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IAEA TM on Passive Shutdown Systems for LM Cooled FRs

Assessment of the efficiency of a passive safety system for prevention of severe accidents for SFR

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Outline

- ✓ Aims, investigation object, tools
- ✓ ULOF transient analysis. ULOF definition
- ✓ ULOF transient analysis. Reactivity effects
- ✓ ULOF transient. Case without ASD (**A**dditional **S**hutdown **D**evice)
- ✓ ULOF transient. Case with ASD
- ✓ ULOHS transient analysis. ULOHS definition
- ✓ ULOHS transient. Analysis of 6 ULOHS cases
- ✓ Conclusions
- ✓ Short information on KIT research of High Temperature Liquid Metals for Energy Technology

Aims, investigation object, tools

Aims: Evaluation of:
1) severe transient behavior in a Sodium-cooled Fast Reactor (SFR);
2) the impact of newly conceived inherent mitigation measures (ASD – additional shutdown device).

SFR design analyzed: SFR(v2b-ST) reactor design, 3600 MW(th), homogeneous core, MOX fuel

Code used: SIM-SFR code

Transients analyzed: ULOF and ULOHS transients

ULOF transient analysis. ULOF (1)

ULOF transient >> several failures occurring simultaneously:

- an unintentional trip of the primary pumps;
- failure of tripping the reactor.

ULOF event is characterized by a mismatch between the production of power and removal of heat by forced or natural convection from the reactor core.

Mass flow rate during ULOF decreases usually faster than the power level.

The sensitive parameter of primary concern during a ULOF process is thus T_{outlet}, while T_{inlet} remains largely unchanged during the initial phase of the pump coast-down process.

ULOF transient analysis. ULOF (2)

Extensive boiling of sodium (T_boil ~ 880°C at 1 bar, and 937°C at 1.57 bar) in the central core region will most likely insert significant positive reactivities in excess of one dollar.

Conditions that could lead to boiling of sodium in the central core region are thus to be avoided under all circumstances.

Limited boiling of sodium in the upper core regions, or the core outlet, can be tolerated to some extent as in this case negative reactivities are inserted into the core.

Limiting boiling of sodium to just the upper core outlet regions has been shown experimentally to be a very delicate task.

ULOF transient analysis. ULOF (3)

Any minor disbalance between power production and heat removal (flow rate) could trigger a very rapid progression of the boiling front downward towards the core center.

It is thus of highest interest to understand how these two major parameters can be influenced by "intelligent" design choices in order to improve the ULOF transient response characteristics of a particular SFR design.

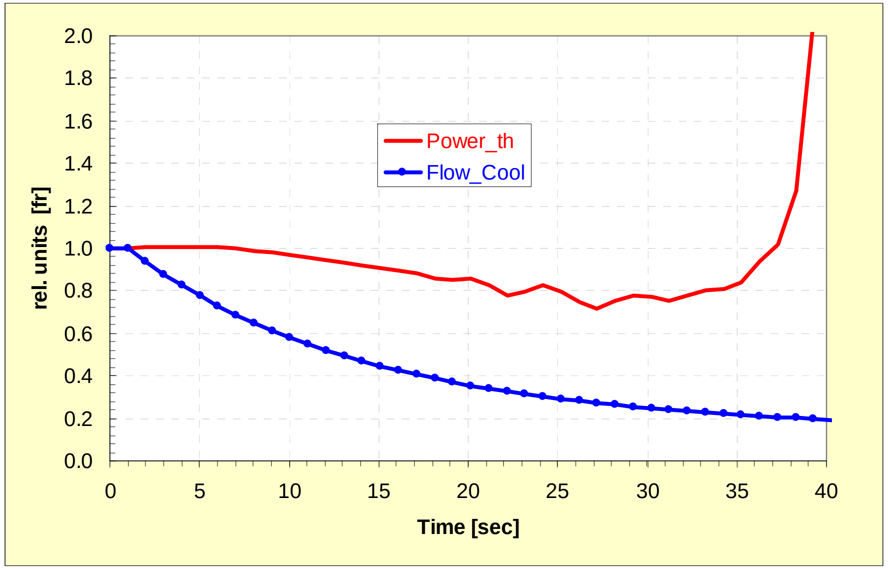
Should coolant temperatures approach the local saturation temperature, immediate remedial action must be activated in order to decrease the core coolant outlet temperatures below the boiling point.

ULOF transient analysis. Reactivity effects

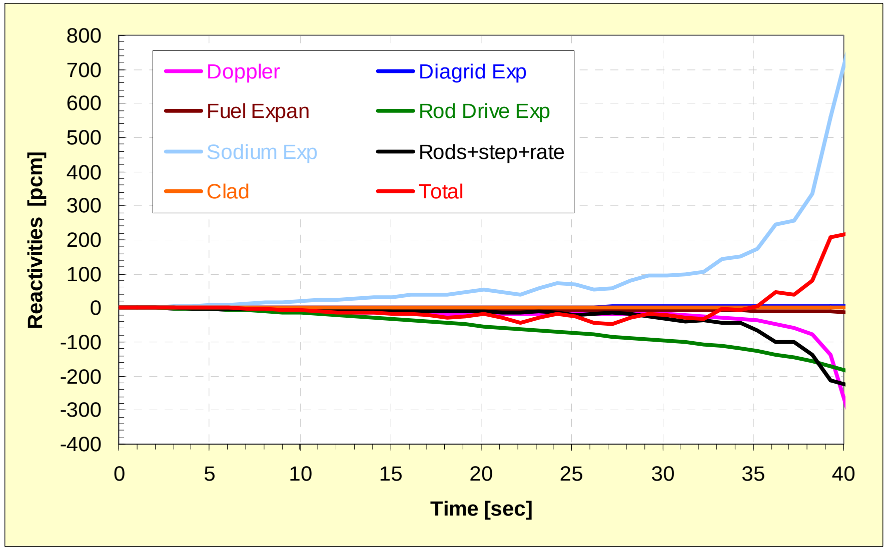
There are various reactivity feedback mechanisms acting during ULOF:

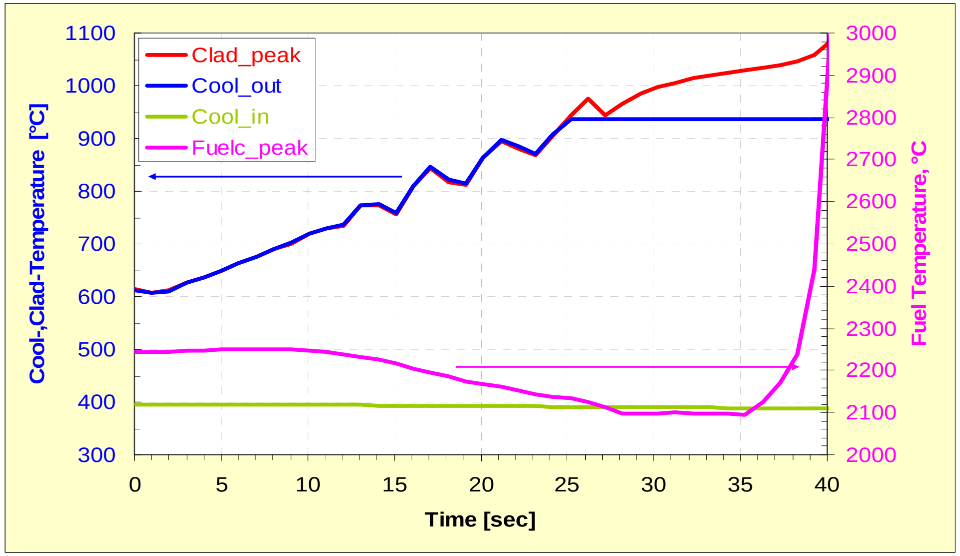
Reactivity Effect	Reactivity Sign	Reactivity Magnitude	Reactivity Coefficient Value for SFR(v2b-ST)	Response time of reactivity to become effective	Comment / Importance during ULOF
Doppler	negative	medium	- 881 pcm	immediate	**positive reactivity insertion during ULOF due to decreasing power and thus temperature level**
Sodium Temperature	positive	medium / large	+ 0.445 pcm/°C	fast	**significant as it is ULOF's driving positive reactivity insertion**
Axial Fuel Expansion	negative	small	- 0.191 pcm/°C	very fast	**relatively insignificant**
Axial Clad Expansion	negative	small	-	fast	**Negative during ULOF**
Diagrid, radial expansion	negative	small	- 0.784 pcm/°C	delayed	**diagrid plate needs to change in temperature to become effective**
Rod drive extensions expansion	**negative**	**large**	**-0.86 / -1.16 pcm/°C (rod position at 25/50 cm)**	**delayed**	**upper plenum region needs to change temperature before it becomes effective**

Results for ULOF case R1 without ASD for EOEC core conditions: rel. power, flow rate, core temperatures, and reactivity feedbacks



Power Excursion: 38 s into ULOF





ULOF transient. Case without ASD

In order to optimize the SFR(v2b-ST) plant response during a ULOF (avoiding initiation of local sodium boiling), 17 different ULOF parameter cases were analyzed using the SIM-SFR code.

Main results:

- No single design modification alone will "fix" the problem (preventing a ULOF power excursion);
- It appears that we need a minimum height differentials between core-MHX mid-planes of ~4.6 m in conjunction with three additional design modifications such as:
  - (1) SPX1 like primary pump (having longer run-down half-life (>> 10 s as currently assumed)),
  - (2) low nominal primary system pressure drop of ~ 2.15 bar,
  - (3) 50 cm rod insertion depth,

  to reach the goal of sustaining a ULOF in SFR(v2b-ST).

ULOF transient. Case with ASD (1)

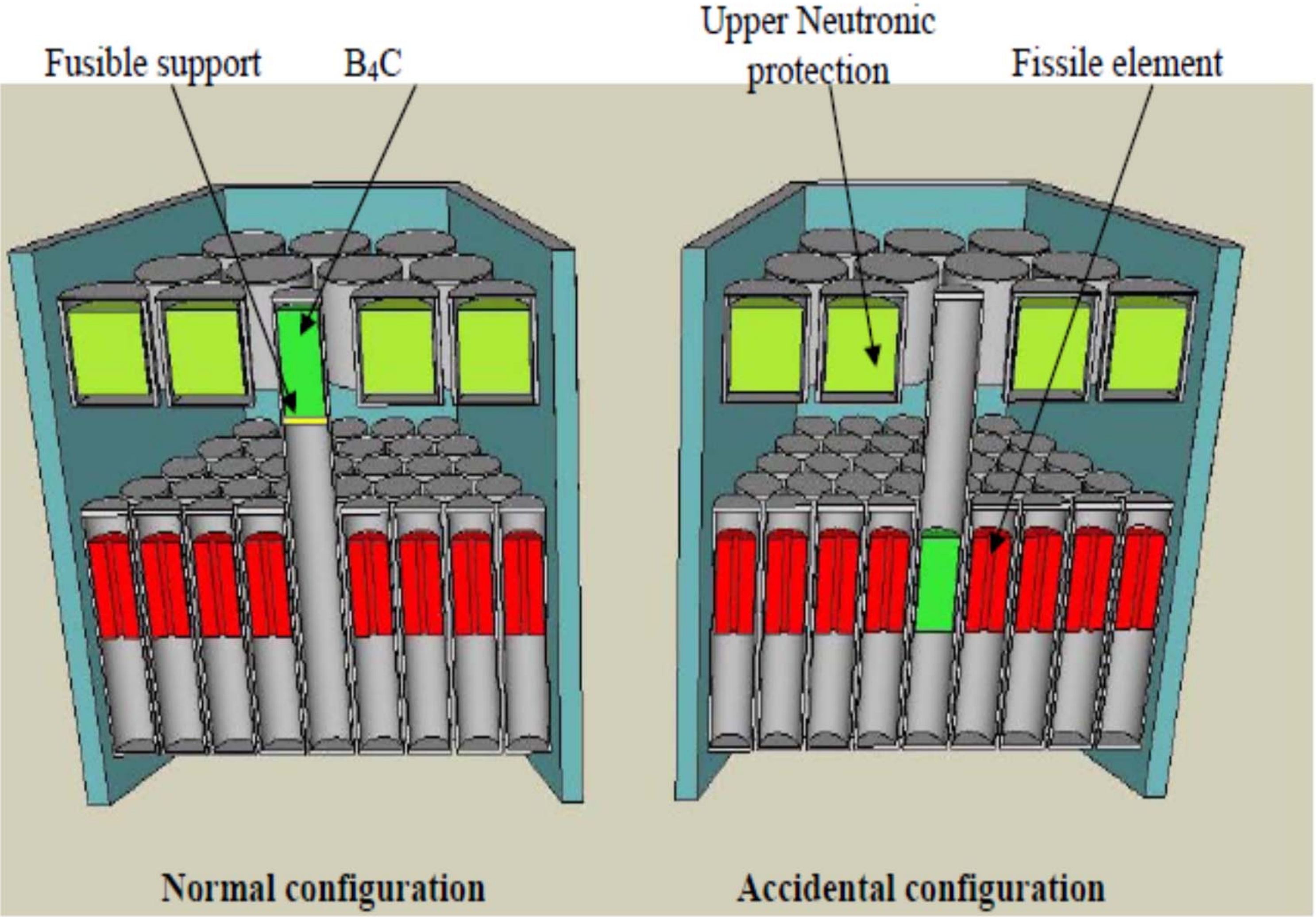
In order to accommodate unprotected transients, AREVA proposes the implementation of a thermally activated dedicated absorber device.

One of the possible design choices - absorber elements B_4C pebbles inside the central pin of the fuel sub-assemblies.

The absorber elements are maintained above the fissile region by a fusible aluminum support linked to the clad, and activated when a certain temperature just above the fissile region exceeds pre-set values.

Melting temperature of the fusible devices should be high enough to prevent unintended delatching of the B_4C pebbles.

ULOF transient. Case with ASD (2)



Self-protected ASD schematics

ULOF transient. Case with ASD (3)

Technical characteristics of proposed ASD are:

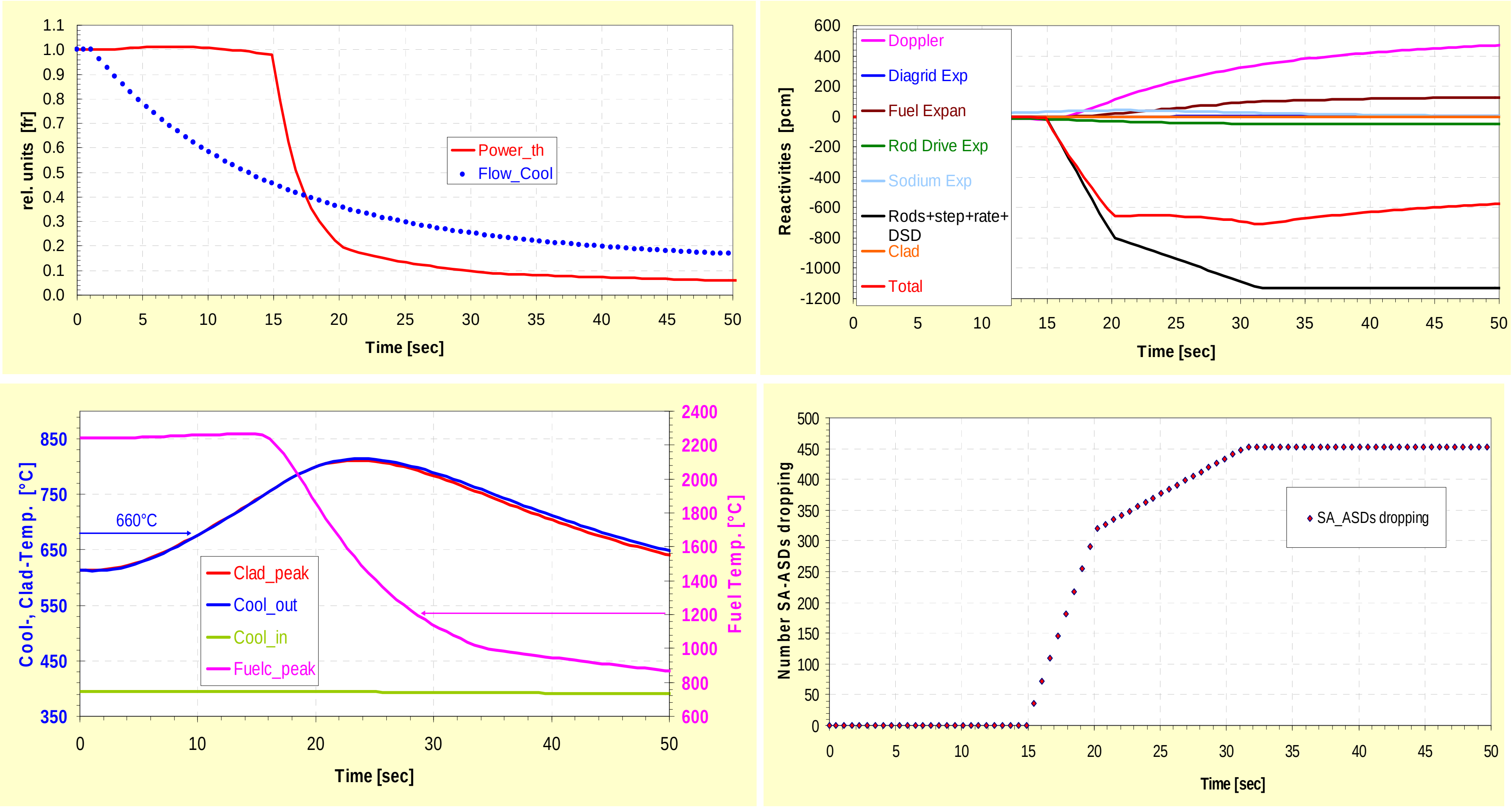
- Melting temperature of the fusible device
  - reference value: 660°C;
  - parametric cases: 640°C – 715°C
- Response time of the fusible devices
  - reference value: 5 s
  - parametric cases: 2 s to 8 s
- Reactivity worth: -2.5 pcm per “self-protected” sub-assembly.

ULOF transient. Case with ASD (4)

ULOF transient (base case):

- The core outlet temperature increases quite rapidly, reaching ~660°C between 9 s and 12 s into the transient;
- The highest temperature SAs will release their B_4C pebbles from above the active core zone to enter the central part of the core region between 14 s and 17 s into ULOF;
- Rate of SA releasing their B_4C pebbles into the core region is determined based on outlet temperature differences between the peak and the average SA and the outlet temperature gradient of the average SA.

Results for ULOF case R1 with ASD for EOEC core conditions: rel. power, flow rate, core temperatures, and reactivity feedbacks



No Power Excursion: ASD system starting to drop neg. reactivity ~15 s into ULOF

ULOF transient. Case with ASD (5)

ULOF Simulations Matrix

Case		Prim. Pump half-life	Fraction SAs with ASD	Trigger Temperature	Delay Time	Rate of ASD dropping	Result :
Impact on :		flow	power	power	power	power	Power Excursion at:
		[s]	[fr]	[°C]	[s]	[fr]	transient time [s]
R0		10	0	660	5	1	37
R1	Ref. Case	10	1	660	5	1	no power excursion
R2		10	1	640	5	1	no power excursion
R3		10	1	715	5	1	no power excursion
R4		10	1	660	2	1	no power excursion
R5		10	1	660	8	1	no power excursion
R6		10	1	715	8	1	no power excursion
R7		10	0.75	715	8	1	no power excursion
R8		10	0.5	715	8	1	no power excursion
R9		10	0.25	715	8	1	local boiling starts at 95 s, power excursion at 158 s
R10		10	0.25	715	8	0.5	local boiling starts at 105 s, power excursion at 158 s

ULOF transient. Case with ASD (6)

<u>Main results</u>:

- In most of the analyzed cases, ASD is capable to safely shut down the reactor in a timely manner during the ULOF transient;
- The only requirement for the ASD implementation is that not less than 50% of the total number of the fuel assemblies in the reactor core should be equipped with the ASD;
- Lower number of the fuel assemblies with the implemented ASD does not have sufficient reactivity potential for reactor shutdown in case of unprotected ULOF transient.

ULOHS transient analysis. ULOHS

ULOHS transient >> several failures occurring simultaneously:

- total loss of heat sink - neither MHX nor the heat exchangers of the DHRS system are assumed available as heat sink;
- failure of tripping the reactor.

The only potential heat sink available is radiative heat transfer from the vessel wall to the ambient, assuming the reactor cavity cooling systems are appropriately dimensioned to extract the heat coming from the vessel wall.

The primary pumps are assumed to continue to operate at nominal flow.

ULOHS transient. Analysis of 6 ULOHS cases

<u>Main results (1)</u>:

- The control rod drivelines expansion reactivity coefficient will lead to a relatively important **positive** reactivity insertion into the core due to significant heat-up of the vessel walls during the ULOHS;

- “Control rod drivelines expansion reactivity feedback effect” is composed of two feedback effects:

  1) the thermal expansion of the rod drive extensions themselves, that cause an insertion of the rod bank into the core, and

  2) thermal expansion of the reactor vessel wall, that leads to an extraction of the entire rod bank out of the core region once the vessel wall heats up.

ULOHS transient. Analysis of 6 ULOHS cases

Main results (2):

- If no ASD system is implemented, SFR(v2b-ST) will enter into a power excursion ~(310-370)s into the ULOHS transient as the high reactor power will initiate sodium boiling ~(20-30)s prior to initiation of the power excursion;

- In case an ASD system should be available, SA-ASDs B_4C pebbles will be released into the core region ~50s into the transient thus decreasing the reactor power to the decay heat level within 50s transient time;

- This demonstrates the effectiveness of the ASD system in preventing a power excursion during ULOHS for SFR(v2b-ST) design.

Conclusions

- This analysis demonstrated that the sodium-cooled reactor design, called “SFR(v2b-ST)” design, is a viable core and primary system design under nominal power conditions;
- Under ULOF conditions and without a third shutdown (ASD based) safety system, at least three design modifications need to be made to the SFR(v2b-ST) system design in conjunction in order to accommodate a ULOF;
- The only other remaining alternative to the basic SFR(v2b-ST) design would be the introduction of an additional independent device (ASD), as proposed by AREVA;
- This study has shown the effectiveness of such a ASD system in limiting the consequences of a ULOF and ULOHS, should the proposed ASD design actually function within the parameter range as investigated.

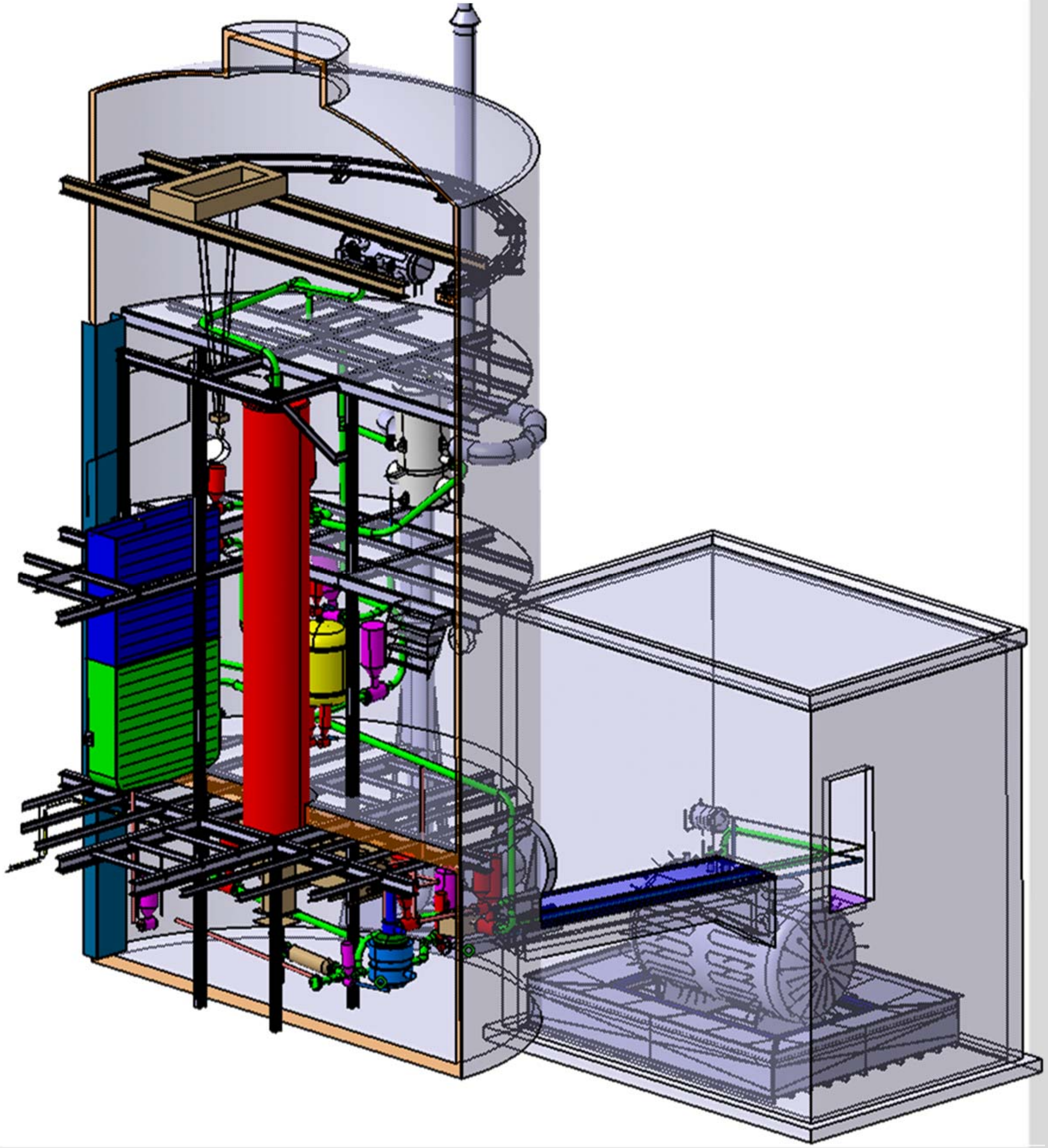
Short information on KIT research of High Temperature Liquid Metals for Energy Technology

Research goals

- Fundamental research of single and two phase fluid dynamics;
- Development of components in prototypical scale for high performance & safety;
- Component interaction and dynamics;
- Demonstration of dual cycle (thermal and thermoelectric);
- Efficiency enhancement of thermal energy storage systems.

Medium Scale facility KASOLA (1)

- The KASOLA (**KA**rlsruhe **SO**dium **LA**boratory) at INR is a versatile experimental facility to investigate flow phenomena in liquid sodium for nuclear and non-nuclear applications.
- It hosts a sodium inventory of 7 m³, and it can operate in the range of about 150–550 °C.
- A magneto-hydrodynamic (MHD) pump can deliver a flow rate up to 150 m³/h at a pressure head of 0.4 MPa.
- Operation test scheduled for November 2015.



Medium Scale facility KASOLA (2)

- Three experimental ports are foreseen to serve all needs of liquid metal experimental investigations:

(1) The versatile test section has a height of nearly 6 m. It is situated above the MHD pump and can be used for development and investigation of targets, component tests, and/or experiments, which require high mass flow rates. For higher mass flow rates, a second MHD pump can be installed in series with the first one.

(2) For the second test port, a pool section with dimensions of about 4x4x0.4 m is foreseen parallel to the versatile test port to hold a slab pool simulator, at a maximum power of 400 kW. It may be used for tests of nuclear and non-nuclear industrial components at a scale of about 1:5. Due to its geometry, it can be described by the Hele-Shaw approximation.

(3) A third port, namely a low temperature port, is foreseen as an auxiliary port to connect separate experimental loops or devices, which can use the calibration and cleaning units of KASOLA.

KASOLA facility. Key features

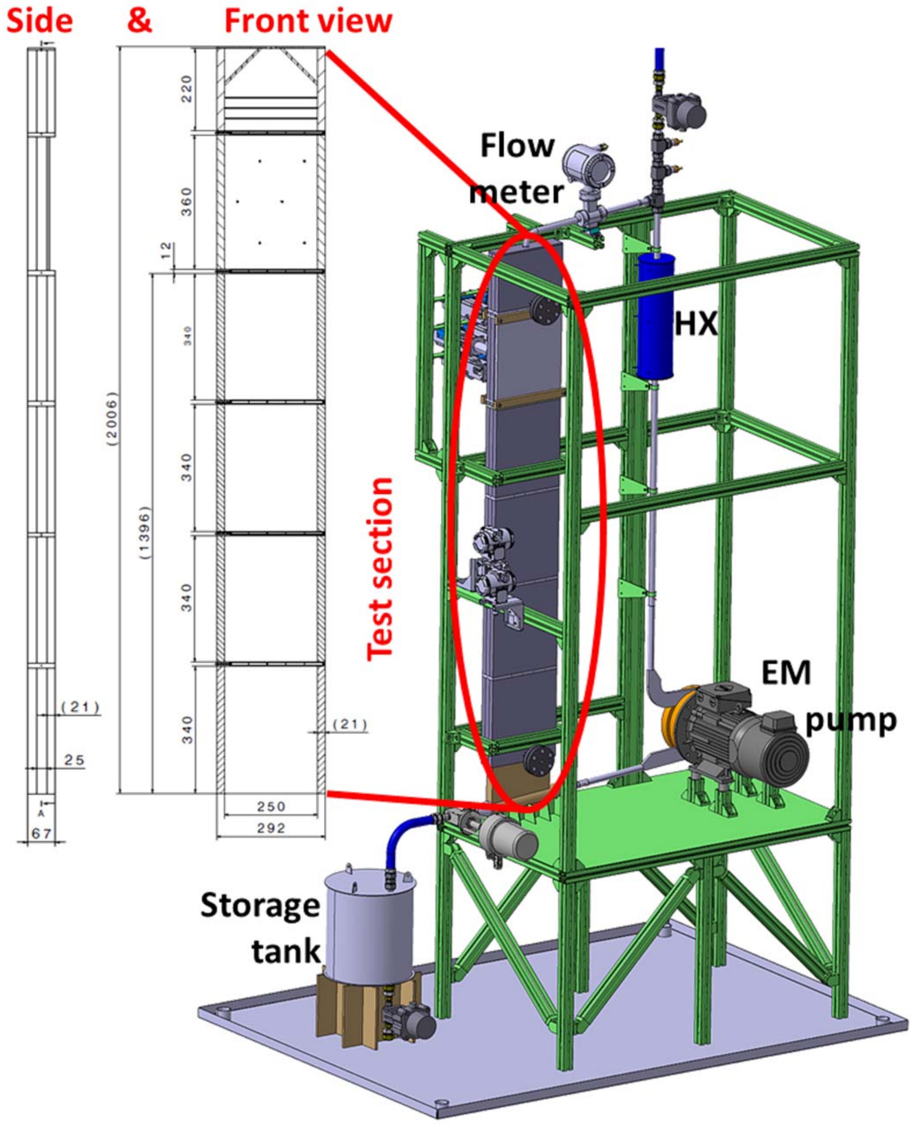
Capabilities include non-nuclear and nuclear applications for prototypical configurations:

- Validation and improvement of turbulent liquid metal heat transfer models in CFD tools on limited geometric scale;
- Development of free surface liquid metal targets for accelerator applications;
- Development of models to describe free surface liquid metal flow;
- Investigation of transition in convective flow patterns between forced, mixed and free convection modes;
- Qualification of CFD and system codes to simulate adequately the transition from the channel flow to large plenum (collector tank);
- Thermal-hydraulic investigations of flow patterns in fuel bundles or pool configurations at prototypical or scaled heights;
- In-Service Inspection & Repair (ISIR) monitors for liquid metal systems.

In the nearest future, it is intended to demonstrate the feasibility of sodium usage for thermal storage systems and direct energy conversion at high temperatures.

Small Size Facility DITEFA

- DITEFA (**DI**vertor **TE**st **FA**cility) – a small multipurpose liquid metal test facility for thermo-hydraulic investigations related to solar, fusion and nuclear energy.
- Currently, DITEFA is under construction and scheduled to be online in 2016.
- For the first experimental campaigns, the focus will be on the flow in vertical rectangular channels. Thereby, the transition from forced convection to free convection will be studied.



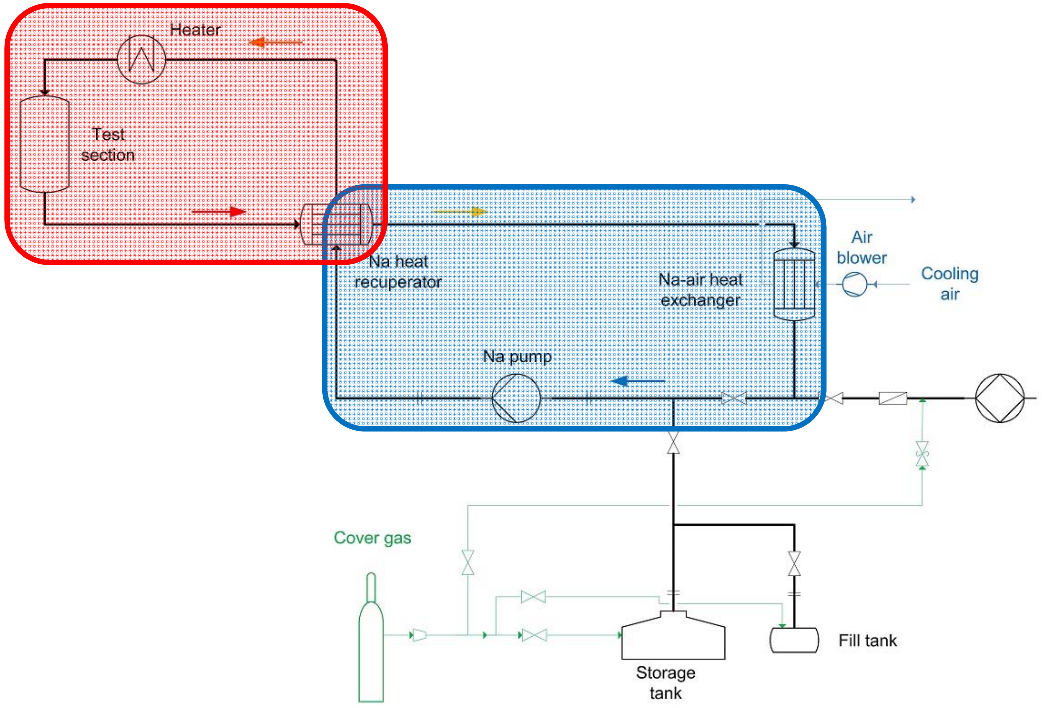
DITEFA characteristics

- During the transition between different flow regimes, detailed information available on the velocity and temperature fields on a global and local levels.
- Measurement devices consist of thermo-elements in connection with small permanent magnets that are inserted into the flow.
- The cross section of the device in the range of 2 mm – does not perturb the flow or at least keep the perturbations minimal.
- Velocity information obtained by means of the Ohms law directly from the thermo-elements due to the electrical conducting liquid metal coolant.
- Qualitative and quantitative statements of velocity as a function of the transition time and the flow regime will be made.
- Operational guidelines can be developed for a safe operation of facilities during flow regime transition.
- Knowledge gained during the experiments will serve possible improvement of the numerical tools and will be helpful when designing experimental facilities or real plant components in the future.

SOLTEC Facility

SOLTEC – **SO**dium **L**oop to **TE**st materials and **C**orrosion

- Applications:
  - Material qualification, long term low cycle fatigue tests in hot Na,
  - Steel corrosion investigations (fast transient stress tests),
  - Long term tests for thermoelectrical converters;
- Temp.: cold loop: ~ 700 K,
  hot loop: ~ 1000 K;
- Mass flow rate: ~ 300 kg/h;
- Design: finished;
- Present state: in construction;
- Operation foreseen in 2016.



SOLTEC sketch

KIT/INR facility links on the Web

- KASOLA facility - http://www.inr.kit.edu/english/258.php;
- DITEFA facility - http://www.inr.kit.edu/english/702.php;
- SOLTEC facility - http://www.inr.kit.edu/english/701.php.