DESIGN AND SAFETY-SUPPORT ANALYSES OF AN IN-PILE MOLTEN SALT LOOP IN THE HFR

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Introduction

- Molten Salt Reactor (MSR) - a class of fission reactors in which the primary nuclear reactor coolant is a molten salt mixture, which can include the fuel itself.

- MSRs run at higher temperatures than LWRs for higher thermodynamic efficiency.

- The reactors are believed to have potentially significant advantages in terms of safety, resource efficiency, waste production, proliferation and costs.

- MSR reactor technology is fundamentally different compared to reactor technology currently adopted, and will require significant development work.

- MSRs were first investigated at Oak Ridge National Laboratory (ORNL)
  - Molten Salt Reactor Experiment (MSRE) – 7.4 MW_{th} system operated from 1965 to 1969.
  - Molten Salt Breeder Reactor (MSBR) – 1000 MW_{el}, stopped in the early 1970s due to a prioritization of sodium-cooled reactor technology.

- MSR has seen a surge in interest in recent years. This interest is fueled by the MSR's expected characteristics, compatible with 'CO_2-free' energy technologies.

NRG Role in Molten Salt Technology

- Despite the work done at ORNL, R&D-level work is needed, in 3 main areas:
  - **Salt selection/optimization**
  - **Chemical processing of the salt**
    - Fission product removal (helium bubbling and advanced processing)
    - Salt chemical control (fluorine and oxygen potential)
    - Addition of fresh fissile material (assuming net fissile consumption)
  - **Materials qualification**
    - Chemical interaction between salt and structural materials (corrosion)
    - High-temperature mechanical stability
    - Radiation effects (radiation hardening and transmutation)
    - The interplay between the above three factors

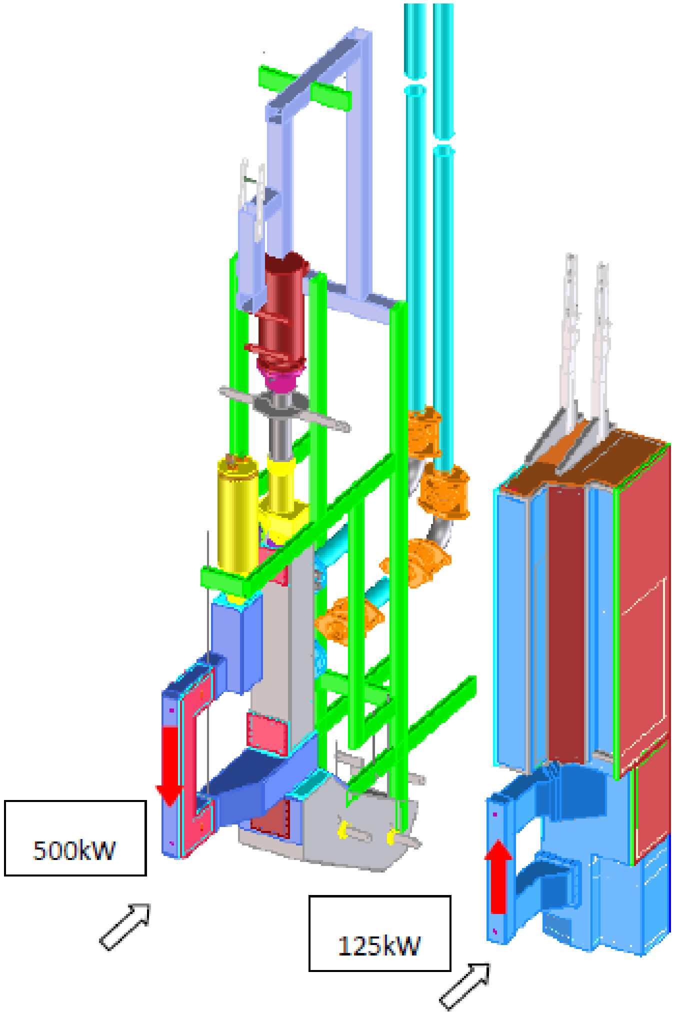
- To support the development, NRG initiated MSR R&D program, in which experimental molten salt bearing facilities are designed in the High Flux Reactor (HFR).
  - ✓ Irradiation of thorium-bearing molten salts in medium flux core positions - currently ongoing (SALIENT irradiation program), and additional similar tests are under development.
  - ✓ MSR waste treatment and management, and salt behavior under gamma irradiation (SAGA gamma irradiation program) are also part of the program.

Molten Salt Loop Conceptual Design

- Goal: constructing and operating the loop in the flux field directly next to HFR core.
- Purpose:
  - provide a material and salt test bed under representative conditions, combining flowing fuel salt with a moderate flux irradiation field;
  - allow testing of components in a in a fuel-bearing salt environment.
  - allow testing of fission product management methods.
- Development needs expertise from different disciplines:
  - **Engineering**: addresses construction, components, containments & gas gaps, instrumentation, mechanical aspects such as thermal stresses and operational aspects.
  - **Neutronics**: addresses neutronic aspects of the loop's core simulator (the section next to the HFR core box). MCNP and SCALE modelling was performed to estimate power production, long term depletion, and breeding performance of the thorium fuel cycle.
  - **Thermal-hydraulics**: addresses heat production, transport and losses, mass flow rates and pressure drops. SPECTRA model was developed to analyze the start-up procedure.
  - **Chemistry**: addresses the loop's chemical aspects, such as salt selection, redox buffering, re-fueling, tritium production, material selection and other considerations.
  - **Safety concept**: addresses single and multiple failures as well as external hazards. A preliminary list of postulated initiating events (PIEs) was established that will be considered in order to demonstrate the safety of the molten salt loop.

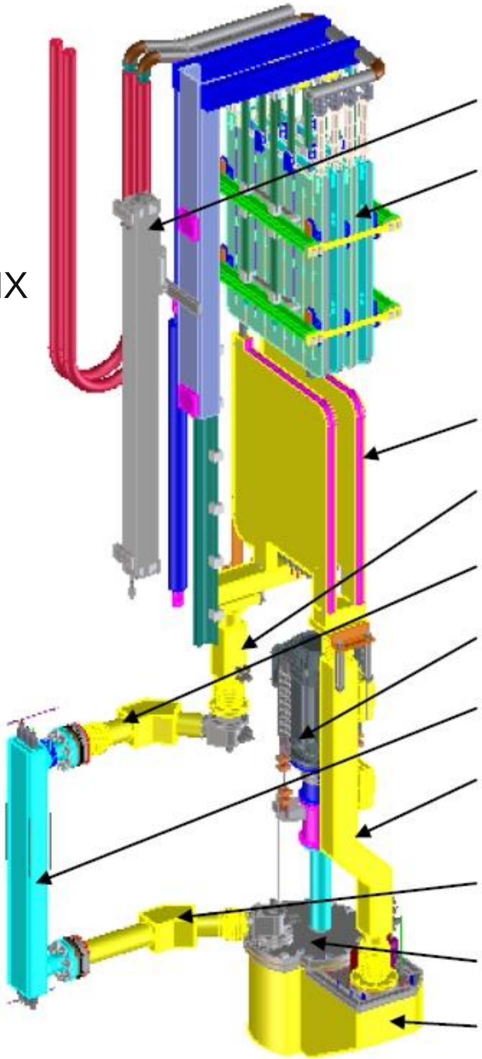
Description of the Loop Design (1)

- LUMOS Loop design v17 consists of
  - primary molten salt loop, power of ~ **500 kW**
  - secondary coolant loop for heat removal
- Sub-critical - powered by neutron flux from HFR
- Power control: by moving the rig towards HFR core
- First comprehensive design finalized in 2016
- This design was followed by
  - thorough safety review,
  - checks on manufacturability and
  - maneuverability of the main components.
- Design was to a large extent modified in 2017:
  - constraints were put on the loop size (maneuverability)
  - reduced size lead to reduction of power: **125 kW**.
- Figure shows a comparison of the loop size in
  - design concepts of 2016 (left)
  - design concepts of 2017 (right).



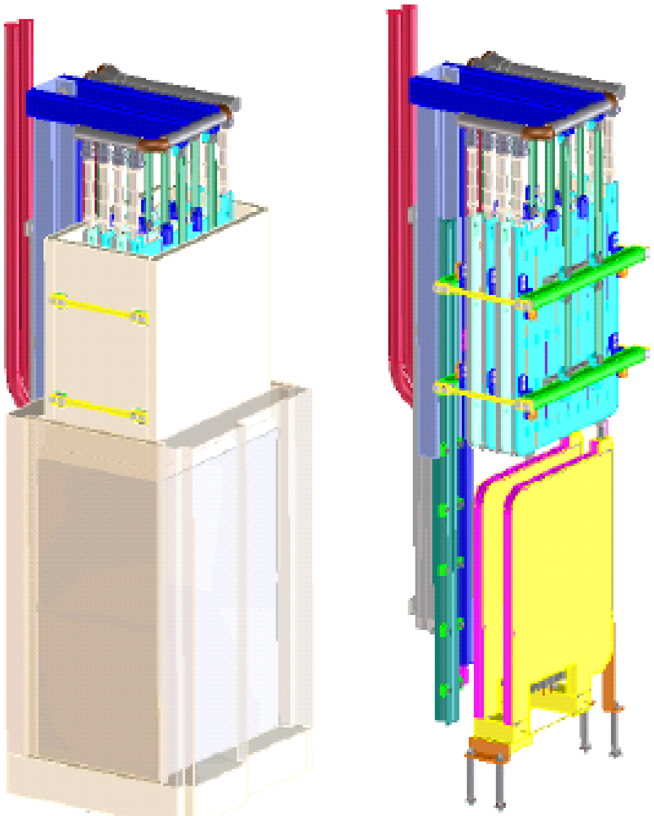
Loop Design

- Primary loop:
  - fissile region, “hot-leg”, next to HFR,
  - detachable plate heat exchanger, DPHX
  - primary pump
  - salt tank
  - connecting pipes
  - Salt flow is upward in the hot-leg.
- Triple containment
  - Molten salt circulates inside the 1st containment, made of Hastelloy.
  - 2nd containment, steel alloy, Low pressure Ar in the space between 1st and 2nd containment.
  - 3rd containment, aluminum. Pressurized He in the space between 2nd and 3rd containment.
  - Aluminum shroud is immersed in the HFR pool water.

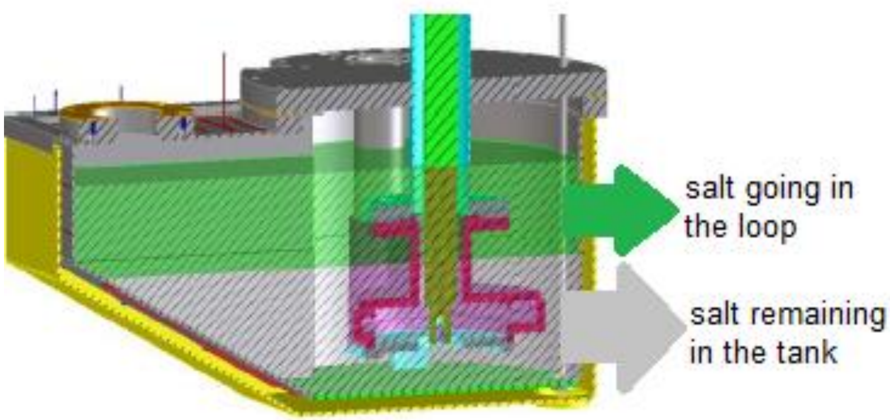


Loop Design

- DPHX:
  - radical change compared to previous concept.
    from:
    classical shell / tubes,
    to:
    plate-type HX, where secondary side can be engaged / disengaged during operation.

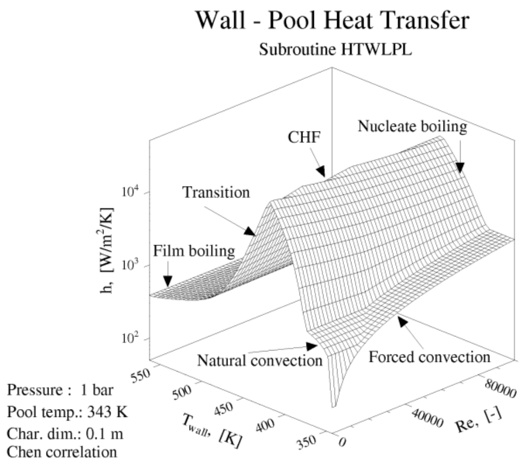


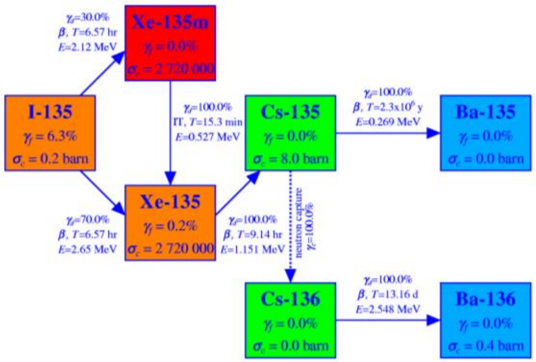
- Salt tank:
  - reservoir containing the salt mixture
  - at start-up: whole salt inventory in the tank
  - in operation: part of salt inventory (green area) fills the loop. Minimum level of salt (grey area) always present in the tank.
  - Neon occupies the region above the level of the salt and is connected to a pressure control room.



STH Code SPECTRA

- SPECTRA – System Thermal-Hydraulic (STH) code, developed by NRG, for accidents and transient analyses of nuclear power plants.
  - **Applicability**: LWRs, HTRs, LMFRs, MSRs.
  - **Accidents**: LOCAs, operational transients, other.
  - **Models**: multidimensional two-phase flow, non-equilibrium thermodynamics, transient heat conduction, general heat and mass transfer, steam/water/non-condensable gases, natural / forced convection, condensation, boiling.
  - For **liquid metal and molten salt reactors** applications fluid properties and heat transfer correlations are defined by the user in input (possible to analyze various types of salts without a need for code modification).
  - **Point reactor kinetics** model is available, with an isotope transformation model to compute concentrations of important isotopes (e.g. Xe-135).
  - Recently the reactor kinetics model has been extended to account for **delayed neutron precursor drift**, characteristic for molten salt reactors with circulating fuel. The radioactive particle transport package deals with release radioactive **isotope chains**, **transport of fission products**, aerosol transport, deposition, and resuspension.

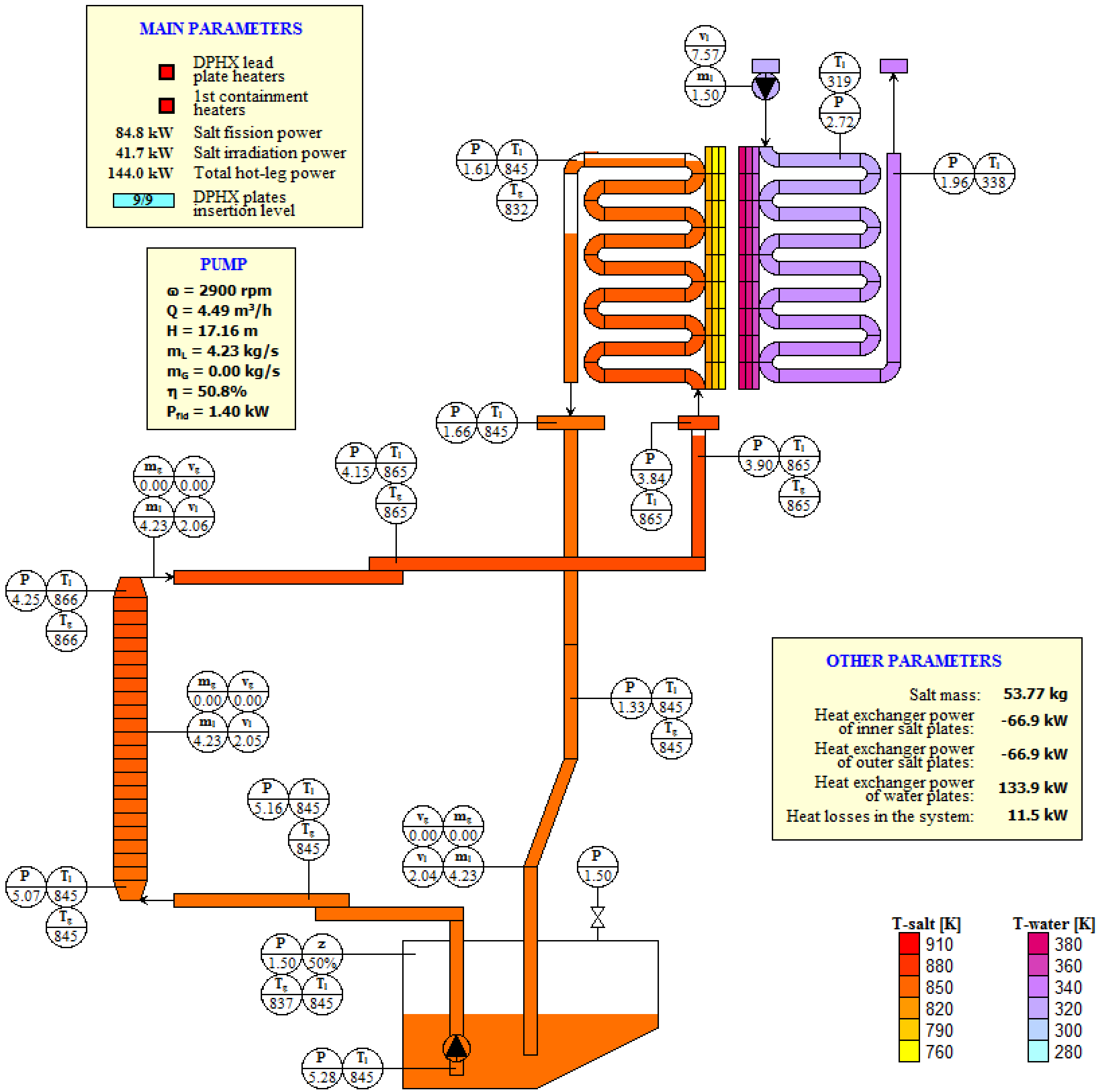




TH Model (1)

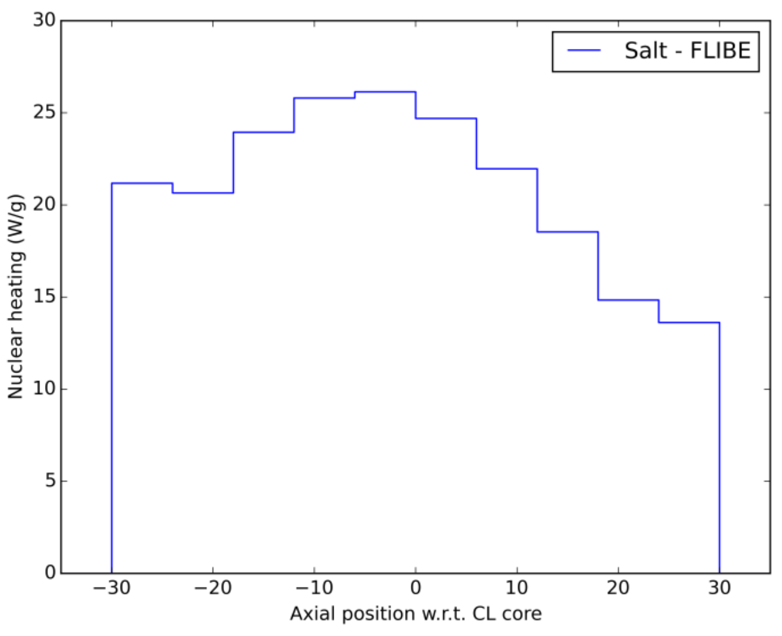
- Model consists of primary and secondary loops.
- Model is built using
  - Control Volumes (**CV**)
  - connected with junctions (**JN**)
  - solid materials represented by Solid Heat Conductors (**SC**).
- Figure shows loop model at steady-state conditions.

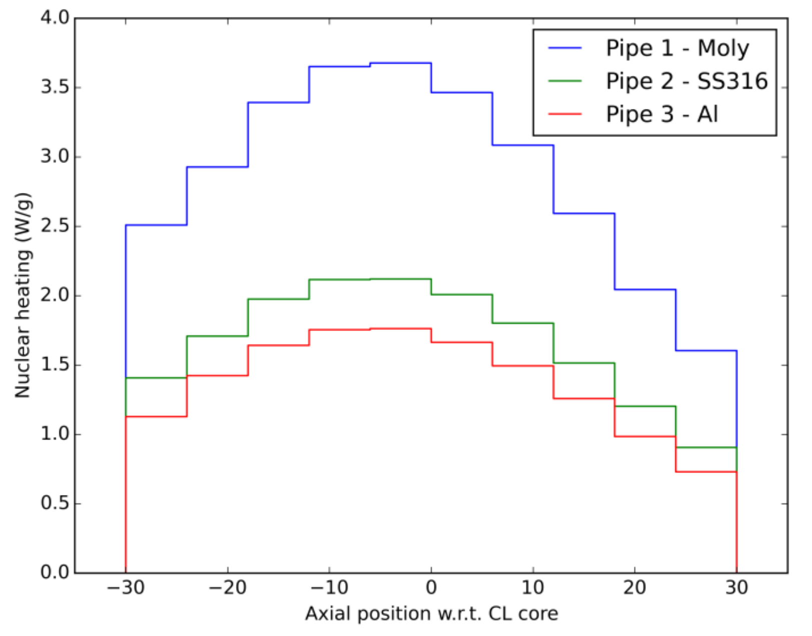
SPECTRA, LUMOS-2017, Salt loop, Time = 7200 s, Δt = 2.50E-003 s



TH Model (2)

- Power is generated in the hot leg by fission and irradiation.
  - **Irradiation power** - due to capture of (mostly) photons. Both in the salt and in the solid materials of 1st, 2nd, 3rd containments - calculated by MCNP.
  - **Fission power** - current model: fission and decay power defined as time-dependent heat sources.





Irradiation power in salt (left) and structural materials (right)

Results

- Design-support analyses aimed at developing a safe start-up procedure.

- The procedure was determined in multiple iterations in cooperation with the design engineers.

- Two distinct stages of the start-up procedure:
  - ***Pre-conditioning***:
    - primary loop is empty,
    - needs to be heated up to a desired level, before the molten salt is brought in,
    - target temperature of ~550°C is sought for the 1st containment (in contact with the molten salt).
  - ***Filling up with salt and initiating normal operation:***
    - primary loop is filled up with molten salt from the tank,
    - system is brought to the desired power level,
    - plates of the DPHX are inserted to allow the removal of power.

Pre-Conditioning

- ❑ Heating-up of the system by means of the electrical heaters (located on 1st containment and salt plates of DPHX).
- ❑ No forced circulation of Ne inside the 1st containment; Ar between 1st and 2nd containment is circulating.
- ❑ Pre-conditioning time ~8 hours, secondary side of DPHX inactive; plates at full-out.
- ❑ Results showed: possible to bring 1st containment to ~550°C by electrical heaters.
- ❑ Heat losses in the various parts of the loop:
  - ❖ **Largest contribution from un-insulated parts:**
    - ➢ hot-leg,
    - ➢ connection lines,
    - ➢ return line.
  - ❖ **Salt tank and the DPHX chamber:**
    - ➢ surrounded by a thick layer of insulating material
    - ➢ → much smaller heat losses.

LUMOS-2017 Heat Losses

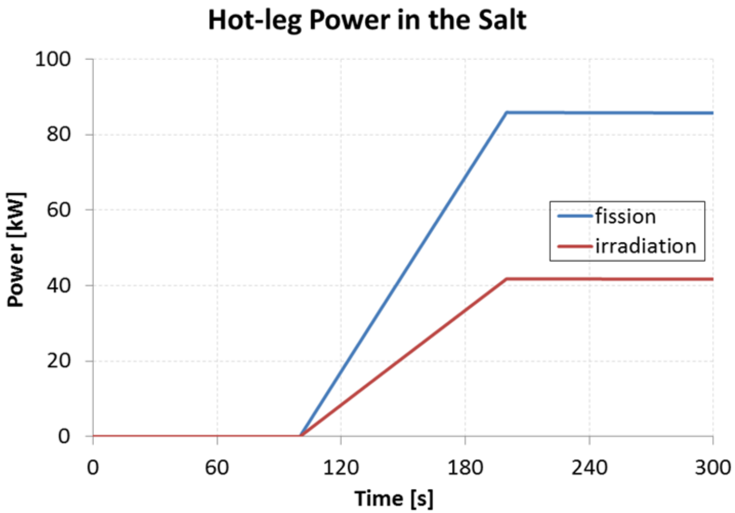
Time: 0.0 s

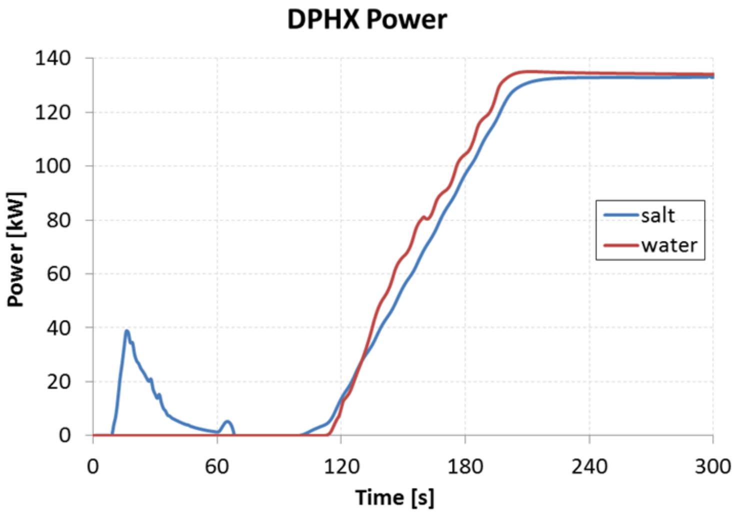
Heat Losses Summary Table

Top connection line	1.14 kW
Bottom connection line	0.83 kW
Core (Hot Leg)	1.00 kW
Tank	0.36 kW
Return line	1.17 kW
DPHX headers	0.48 kW
DPHX	0.08 kW
Total	5.05 kW

Approach to Steady-State (1)

- Primary loop is filled up with molten salt.
- System is brought to the desired power level.
- The procedure consists of :
  - starting up the primary pump,
  - circulating the salt from hot-leg to DPHX → simulations showed difficulty in pushing Ne downwards, towards the tank (slide 8), unstable two-phase flow for a significant time .
- Irradiation power (~40 kW) has a significant contribution to the total power (~145 kW).





Approach to Steady-State (2)

- Global energy balance in the loop at steady state conditions is shown
  - Heat losses at stationary conditions increased *from* ~5 kW at the pre-conditioning *to* ~11.5 kW, mainly due to the irradiation power in the hot-leg.
- Furthermore: small amount of Ne remained trapped at the top of the salt plates of the DPHX.

LUMOS-2017 Energy Balance

Time: 7200.0 s

Power generated

Fission power in the salt	85.7 kW
Irradiation power in the salt	41.7 kW
Irradiation power in the 1st cnt	6.7 kW
Irradiation power in the 2nd cnt	5.0 kW
Irradiation power in the 3rd cnt	5.0 kW
Total electrical power	0.0 kW
Pumping power in the salt	1.4 kW
Total	**145.4 kW**

Power removed

DPHX power in the water plates	133.9 kW
Total power losses in the HFR pool	11.5 kW
Total power losses in the leak detection system	0.0 kW
Total	**145.3 kW**

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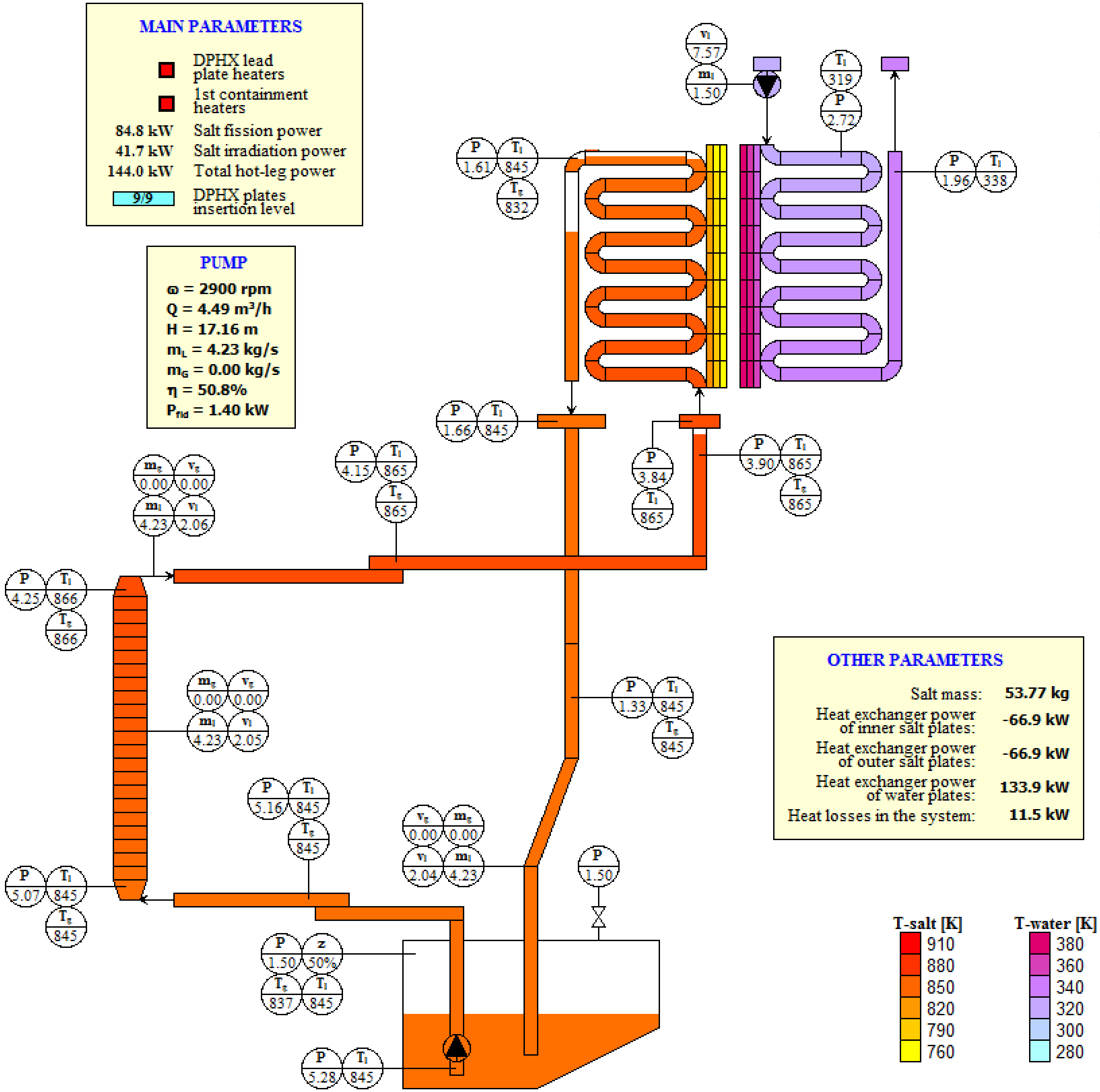

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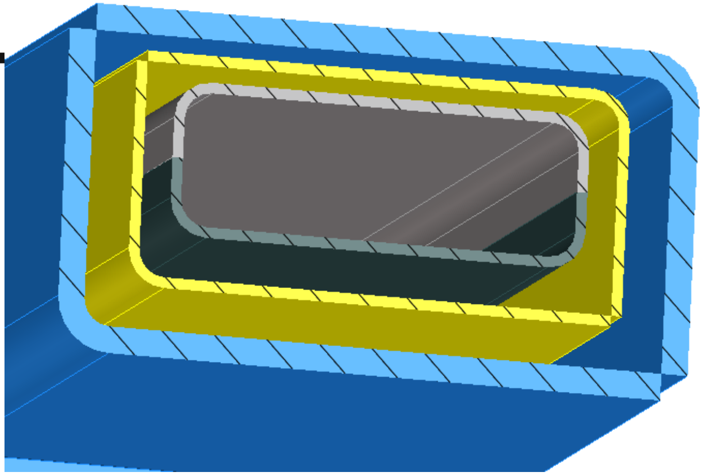
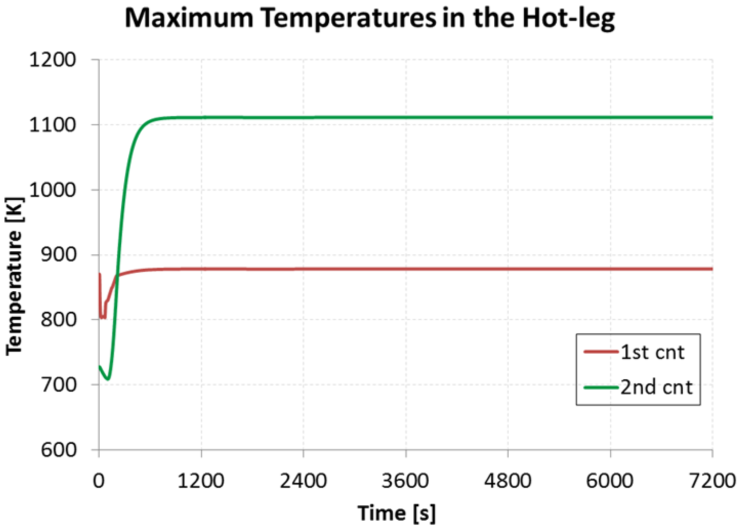
Approach to Steady-State (3)



- Large irradiation power → trouble with 2nd containment.
  - 1st containment cooled from inside by the salt
  - 3rd containment cooled from outside by the pool
  - 2nd containment, between Ar and He → bad cooling.
- Figure shows temperature in
  - 1st containment walls of the hot-leg
  - 2nd containment walls of the hot-leg.
- Temperature of the 2nd containment is too high.
- This fact must be addressed in future work by designing an additional cooling of the 2nd containment.



Summary and Conclusions

- Conceptual design of the molten salt loop (v17) was prepared at NRG.
- Intended to provide: MSR-representative test environment (for material testing).
- Design-support analyses (codes MCNP, SCALE, SPECTRA) main results:
  - The v17 design allows ~145 kW during steady-state conditions.
  - Pump-driven filling procedure should be verified by additional analysis (CFD and/or experimental efforts needed).
  - Additional cooling capabilities required to prevent overheating of 2nd containment.
- Conclusions:
  - **flexible design of the loop is ready**
  - **several open issues should be addressed in a detailed design phase.**
  - **It is necessary to enter the next design phase in a collaboration with external partners, for reasons of cost sharing and tailoring of the loop to a specific molten salt reactor design. The flexible design of the current LUMOS v17 loop should allow to adapt relatively easily to such external needs.**