Gas Cycle testing opportunity with ASTRID, the French SFR prototype

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Outline

- **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° wi th Na, *Material*)

See dedicated paper from F. Rouillard (CEA-DEN/DPC) at this sCO2 symposium

- **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

G. Rodriguez, CEA-CAD/DTN

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

energie atomique • energies alternatives

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 :
  ↳Basic Design, End of 2017.

ISO 9001
ISO 14001
OHSAS 18001

Gas PCS : the path to identify N_2 for ASTRID ref. gas cycle

L. Cachon, D. Haubensack, N. Alpy, CEA-CAD/DTN-DER

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

- **Common component performance hypothesis :**
  - **Isentropic total-total efficiency = 93% turb., 88-89% comp.**
  - **HX pinch point : 15℃.**
- **Bound. Cond: TIT = 515℃ , Heat sink Temp. = 21℃ , Pmax= 180bar & Tin $_{Na\text{-}vessel}$ = 395℃ .**

Thermo. Dyn	Gas nature	N_2	He-N_2	He-Ar	Ne
	Net Cycle efficiency, %	38.5	38.9	38.6	39.2
HX	Tin, °C	351	364	364	364
	Tout, °C	515			
	Compacity, MW/m^3 *Tubes&shells*	1,11	1,03	1,07	0,76

↳ **Cycle performance difference < 1 point.**

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

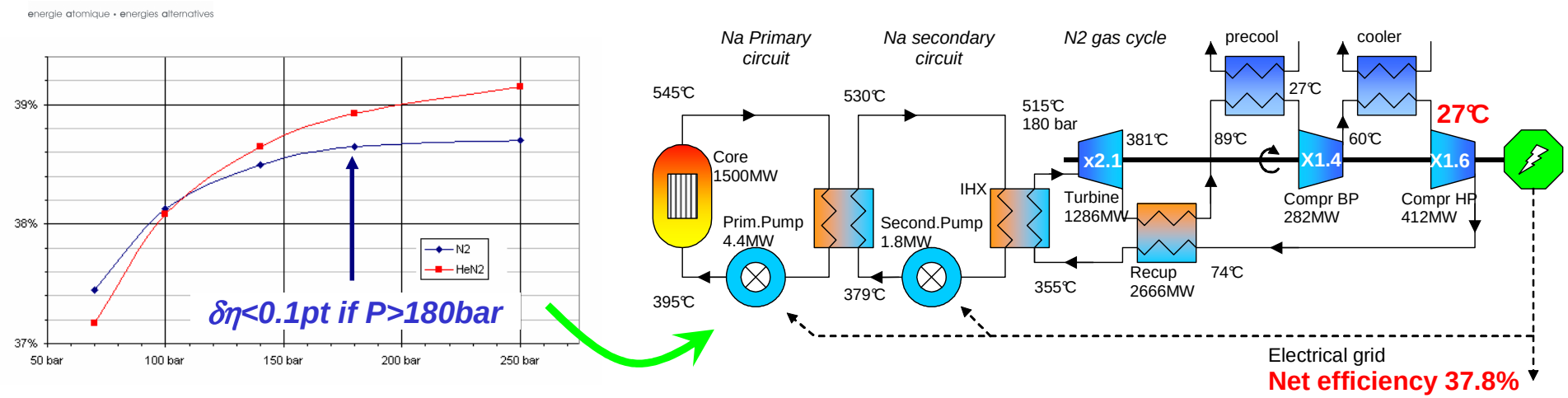
- **But for Neon, similar compactness.**
- **Peculiar point : Poorer intrinsic thermal perf. of pure N_2 Vs He-N_2 is balanced by a higher HX pinch point. This is due to a Cp *light* unbalance between repecurator sides for N_2 case which limits its – thermodyn. optimized - inlet T in the HX.**
  (if bypass + recup. split implemented such as for sCO_2 case ↳ 1 pt would be gained for η).

↳ **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_2 reference cycle

> Most decisive argument for gas selection : PRAGMATISM. N_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_2 cycle design by Optim. Pmax & Integrat. Press. losses from detailed HX design



> Next:

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

— HX : test of compact Na/gas component carried out in Cadarache in 2012 on DIADEMO-Na facility (Stamped plates & PCHE technologies)
↳ Address: HT perf. (12.6 MW/m^3 PCHE ?), plugging test (channel ∅), response to cyclic therm. stress

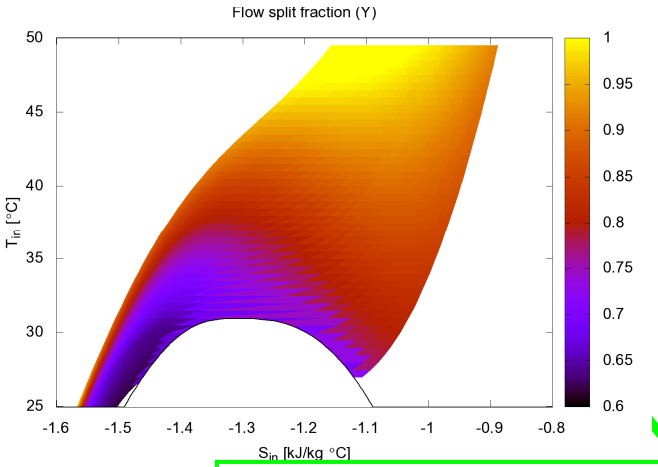
sCO2 cycle : Status & On-design perf. map at 515℃ TIT

J. Floyd, N. Alpy, G. Avakian CEA-CAD/DER

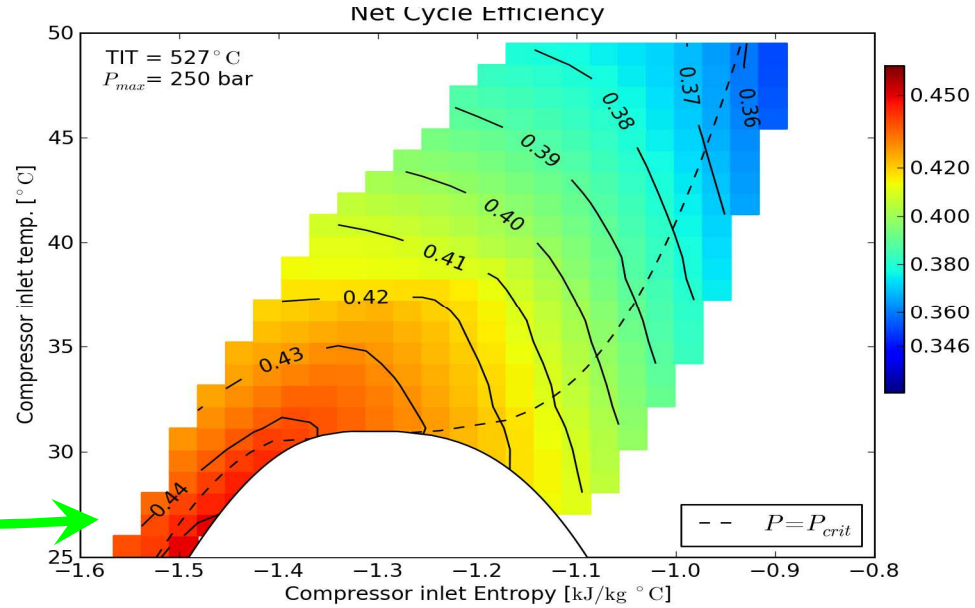
> **sCO_2 cycle status within SFR strategy:** due to given short project timescales & significant R&D work that remains to be carried out before perf. & safety of this innovative system can be demo. at an industrial scale ↳ developed independently from ASTRID.

> **However, ASTRID is intended to have the ability to test innovative options:**
↳ May be part of future test of new techno. on the prototype
↳ Integ. SFR R&D longer term program : *covers Thermodyn., System Dynamic, Chemistry, Material.*

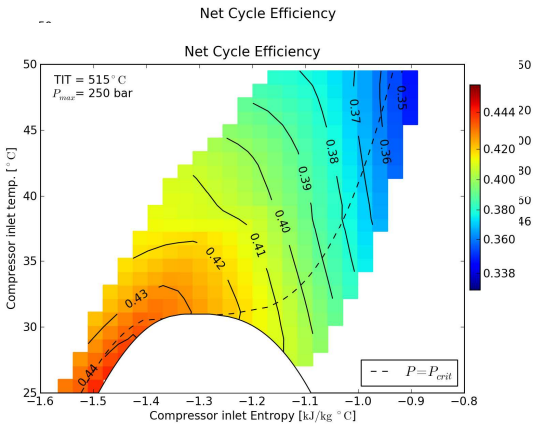
> **Thermodynamic: as an engineering guideline, mapped the relationship between cycle thermodyn. performance & main compressor inlet T- P, for which design choice depends on:**
- Available Heat sink temperature (usually chosen in a 32-35℃ range).
- Feed-back regarding cycle operability-stability studies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



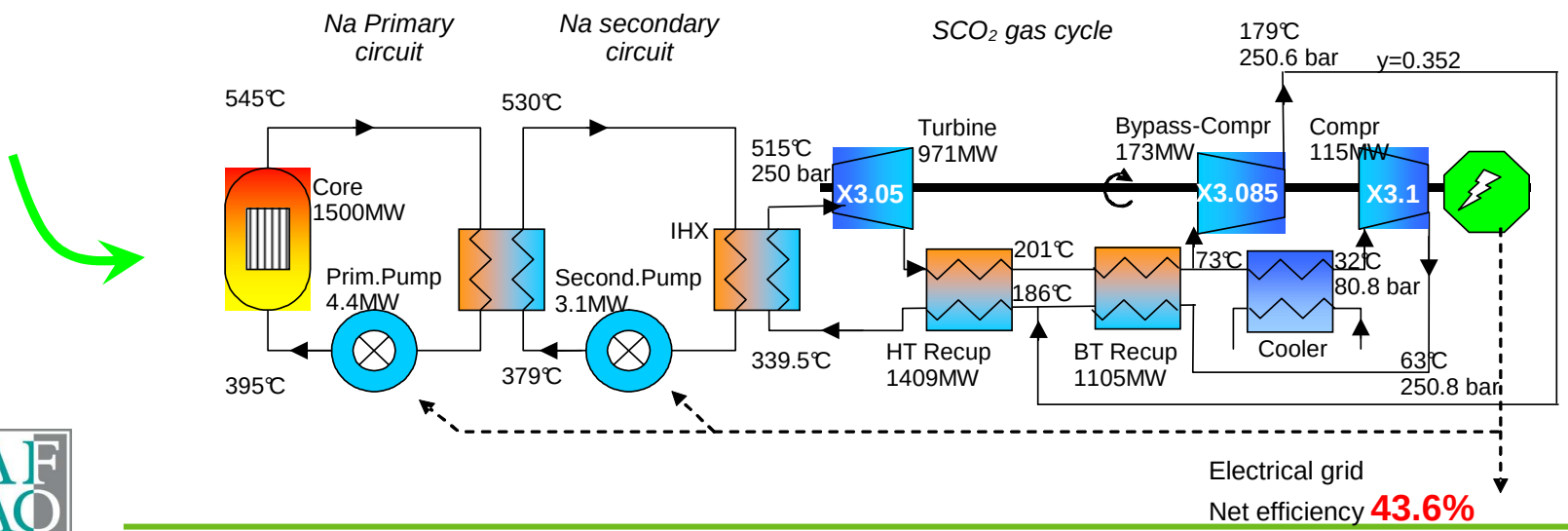
Optimizations of Flow & thermal flux splits between HT&BT recuperators using "simplex" algorithm



TESTCASE: Applicat°of an sCO_2 cycle complying with ASTRID



- **Starting design choice for "paper-code" studies: 32°C for Comp. inlet T, the <u>optimal</u> P *(see thermodyn. Perf. chart)* found to be 80.8 bar.**
- **If one compares to N_2 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 N_2 case even with more Temp. margin to T_{crit} : e.g. +3 points (41%) if Tin ≤ 40℃.**



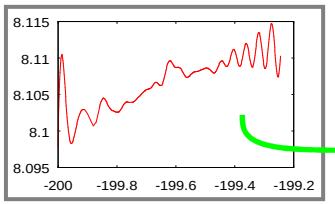
sCO2 : simulation of reactor transient studies

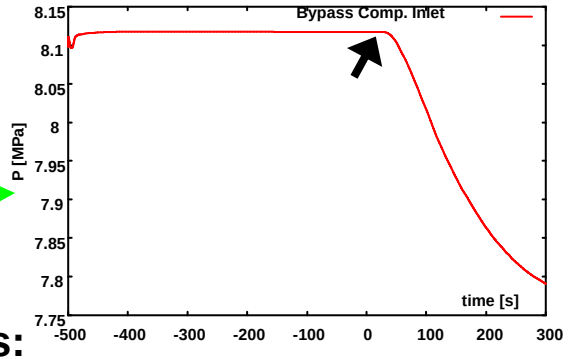
- **CEA's CATHARE reference code for transient studies (water, gas, Na) does not comply with sCO_2 thermodyn. specifics ↳Framework of GEN IV CD-BOP, at present modeling using the Plant Dynamic Code from ANL.**
- **So far, completed analysis of PDC code. Is implemented:**
  - ☺ A convenient approach for 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

ASTRID testcase (750 MWth loop): main RADIAL compressor design, 50 rev/s using PDC	
Number of stages	2
Inlet guide vanes / splitters / shrouded	no / yes / no
Number of blades per stage	29
Mean radius of impeller eye, m	0.18
∅ of impeller / ∅ of vaneless diff., m	0.9 /1.5
Impeller flow angle at exit, deg	65
Speed at vaneless diffuser exit, m/s	65
Maximum Mach number	0.29
Total to total isentropic η, %	89.0

- **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 N_2 cycle studies with CATHARE)
    > Pay attention to technological realism regarding inputs *such as control-command data*.

sCO_2 : studies regarding chemical interaction with Na

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

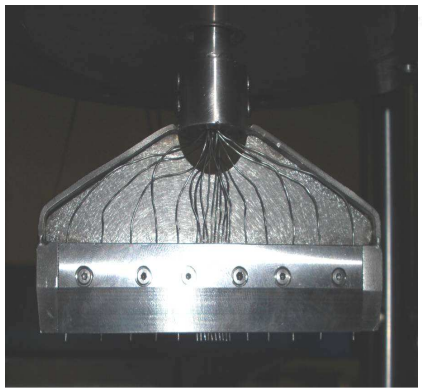
Experimental facility, "DISCO2", built to study reaction kinetics between a CO_2 jet & Na

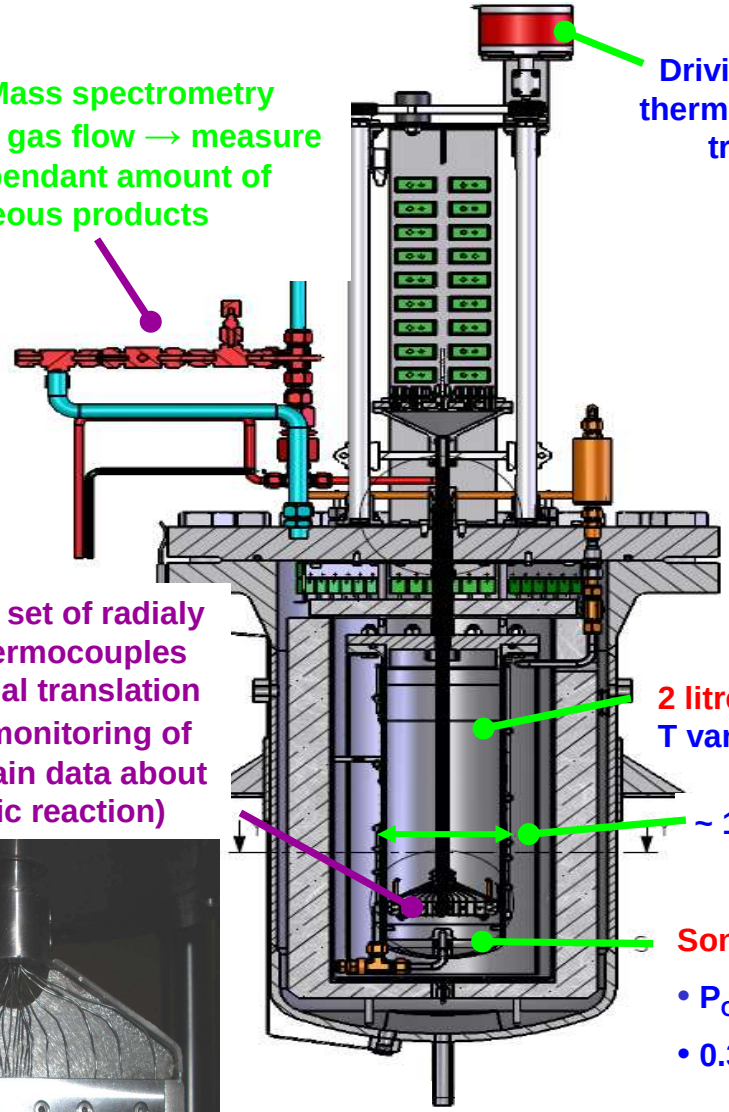
Online monitoring → data for kinetics model

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

Driving motor for thermocouples axis translation

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





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

~ 10 cm width

Sonic CO_2 injection:

- **P_{CO2} ≤ 15 bar, ~10 l/min**
- **0.3 to 1 mm ∅ Nozzle**

sCO_2 : chemical interaction mechanism

> Calorimetric studies : dual phenomenology depending on T range along HX

- Below 500℃:

  (1) $Na + CO_2 \rightarrow (1/4)\ Na_2C_2O_4 + (1/4)\ CO + (1/4)\ Na_2CO_3$

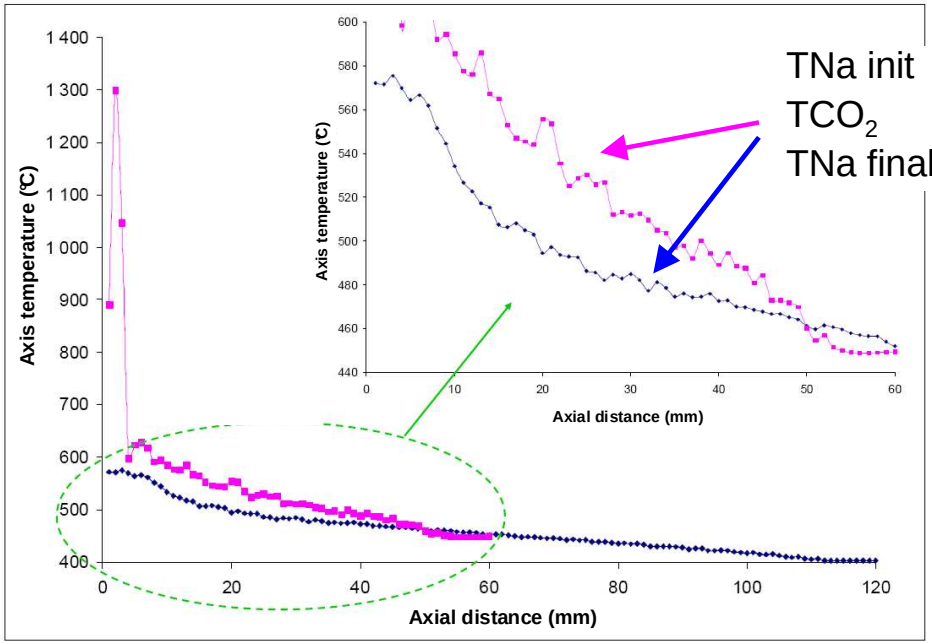
  (2) $4Na + Na_2C_2O_4 \rightarrow 3Na_2O + CO + C$

- Above 500℃:

  (3) $4Na + 3\ CO_2 \rightarrow 2\ Na_2CO_3 + C$

  (4) $4Na + Na_2CO_3 \rightarrow 3Na_2O + C$

> Temperature threshold confirmed in dynamic conditions : close to the Nozzle, large difference of the T profiles along CO_2 Jet "axis", depending on TNa



TNa init = 400 & 450℃

TCO_2 = 470 & 505℃

TNa final = 460 & 495℃

↳ **Comments about solid byproducts:**

☺ Wastage : no highly corrosive, no corrosion/erosion highly destructive coupled mechanism

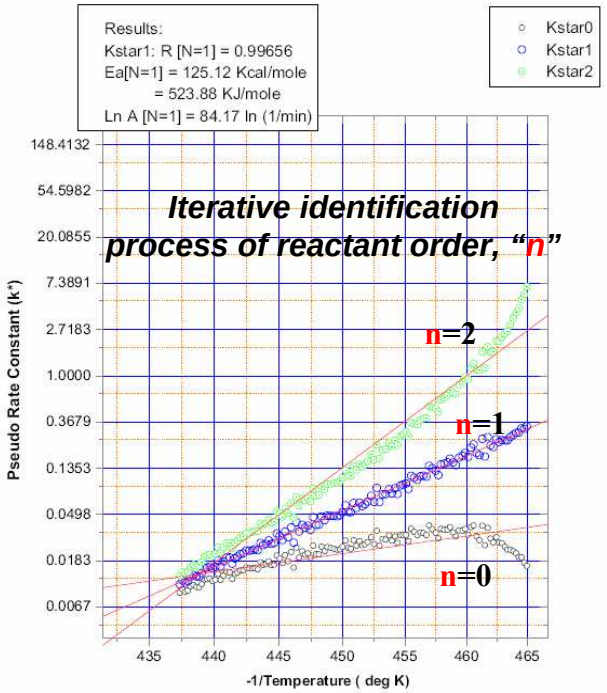
(+ could relax the issue of Na circuit pressurization by CO_2)

☹ Efficient solid trapping required.

sCO_2 : identification of kinetic law parameters

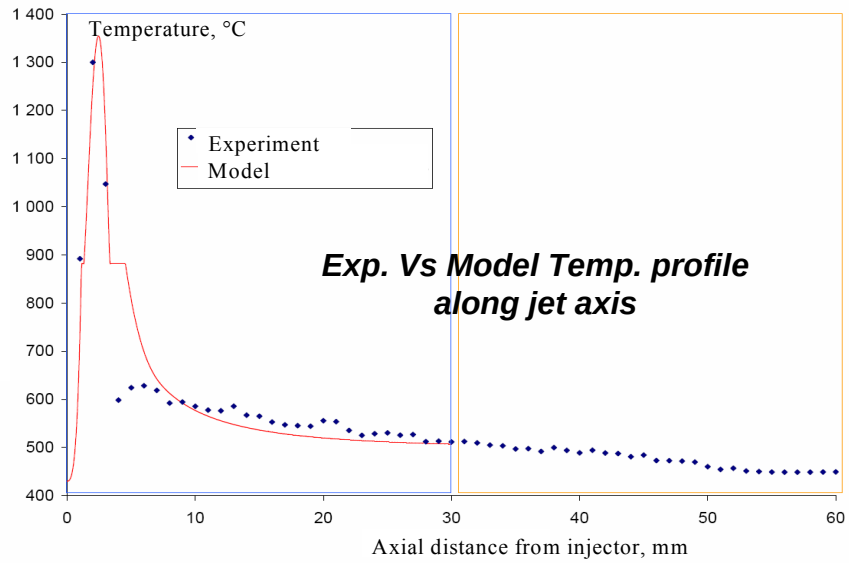
energie atomique • energies alternatives

> From Calorimetric studies
(consist in Adiab. self heat rat experiments):
1st order for Na & CO_2 reactants evaluated



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

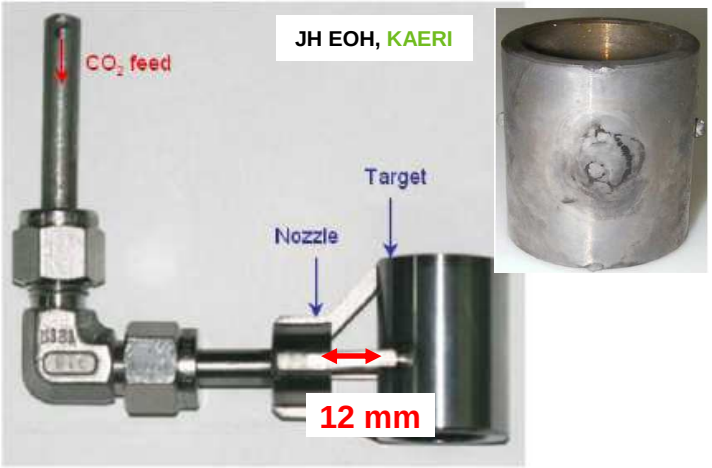
Temperature range	> 500°C		<500°C	
Reaction number	(1)	(2)	(3)	(4)
Pre-exponential factor, m^3/mol/s	1.10^6	5.10^4	1.10^5	$1.8.10^1$
Activation energy, kJ/mol	18	18	20	20
Heat of reaction, kJ/mol_{Na}	-180	38	-25	-10



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℃)
  > using a 0.3mm Nozzle, Target located **12mm farer**

  ↳ 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℃ …**

  ↳ 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_2O 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 η) :**
  - ↳ 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.

ANNEX

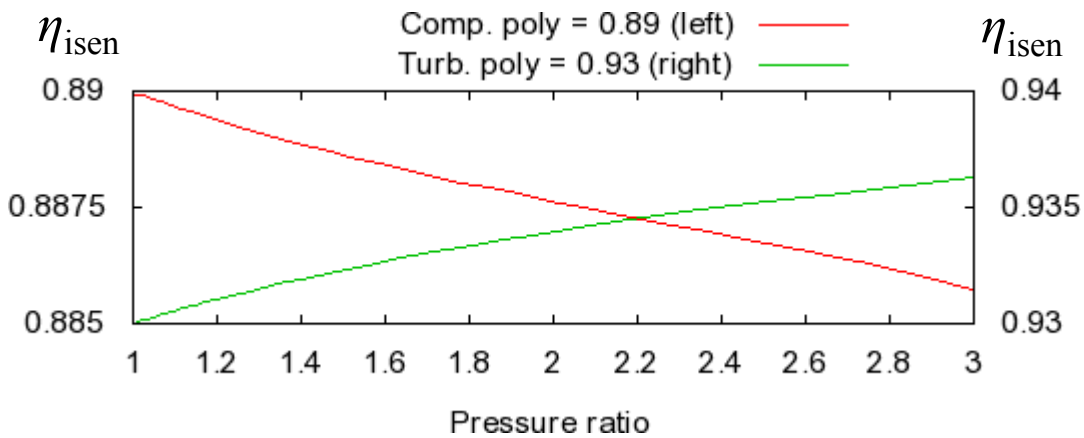
Polytropic efficiencies

Have *so far* assumed fixed **Isentropic** efficiencies for TM

But:

$$\eta_{\mathbf{isen}} = f\,(\,P_{\mathbf{out}} / P_{\mathbf{in}}\,)$$

[for a fixed design 'quality']

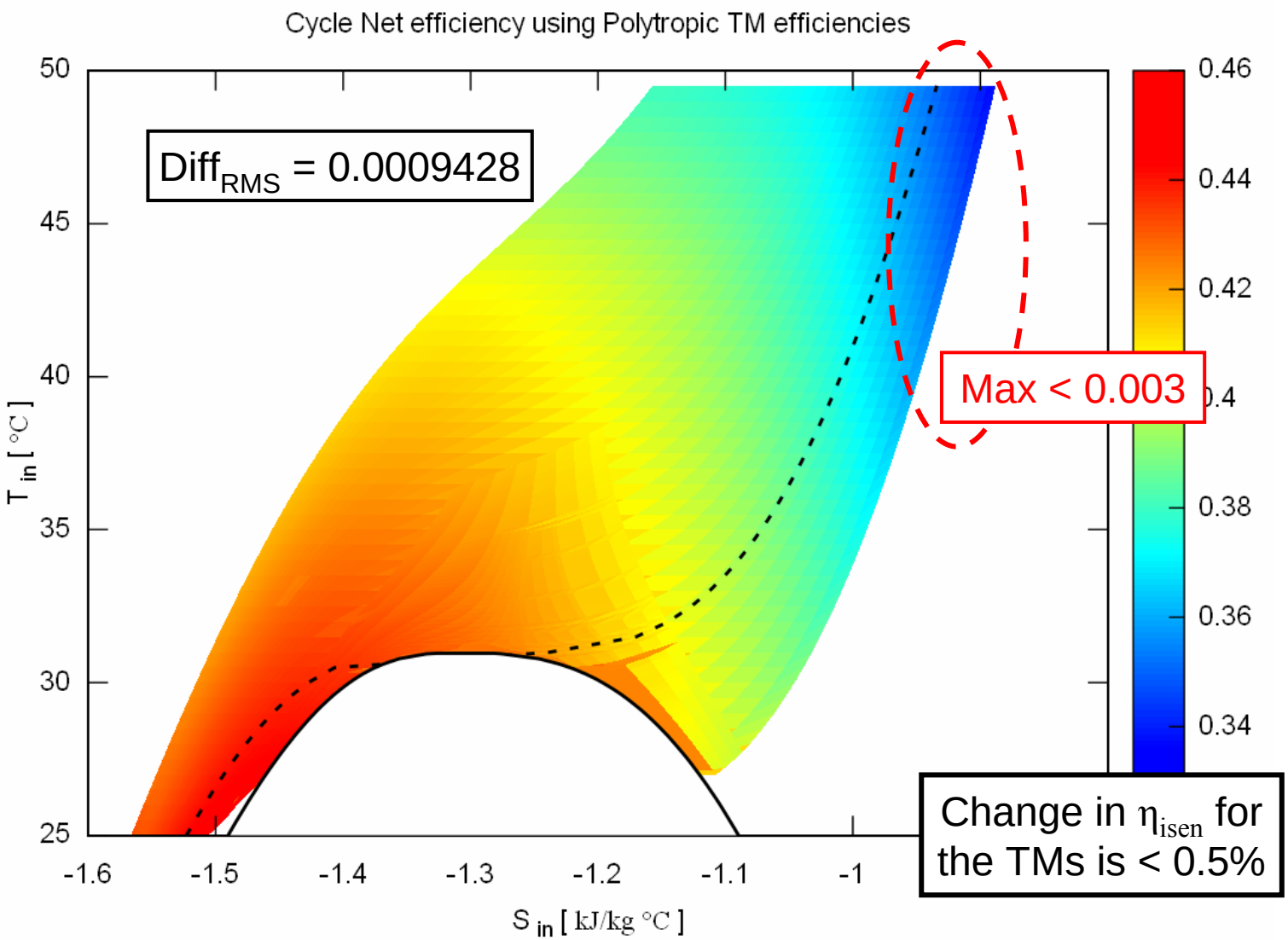


- For comp. $\eta_{\mathbf{isen}}$ decreases with R_p because entropy increases.
- For turb. $\eta_{\mathbf{isen}}$ increases with R_p because the entropy increase results from frictional heating which is recovered as work

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

- Numerical solution (no-modelling) of: $\eta_{\mathbf{poly}}\,\mathbf{d}h = V\,\mathbf{d}P$

Polytropic efficiencies



Dynamic

10℃ 1℃

Impact of T Change

Power and density changes at compressor inlet

SIMULATION	T_{in}, ℃	P_{in}, bar	P_{out}, bar	ρ, kg/m^3	W_{isen}, kJ/kg	δρ/ρ	δW/W
SCO2	**32**	**76,9**	**200**	**598**	**18**	**-44%**	**28%**
	33			**414**	**24**		
Perfect Gas	**21**	**23,3**				**3,3%**	**3,3%**
	31						