. \( 4\text{Na} + \text{Na}_2\text{CO}_3 \rightarrow 3\text{Na}_2\text{O} + \text{C} \)

> Temperature threshold confirmed in dynamic conditions: close to the Nozzle, large difference of the T profiles along CO₂ Jet “axis”, depending on TNa

![Graph showing temperature profiles along CO₂ Jet](image)

- TNa init = 400 & 450°C
- TCO₂ = 470 & 505°C
- TNa final = 460 & 495°C

⇒ Comments about solid byproducts:

😊 Wastage: no highly corrosive, no corrosion/erosion highly destructive coupled mechanism
(+ could relax the issue of Na circuit pressurization by CO₂)
😊 Efficient solid trapping required.
sCO$_2$ : identification of kinetic law parameters

> From Calorimetric studies (consist in Adiab. self heat rat experiments): 1$^{\text{st}}$ order for Na & CO$_2$ reactants evaluated

> On this basis, from reactive jet experimental results: Activation Energy & kinetic constants evaluated

<table>
<thead>
<tr>
<th>Temperature range</th>
<th>&gt; 500°C</th>
<th>&lt;500°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction number</td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>Pre-exponential factor, m$^3$/mol/s</td>
<td>1.10$^1$</td>
<td>5.10$^4$</td>
</tr>
<tr>
<td>Activation energy, kJ/mol</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Heat of reaction, kJ/mol$\text{_{gas}}$</td>
<td>-180</td>
<td>38</td>
</tr>
</tbody>
</table>

Iterative identification process of reactant order, “$n$”

Exp. Vs Model Temp. profile along jet axis
**sCO$_2$: Next necessary steps of chemical interaction modelling**

- **Remind, 2010 wastage possibility studies by KAERI**
  - impacted a 55 bar CO$_2$ jet (2 L/min)
  - on a steel pipe target (9Cr-1Mo, ∅23)
  - immersed into 60 L of Na (300-550°C)
  - using a 0.3mm Nozzle, Target located 12mm farther

  - in spite of large amount of solid by-products, observed, damage depth was < 10µm

- In parallel, at CEA, DISCO 2 experiments outlined that at 3mm from the nozzle (cf. compact HX channel ∅ …), T > 1000°C …

  - Albeit, so close to the nozzle, total T monitored by thermocouples are potentially within the shock wave region, so that possibly large Δ between static and total T.

  - Hence, need to **refine interpretation with a model** which will more realistically couple chemical reaction & thermal hydraulic, e.g. to be able to reproduce a rate of reaction which would be controlled by turbulent mixing (if chemical reaction rate is fast enough / transport process in the flow).

  - Introduce **chemistry** in a CFD tool or reverse…
Conclusion

- **Frame of Gen IV SFR R&D prog. & to avoid issues related to the fast-energ. Na/H\(_2\)O react°:**
  - A radical alternative viewed by CEA would be to replace the standard steam PCS by a gas cycle.
  - So far, comparison of “classical” gas cycles potential, completed (thermodyn., sizing);
  - Decisive argument for gas type choice relies mostly on pragmatism :
    - due to short project timescales for ASTRID 1500 MWth prototype, N\(_2\) cycle is viewed by CEA as the only option offering a potential for starting phase.

- **However, due to marked attractiveness of sCO\(_2\) perf. (up to 6% gain in \(\eta\)):**
  - sCO\(_2\) is a relevant candidate for a longer term application.
  - Depending on the international advances (cf. GEN IV CD&BOP collaboration) and since ASTRID is intended to have the ability to test new innovations, the sCO\(_2\) cycle may then form part of future tests of new technologies on this prototype reactor.

- **Current CEA studies onto sCO\(_2\) address:**
  - Materials (see F. Rouillard’s presentation at this symposium, CEA-DEN/DPC).
  - Cycle performance & Stability : go on dynamic simulation with PDC (ANL collab., CD&BOP, GEN IV).
  - Chemistry : mandatory pre-requisite to see whether Na/CO\(_2\) interaction has markedly fewer consequences than the Na/water interaction that may be mitigated much easier.
  - CEA has been perf. an exp. prog. for the last few years on this strategic topic & gained knowledge:
    - The Na/CO\(_2\) chemical interaction phenomenology (exothermicity, products) will highly depend on the place where the leak may occur in the HX.
    - The products are mainly solids (C, sodium carbonate & oxalate) and not highly corrosive so that highly destructive corrosion/erosion coupled mechanism is discarded. On the other hand, release of particulates requires implementing adequate purification systems.
    - First modeling of calorimetric and reactive jet experiments allowed to build a kinetic law but need to be refined, especially in the area close to the leak where T\(>>\) have been monitored.
Have *so far* assumed fixed *Isentropic* efficiencies for TM

**But:**

\[ \eta_{\text{isen}} = f \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \]

[for a fixed design ‘quality’]

- For comp. \( \eta_{\text{isen}} \) decreases with \( R_p \) because entropy increases.
- For turb. \( \eta_{\text{isen}} \) increases with \( R_p \) because the entropy increase results from frictional heating which is recovered as work.

As \( P_{\text{in}} \) varies within a map we have *recomputed* the 515 map using *Polytropic* TM efficiencies (89% for Comp. 93% for Turb.)

- Numerical solution (no-modelling) of:  \[ \eta_{\text{poly}} \, dh = V \, dP \]
Polytropic efficiencies

Diff_{RMS} = 0.0009428

Max < 0.003

Change in $\eta_{\text{isen}}$ for the TMs is < 0.5%
### Impact of T Change

Power and density changes at compressor inlet

<table>
<thead>
<tr>
<th>SIMULATION</th>
<th>$T_{\text{in}}, \degree\text{C}$</th>
<th>$P_{\text{in}}, \text{bar}$</th>
<th>$P_{\text{out}}, \text{bar}$</th>
<th>$\rho, \text{kg/m}^3$</th>
<th>$W_{\text{isen}}, \text{kJ/kg}$</th>
<th>$\delta\rho/\rho$</th>
<th>$\delta W/W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCO2</td>
<td>32</td>
<td>76.9</td>
<td>200</td>
<td>598</td>
<td>18</td>
<td>-44%</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Perfect Gas</td>
<td>21</td>
<td></td>
<td></td>
<td>32</td>
<td>414</td>
<td>3.3%</td>
<td>3.3%</td>
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<td>31</td>
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