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CADARACHE

ASTRID

Advanced Sodium Technological Reactor for Industrial Demonstration

Large electro-magnetic pump design for application in the ASTRID sodium-cooled fast reactor

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TOSHIBA Leading Innovation

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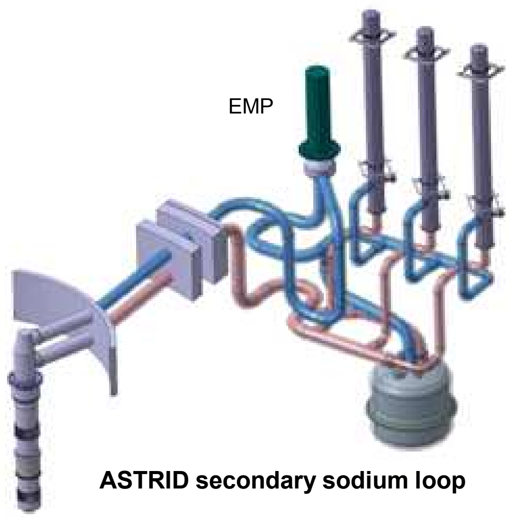
ASTRID main features

ASTRID pre-conceptual design

- Based on a sodium-cooled pool type reactor of 1500 MWth and generating about 600MWe.
- Four intermediate sodium loops
- The target lifetime for ASTRID is 60 years
- First pre-conceptual design phase (2010-2012) focusing on innovation and technological breakthroughs, while maintaining risk at an acceptable level.
- Among the numerous open options investigated, implementation of LEMPs in place of mechanical pumps on the intermediate sodium circuits.
- Each sodium loop is equipped with a LEMP. The LEMPs are located on the cold legs of the intermediate sodium loops.



ASTRID secondary sodium loop

Advantages of the LEMP

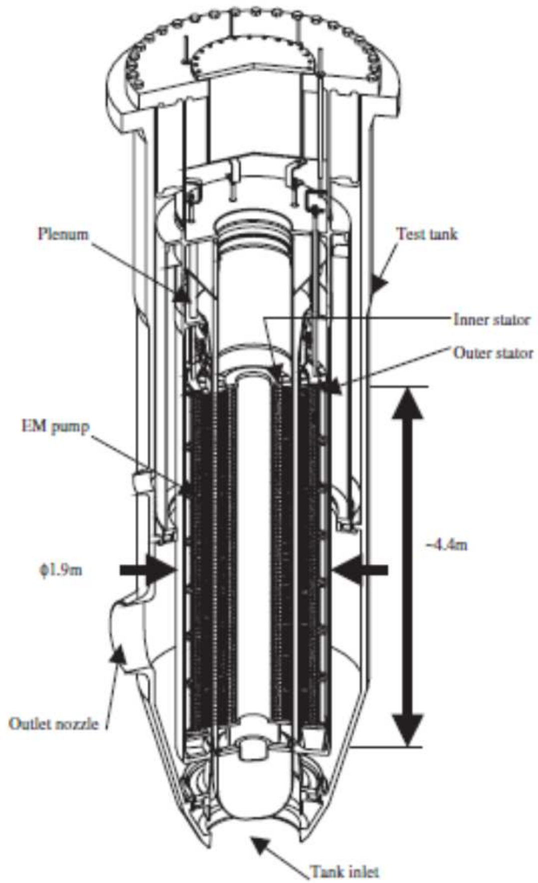
- **Use of LEMPs motivated by several potential advantages in the design and maintenance and more generally speaking for a better balance-of-plant of a SFR.**
  - EMP advantages
    - no moving parts, no penetration through the sodium vessel, low flow velocity favourable for noise reduction,
    - simpler technology than for mechanical pump (no reduction gear, no mechanical seals, no lubricating oil system and pump over-flow system to recover sodium leakage on the rotating shaft) , reduced maintenance.
    - simplification of the intermediate loop design itself (reduction of the piping length and sodium volume, impact on civil work).
  - EMP drawbacks
    - Limited efficiency
    - Heavy component
- **To fully benefit from the EMP advantages, the LEMP has to be self-cooled** :
  - No auxiliary active cooling system.
  - Recovery of the heat in the intermediate sodium loop (global efficiency).

TOSHIBA feed back on LEMP design

- **TOSHIBA is one of the ASTRID project industrial partners since April 2012, more specifically for EMP design.**

- **A LEMP was developed by TOSHIBA for application to the main circulation pumps of SFR.**
  - Pump immersed into sodium at 335°C. The heat power transferred to the surrounding sodium.
  - High temperature electric insulation to reach self-cooling.

- **TOSHIBA designed, manufactured and then tested the LEMP on a sodium test facility.**
  - Magnetic field measurements in air and many sodium tests over 2550 hours which satisfied the design target.
  - Pump efficiency that exceeded 40% at the rating (160m^3/min, 0.28MPa).
  - Applicability of the LEMP for SFR was confirmed on the basis of the test results and post-test inspections.



ASTRID LEMP specifications

ASTRID EMP specification

- ASTRID : 1500MWth
  - Objective : implementation of EMPs on ASTRID secondary loops.
  - 4 secondary sodium loops, 1 EMP per secondary loop.

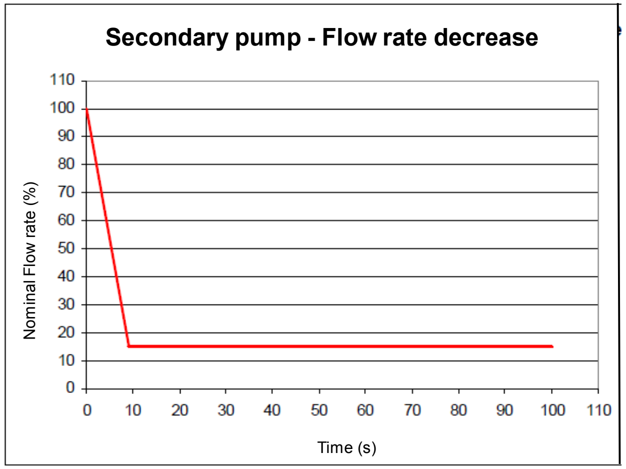
Nominal operating conditions

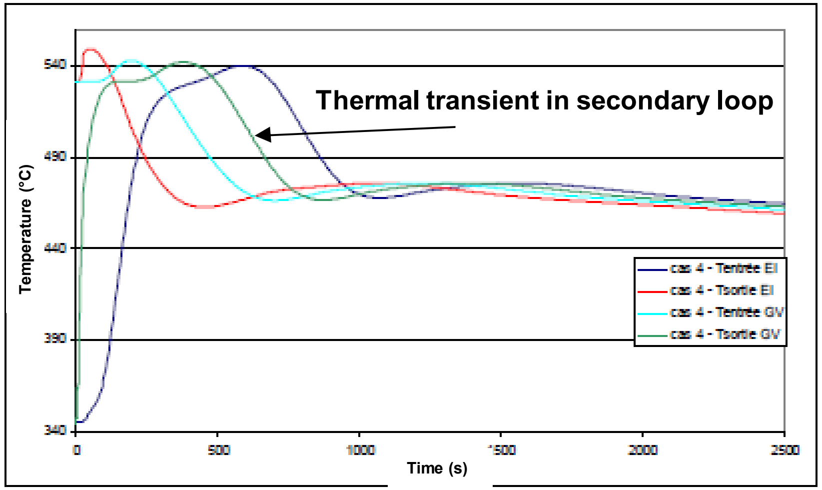
Configurations ASTRID	Flow rate (m^3/s)	Na temperature (°C)	EMP pressure difference (MPa)	Pressure at the EMP inlet (bar)	Pressure loading on EMP channel (bar)
Nominal conditions	1.88	345	0.34	1.2 – 1,6	5.5
Design conditions (with margin)	**1,98**		**0.37**		**8**

- In normal conditions
  - Flow rate variation range : from 15% to 100% NFR (Nominal Flow Rate)
  - Variation speed in normal conditions : ~10% NFR/mn
  - ASTRID start-up isothermal tests :T_{Na} ~ 425°C at NFR (steady state)

ASTRID LEMP specifications

- **Transient conditions**
  - Most severe situation considered : loss of SG feeding water
    - Envelope transient conditions for the EMP
    - Loss of SG feeding water with SG drying initiated at 100% of nominal power
    - Emergency shutdown on Na temperature threshold (380°C) at the SG outlet
    - Reduction of secondary Na flow rate from 100% to 15% in 9 s
    - Fast increase of temperature at SG outlet and propagation of hot shock in secondary loop cold leg.



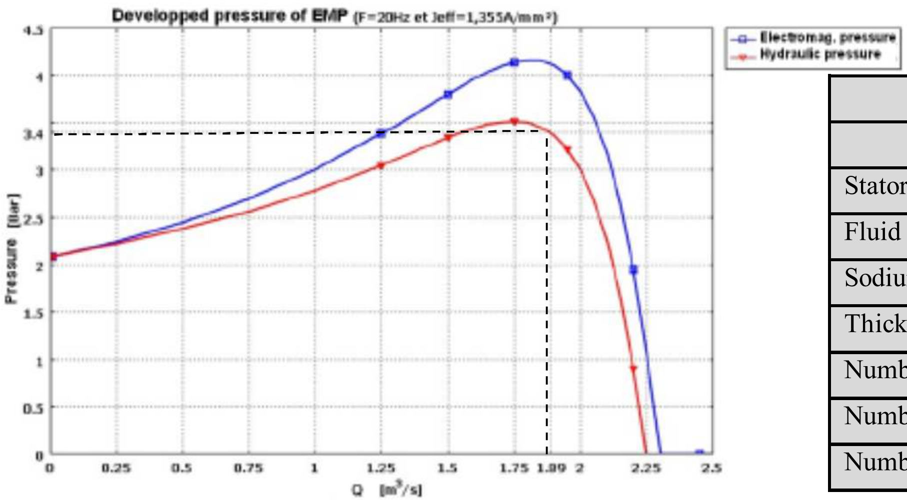


EMP transient : from 345 to 540°C in 200s, then decrease to 480°C
Number of occurrences during 60 years of the reactor life time : 150

Preliminary ASTRID LEMP design

CEA design

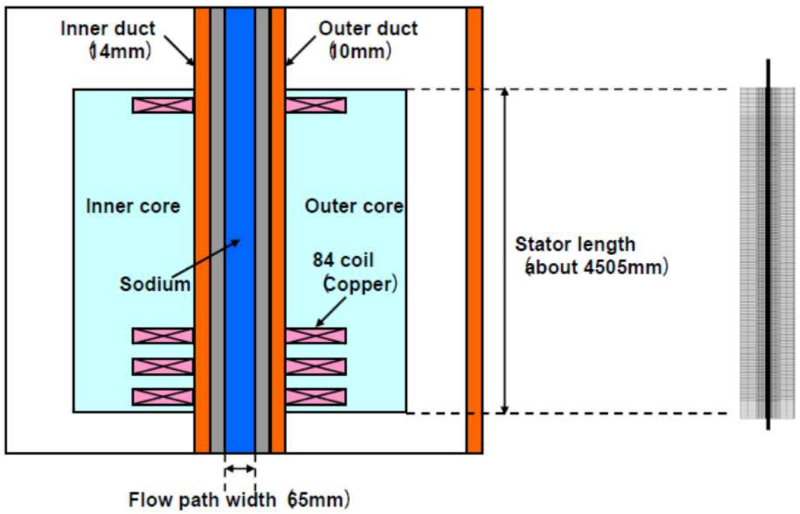
- Design code for EMP currently used by the CEA : commercial code COMSOL Multiphysics® based on FE method. This model is used to solve uncoupled MHD equations (Maxwell's equations and Ohm's law) by means of a frequency harmonics method.
- The calculated EMP has a cylindrical shape with two concentric stator windings, with one stator on each side of the sodium channel
- The stator coils are placed in a ferromagnetic yoke.
- The stator electrical arrangement is composed of two coils per pole and per phase.
- The sodium flow path is located between two non-magnetic concentric stainless steel tubes

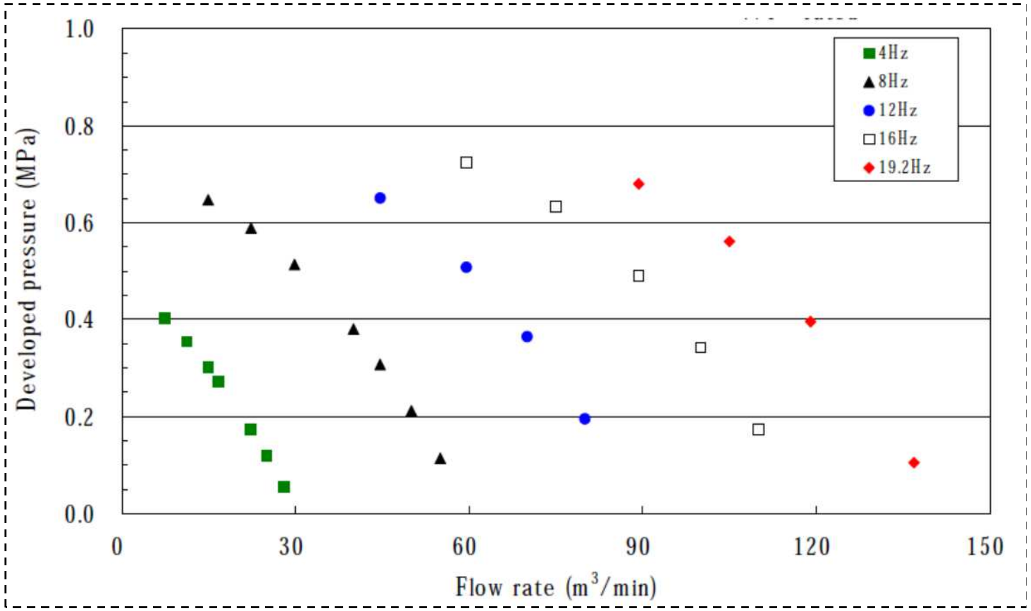


Characteristics of the EMP for the ASTRID intermediate loop			
Geometry		**General characteristics**	
Stator active length	4575 mm	Electric power	1.74 MW
Fluid channel mean diameter	800 mm	Sodium flow rate	1.88 m3/s
Sodium channel width	75 mm	Pressure head	0.34MPa
Thickness of pump pipes	10 mm	Sodium temperature	350°C
Number of poles	14	Frequency	20 Hz
Number of phases	3	Efficiency	38%
Number of coils	84	Rm*slip	1.42

TOSHIBA design

- TOSHIBA performed an electromagnetic fluid analysis to define the pumping function and the electromagnetic characteristics for the LEMP design of the ASTRID secondary loop.
- The electromagnetic fluid analysis code was performed with the code named EAGLE developed by TOSHIBA.
- EAGLE solves coupled equations of the electromagnetism (Maxwell's equations) and the fluid dynamics (Navier-Stokes equation) in a two-dimensional model.
- The electromagnetic fluid analysis provides the Q-H (flow rate vs pressure) characteristic, the electromagnetic force distribution, the magnetic field in the inner and outer iron cores.



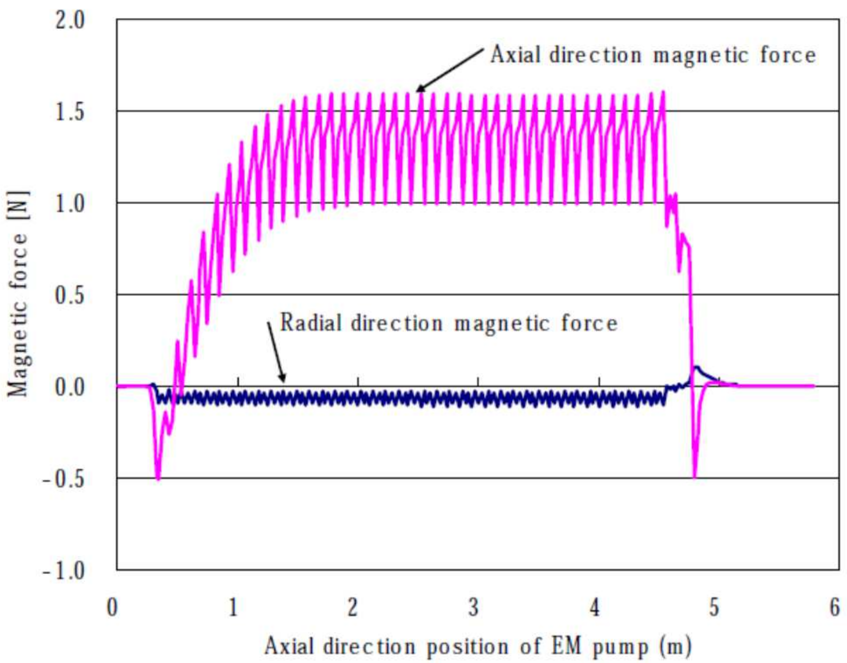


Preliminary ASTRID LEMP design

TOSHIBA design

- Design point :
  - Nominal pressure + 10%
  - Nominal mass low rate + 5%
- Main characteristics and performances in good agreement with the CEA results
- Negative thrust as the consequence of the classical end effect of the stator.

Electromagnetic force distribution in the sodium channel



Main characteristics of the ASTRID EMP

Item	Specification	Unit
Type	ALIP / **Double** stator	-
Sodium flow rate	119	m3/mn
Pressure head	0.37	MPa
Sodium temperature	345	°C
Electric Power	1.94	MW
Frequency	19.2	Hz
Efficiency	40	%
Rm*s	0.99	-
Sodium channel width	65	mm
Sodium channel mean diameter	1030	mm
Number of coils	84	pieces
Number of poles	14	poles
Stator active length	4500	mm
Outside diameter of casing	1800	mm

MHD Qualification tool

- **Theoretical Magneto-Hydro-Dynamics (MHD) analysis :**
  - Main objective : better understanding and quantification of additional MHD effects and instabilities which influence both the pump efficiency and operation
    - end effects
    - internal three dimensional flow
    - turbulence generated by the magnetic field heterogeneity.
  - Several parameters take into account the occurrence of MHD instabilities
    - Hartmann number, the interaction parameter defined as the ratio between the flow transit time along the duct axis and the electromagnetic time,
    - Yamamura criterion for the end effects,
    - magnetic Reynolds number multiplied by the slip Rm*s.
  - Computation of both magnetic field and the turbulent flow field inside the EMP gap
    - Feedback influence of the flow on the magnetic field in the Ohm's law taken into account.
    - Preliminary coupling between FLUX3D EM code and FLUENT CFD code indicates that this approach is realistic (mesh refinement in the Hartmann layer is obviously an issue).
    - Need to investigate the effects of the magnetic field on the turbulence since the interaction parameter could be around the unity.

Experimental validation on PEMDYN sodium facility

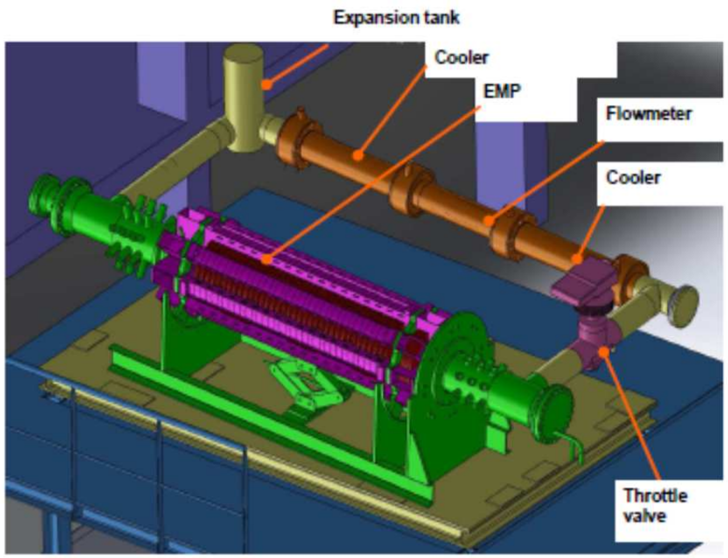
- An EMP mock-up is currently being built by the CEA to support these theoretical developments.

- Middle-size annular EMP mock-up
  - active length : 1 to 2 m,
  - gap thickness : 0.02 to 0.05 m,
  - frequency : f = 10 to 20 Hz,
  - typical value of the magnetic field : from 0.05 to 0.1 T,
  - flow velocity : up to 10 $m.s^{-1}$,
  - magnetic Reynolds number : higher than 10,
  - operating temperature : around 120°C

- In the current design, non-dimensional parameters :
  - Quite high Hartmann number about 240.
  - Interaction parameter is about 5 (velocity profile may be established)
  - Yamamura criterion to 2.3 for *f* = 20 Hz (instabilities should be observed)
  - Magnetic Reynolds number multiplied by the slip Rm*s is about 2.8 for a slip equal to 0.2. (quite high in order to promote possible instabilities in the EMP).

PEMDYN sodium facility

- The EMP mock-up will be implemented in the PEMDYN facility (CEA Cadarache)
  - PEMDYN is a closed loop in sodium together with an EMP, heat exchangers and a regulating valve all connected in series
- Experimental program :
  - Magnetic field measurements and overall electromagnetic ones, such as electrical resistance and power losses.
  - Hydrodynamics : pressure drop and flow rate measurements, flow velocity inside the gap will also be determined.
- Schedule :
  - EMP and sodium loop under construction
  - Commissioning tests in 2014.



Conclusion

- Use of a LEMP motivated by several advantages in terms of the reactor design, operation and maintenance.
- Collaboration agreement between the CEA and TOSHIBA Corporation came into force in April 2012 to carry out a joint work program on the ASTRID EMP design and development.
- Preliminary LEMP calculations carried out by the CEA and TOSHIBA are in good agreement and provide a good confidence in the feasibility of the annular LEMP for the ASTRID intermediate sodium loop.
- Theoretical and experimental investigations are currently underway at the CEA with the aim to improve the numerical tools.
- In parallel, the ASTRID EMP conceptual design studies are ongoing at TOSHIBA (thermal and thermo-mechanical analyses to demonstrate the LEMP self-cooling, structural analysis of the casing, the supporting legs and the mechanical interfaces, definition of the power supply unit, instrumentation and remote control procedure).
- This program is aiming at consolidating the ASTRID EMP conceptual design report and to support the design option choice for the ASTRID basic design.

Thank you for your kind attention !