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ASTRID

Advanced Sodium Technological Reactor
for Industrial Demonstration

Sodium-Water Reaction approach and mastering for ASTRID Steam Generator design

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ASTRID objectives

- **ASTRID design guided by the following major objectives compared to previous Sodium-cooled Fast Reactors:**
  - ***Improved Safety***
  - ***Simplification of structures***
  - ***Improved ISIR (In Service Inspection and Repair)***
  - ***Improved manufacturing conditions for cost reduction and increased quality***
  - ***Reduction of risks related to sodium fires and Sodium-Water Reaction (SWR)***
  - ***Improved robustness against hazards***

Sodium-Water Reaction (1/4)

Exothermal chemical reaction

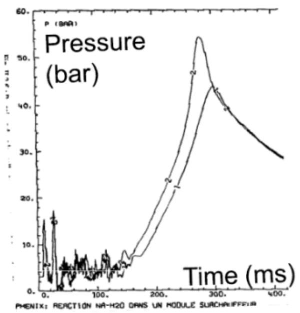
- $Na + H_2O \rightarrow NaOH + \frac{1}{2} H_2$ + 162 kJ/water mole
- (1) $2Na + NaOH \leftrightarrow Na_2O + NaH$
- (2) $Na + \frac{1}{2} H_2 \leftrightarrow NaH$

SWR origins and effects

SWR origins

- **Tube corrosion**: loss of tube wall thickness due to generalized corrosion or stress corrosion cracking (mainly in welded zones) in case of aggressive chemical conditions
- **Thermal shocks**: when under-saturated water is injected at super-heater inlet, inducing thermal fatigue
- **Restraint tube expansion**: buckling, induced by differential expansion with envelope
- **Tube bundle vibrations**: hydraulic effect of Na flow, inducing tube wear

SWR effects



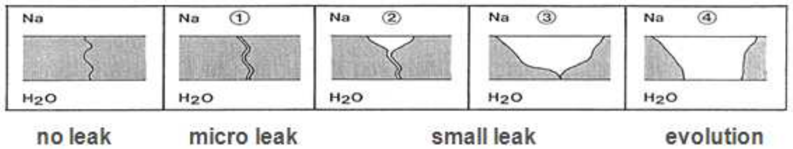
- **Chemical effects**: generalized corrosion due to oxides and stress corrosion cracking due to NaOH, and local erosion / corrosion due to propagation to surrounding structures
- **Mechanical effects due to large water leaks (>100 g/s)**, leading to overpressure
- **Overheating effects due to large water leaks**: deformation, swelling, bursting

Sodium-Water Reaction (2/4)

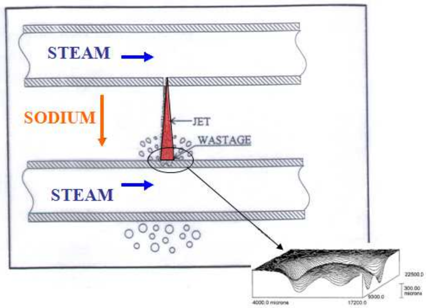
SWR wastage and overheating effects

- ***Origins: initiating defect (mainly in welded zones) leading to a crack, then a leak, plus a SWR leading to a reaction jet***
- ***Effects: growth of the leak orifice (self-wastage), and damage of the neighbouring tubes or wall by removal of material***
- ***Consequences: perforation of adjacent tubes leading to secondary leaks***

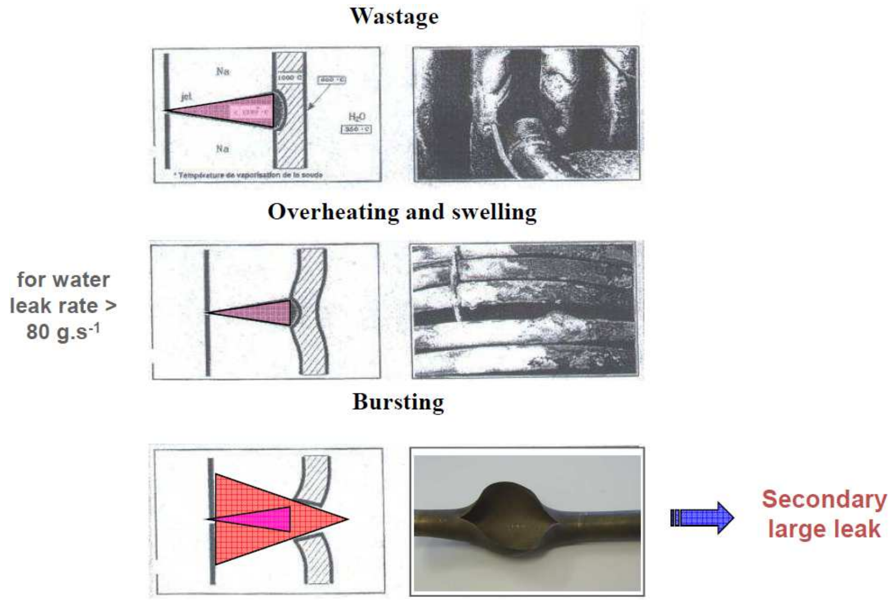
Water leak self-evolution



Wastage of surrounding tubes



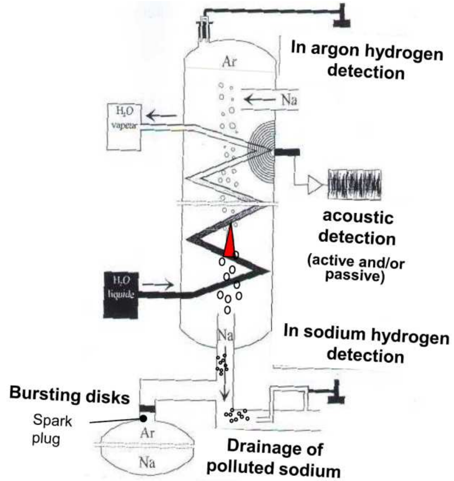
SWR thermal effects



Sodium-Water Reaction (3/4)

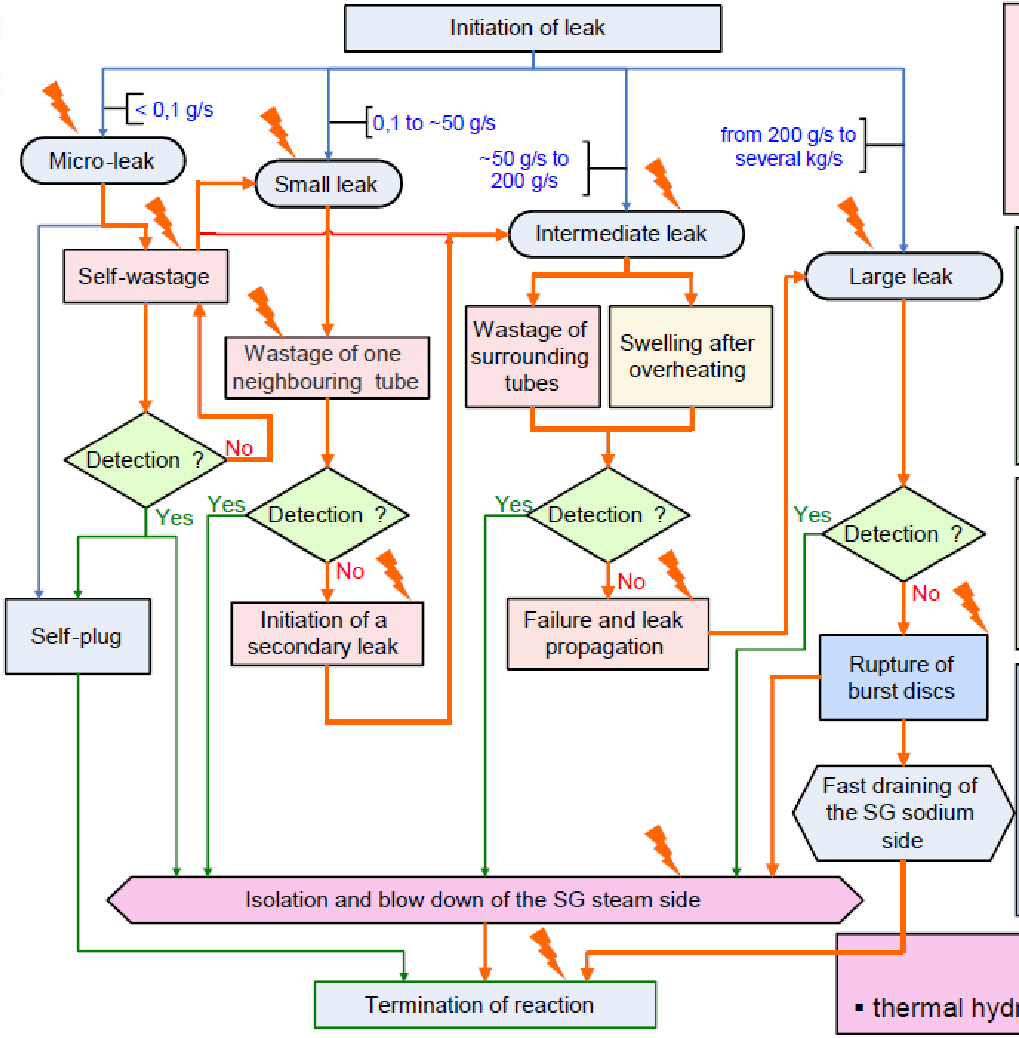
SGU protection and detection

- ***Protection system used to minimize SWR effects in the secondary loop after a water leak into Na. <u>Protections integrated in the design against corrosion risk</u> (for example, draining or not and purification of polluted Na), <u>against wastage risk</u> (protection of tube welds), <u>against overheating and overpressure risks</u> (bursting disks on Na side)***
- ***Small leak detection done by detecting hydrogen produced by the SWR***
  - **Permeation of hydrogen through thin nickel membranes**
  - **Acoustic detection in complement of hydrogen detection**
  - **Electro-chemical hydrogen meters**
- ***Rupture detection of the membranes initiates the system of isolation and blow down of the vapour side of the SG and the shutdown of the reactor***



Sodium-Water Reaction (4/4)

SWR modelling (stages of SWR evolution, and codes to assess SWR consequences on SG and secondary circuit)



PROPANA code

- self evolution calculation,
- wastage modelling (PERCEVAL),
- response time of the hydrogen detection system (HYDET)

CALHYPSO code

- modelling of SWR products evolution and transport,
- hydrogen detection response modelling according leak characteristics (and conversely)

MECTUB code

- calculation of the swelling consequences and bursting effects
- coupled with the wastage impact

EUROPLEXUS-GV code

- pressure waves propagation and effects on secondary sodium circuit

REACNOV code

- long term pressure fluctuation effects on secondary sodium circuit

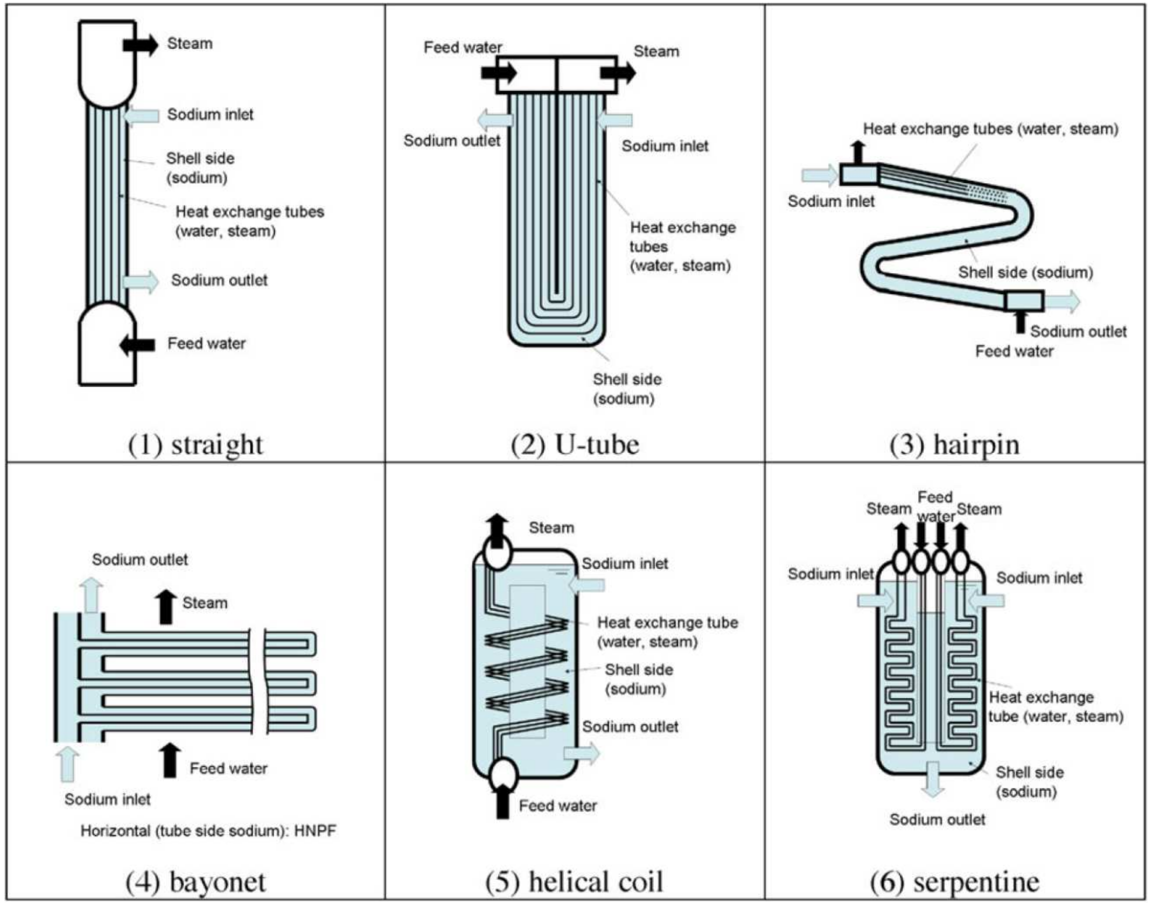
GVNOV code

- thermal hydraulics for blow down transient states

It is foreseen to replace GVNOV and REACNOV codes (used for previous Projects) by CATHARE 3 thermal-hydraulic system code

Steam Generator design (1/2)

- **Large tube types variety in the worldwide experience on Fast Breeder Reactor Steam Generator. Choice criteria: mechanical properties (fatigue creep,…), manufacture aspects (tube fabrication, welding), cost, corrosion strength on water-steam side and on Na side in normal and incidental operating conditions, and wastage behaviour in case of SWR**



Steam Generator design (2/2)

- **ASTRID modular Steam Generators protecting the loop against abnormal pressure increase (Sodium-Water Reaction)**

- **Technical solutions**
  - ***Helical* Steam Generator of Alloy 800**
    - Adapted to a secondary loop with hot leg and cold leg connected at the bottom part of the SG
    - Fabrication issues to be solved
  - ***Straight tubes* Steam Generator of 9Cr**
    - Cheaper component
    - Drawback: faster wastage effect
  - ***Inverted* (Na inside the tubes) Steam Generator of 9Cr**
    - Innovative approach without any leak propagation by wastage as opposed to classical SG
    - Speed up the leak detection
    - Issues: modelling of the SWR, design with external pressurized shell, in service inspection

Sodium-Water Reaction calculations (1/3)

- **SWR studies in support to ASTRID Steam Generator design**
  - ***Wastage and overheating models, from PROPANA and MECTUB codes, correlated with the type of the SG tubes material and with its behaviour***
  - ***Models elaborate and validated for alloy 800 and helical tubes of SUPERPHENIX Steam Generator***
  - ***Evolution towards straight SG tubes made of ferritic-martensitic steel (grade 91) require to improve knowledge in the following fields:***
    - **Influence on the kinetic of evolution of the leak and on the wastage rate**
    - **Behaviour towards the overheating and bursting effects in the field of the high temperatures (up to 1200°C)**
  - ***Studies underway to adapt models and to qualify codes for ferritic-martensitic steel***
  - ***R&D actions based on experimental programs***
    - **Wastage tests on SWAT-1R facility at the JAEA/O Arai research centre**
    - **Bursting tests of SG tubes in SQUAT bench at CEA/Cadarache research centre**

Sodium-Water Reaction calculations (2/3)

Wastage propagation calculations

- ***For steam leak rates in the range from 0.5 to 20 g/s, PROPANA code calculation highlights:***
  - **Helical tube alloy 800 design: more suitable than the straight tube ferritic-martensitic steel 9%Cr concept because penetration times are twice to 6 times longer. In Na hydrogen detection systems sufficiently effective to detect any kind of leak before the initiation of a secondary leak in the helical SG concept**
  - **Inverted SG design: the best one on the wastage point of view. Tube penetration: 3 to 100 times longer than in the other traditional concepts**
- ***PROPANA also used to evaluate the penetration time of the external ring of the SG if the SWR jet is directed towards the internal wall of the ring. Key point: existence of a second external ring, inside of the main one; additional barrel increasing the distance between the leaking tube and the target wall, which involves a strong decrease in the wastage rate***
- ***Inverted SG not affected by this phenomenon because the direction of the pressure gradient in the SG keeps the SWR jet inside of the leaking tube***

Sodium-Water Reaction calculations (3/3)

SWR pressure calculations for ASTRID secondary loop

- ***Loop configuration with discharge lines: 3 DN400 cold discharge lines in the lower part of each module, one DN700 discharge line in the cold pipe and one DN700 discharge line in the hot pipe***
- ***Configurations calculated with EUROPLEXUS code (pressure waves propagation and effects on secondary sodium circuit), considering the bounding case of a simultaneous and instantaneous rupture (< 1 millisecond) of all tubes of a SG module in the lower part of one module***
  - **Secondary loop with 3 straight tubes SG of 125 MW**
    - **468 Double Ended Guillotine Failures (all tubes of a SG module)**
      - **SG maximum pressure: 163 bar (<210 bar, category 4)**
      - **Maximum plastic deformation: <5%**
      - **IHX pressure: 20 bar (<55bar, category 4)**
  - **Secondary loop with 3 helical tubes SG of 125 MW**
    - **84 DEGF (all tubes of a SG module)**
      - **Maximum plastic deformation: <5%**
      - **IHX pressure: 32 bar (<55bar, category 4)**

Conclusions (1/2)

- **Modular Steam Generator concept selected for ASTRID**
  - *Brings flexibility for the expertise of failed modules after their removal*
  - *Intrinsically limit the mechanical consequences of a postulated large Sodium-Water Reaction*

- **Sodium-Water-Air Reaction studies include both prevention and mitigation aspects, with dedicated tools to be developed through R&D**

- **Regarding Safety analysis, the possibility to move from the scenario of instantaneous failure of the whole Steam Generator tube bundle toward a scenario with sequenced failure needs to be investigated**

Conclusions (2/2)

- The Steam Generator is one of the key components in the Sodium-cooled Fast Reactor system for it provides an interface between sodium and water. The design objective for the Steam Generator is related to the improvement of mastering of Sodium-Water Reaction.

- Potential Sodium-Water Reactions can be eliminated by adopting a Gas based Power Conversion System.

→ Next presentation in this technical session "ASTRID Power Conversion System: assessment on steam and gas options"

Thank You for your kind attention