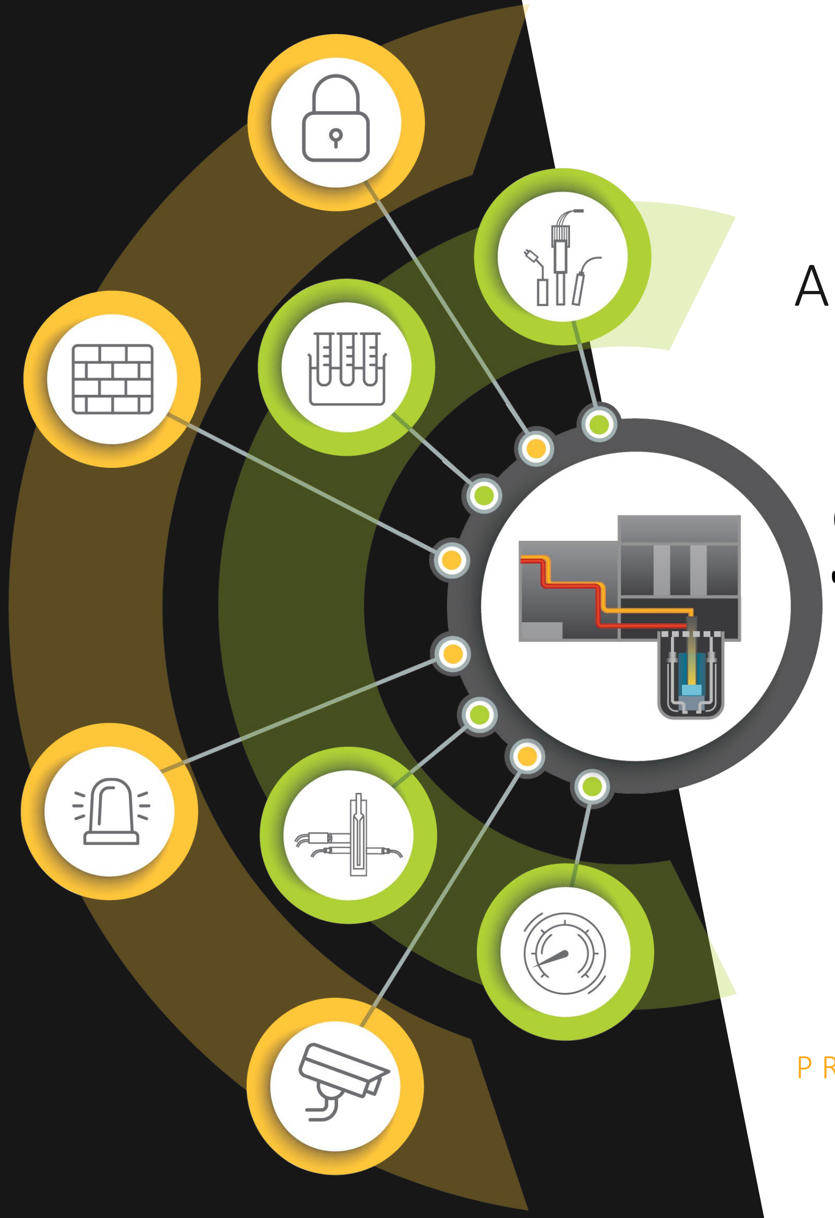

ADVANCED REACTOR SAFEGUARDS

Microreactor Modeling for Sabotage Analysis

Focus on Heat Pipes

PRESENTED BY

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Overview of the Work

- The goal is to analyze sabotage threats for advanced reactors and determine:
  - which could fall within DBT capabilities
  - timeline progression
  - if existing modeling tools are adequate
- This work will feed into the physical protection analysis for advanced reactors

Why is this Important?

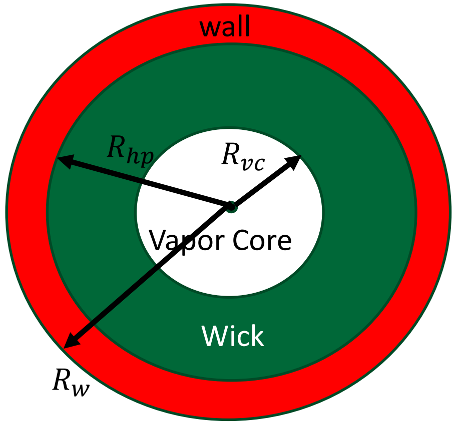
- In the US alone we have approximately 4000 reactor years (100 reactors for 40 years) experience with large LWR reactors.
- That's about 2500 fuel cycles producing electricity and making a profit.
- Current advanced SMRs designs have limited or no operating experience and no experience with producing a profit since they are based on test reactors.
- The cost of safety, security, and safeguards has a large uncertainty due to the lack of data.
- Providing knowledge now, that will be augmented later by experiments and operating experience, reduces the risk to investors.

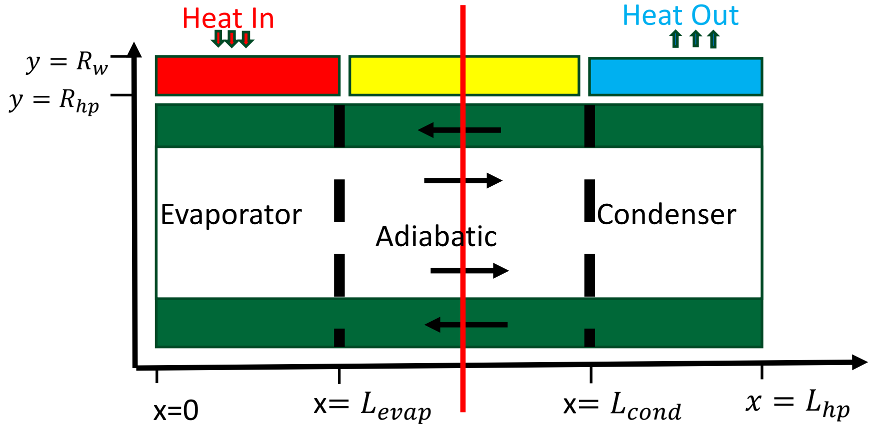
Passively Safe Heat Pipes

- Because there are no moving parts, the reliability of heat pipes is very high, in addition microreactor designs often include a large amount of redundancy which also improves reliability.
- In the microreactor, the heat pipes serves as the equivalent of a BWR primary cooling loop: the coolant boils and condenses and transports heat.
- Transient response of heat pipes requires very similar physics modeling to a BWR primary.

Heat Pipe Basics

- The liquid flows from the condenser to the evaporator because the wick pulls (capillary force) the liquid from wet regions to dry regions (just like a candle or oil lamp)
- The liquid boils in the evaporator due to heat addition
- The vapor flows from the evaporator to the condenser (capillary force)
- The vapor condenses in the condenser due to heat removal



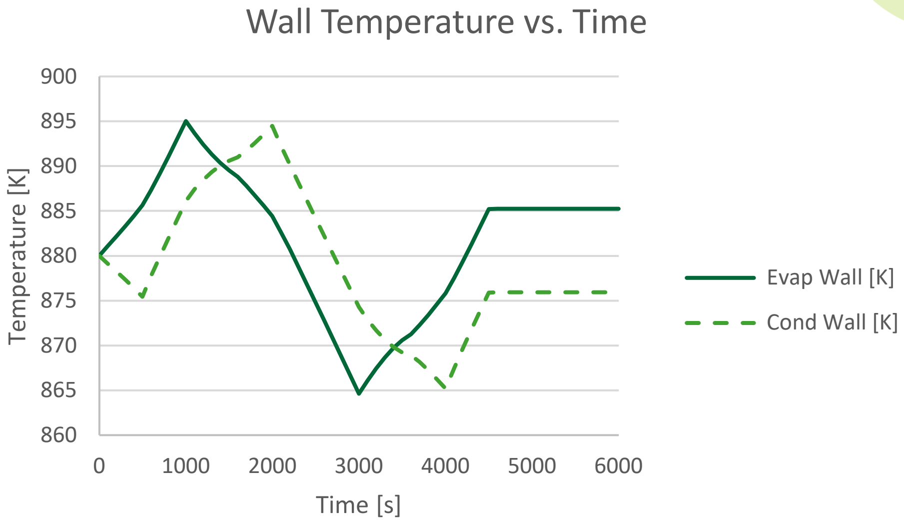


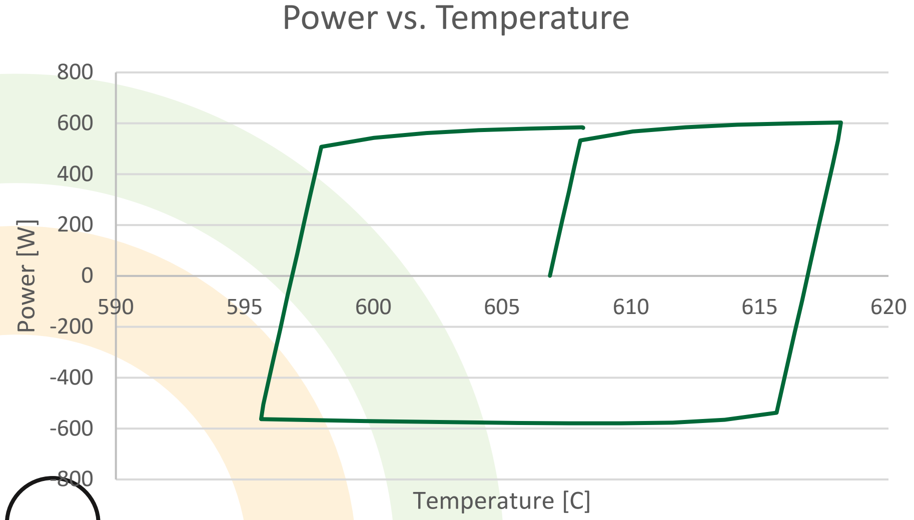
Heat Pipe Transient Analysis

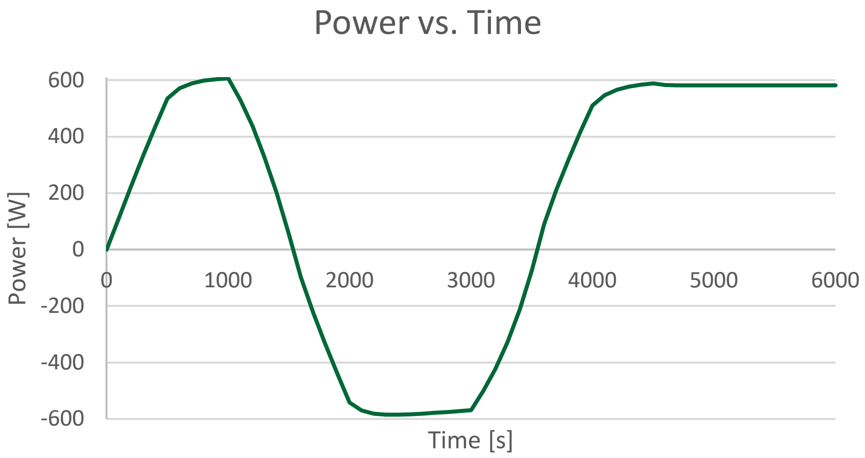
- Flow Reversal – Happens when the secondary gets hotter than the primary
- Vertical Heat Pipes – Gravity plays an important role in heat pipes
- Doppler Feedback – Doppler feedback can be “modeled” by making the heat flux an inverse function of the evaporator temperature
- Moving Heat Pipes – The orientation of the heat pipe impacts both gravity and saturation temperature.
- Small Angle Effects - When operating near the edge where the margin is small, small angle changes can push you over the edge

Heat Flow Reversal

- Most heat pipes do not have a preferential flow direction.
- If the condenser is hotter than the evaporator, the flow is reversed.
- Heating the secondary fluid may result in heat flow into the core.
- In the plot, a negative power flows from the condenser to the evaporator.
- This is the traditional temperature versus power plot

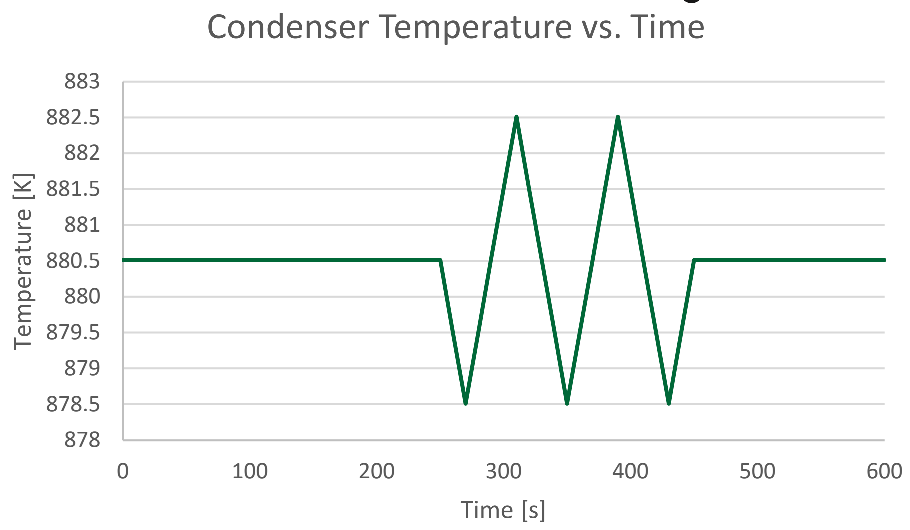


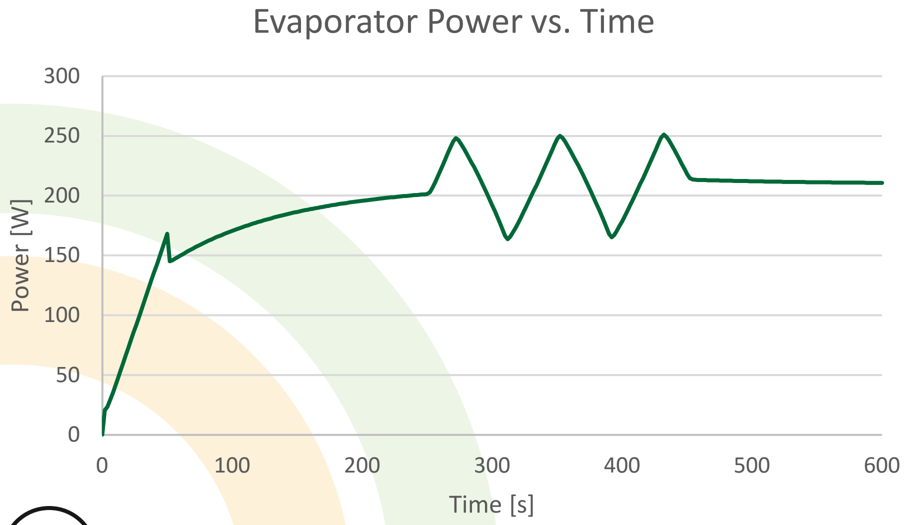


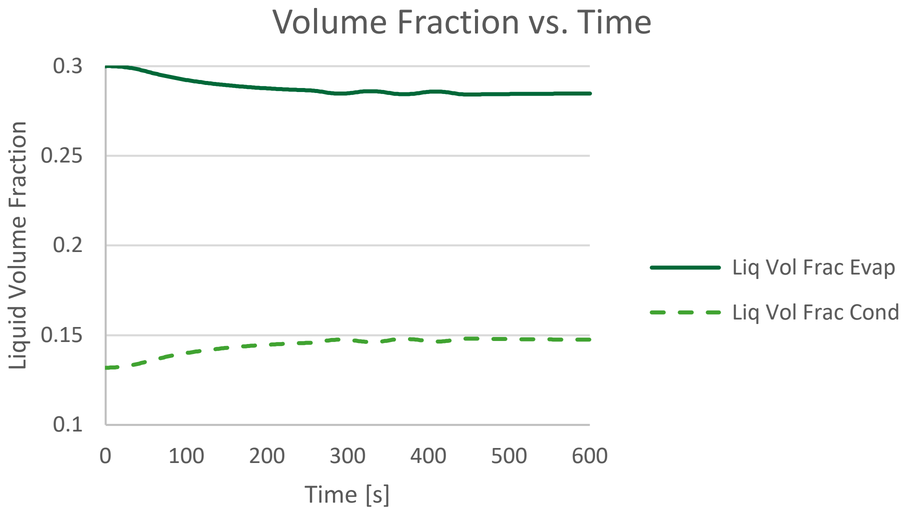


Doppler Feedback

- We see the same impact on power with a small condenser change in temperature.
- Note that this is a vertical problem so there is a difference in liquid volume fraction from top (condenser) to bottom (evaporator)

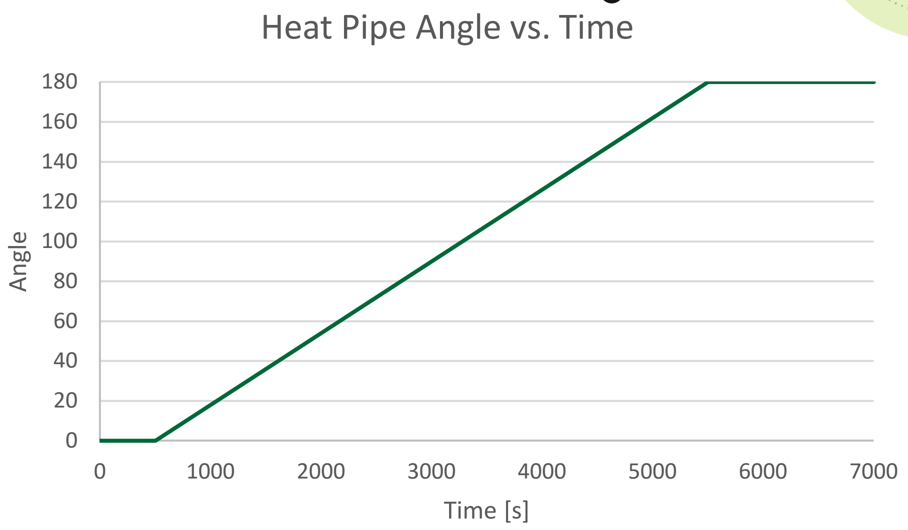


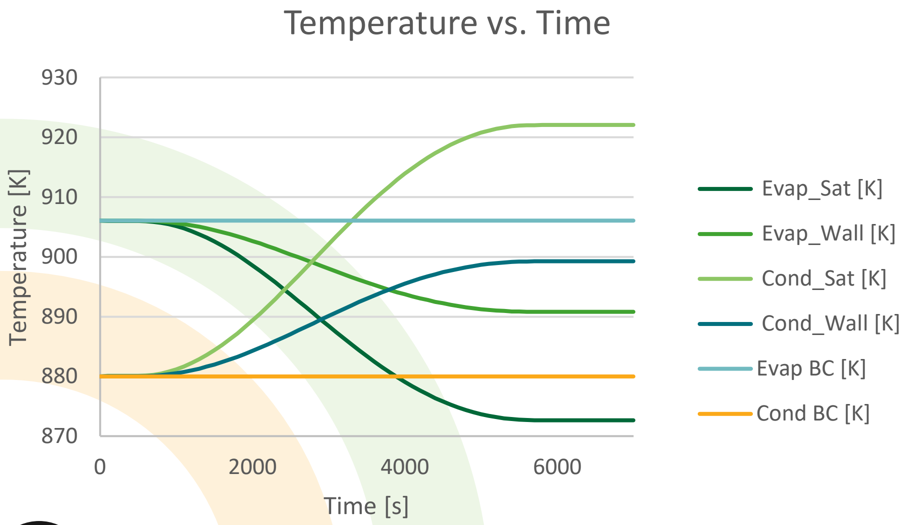


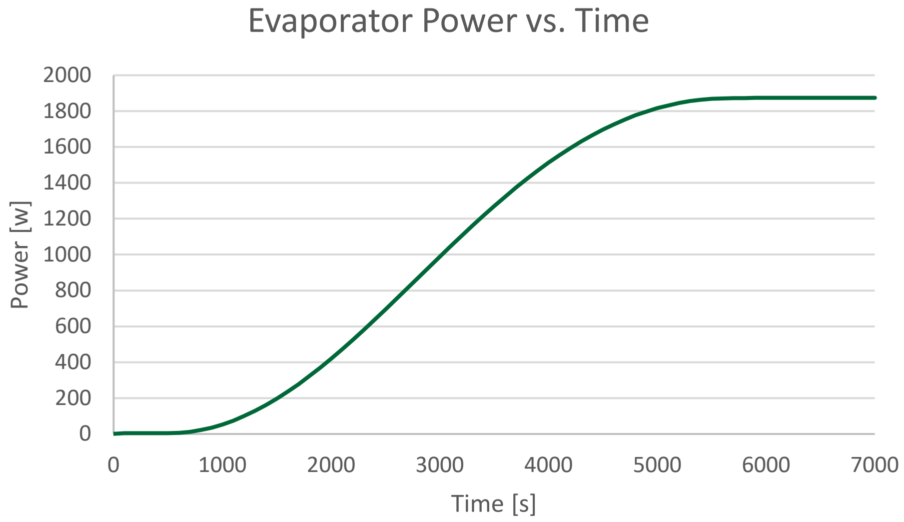


Heat Pipe Orientation

- The power moved by the heat pipe is strongly influenced by the pressure and corresponding saturation temperature.
- To model the dynamic behavior of a heat pipe it's important to know what is happening inside.

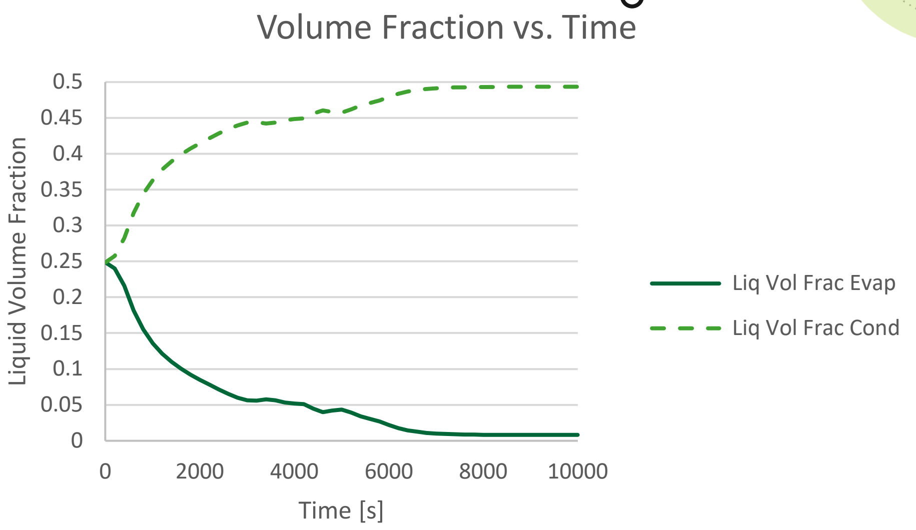


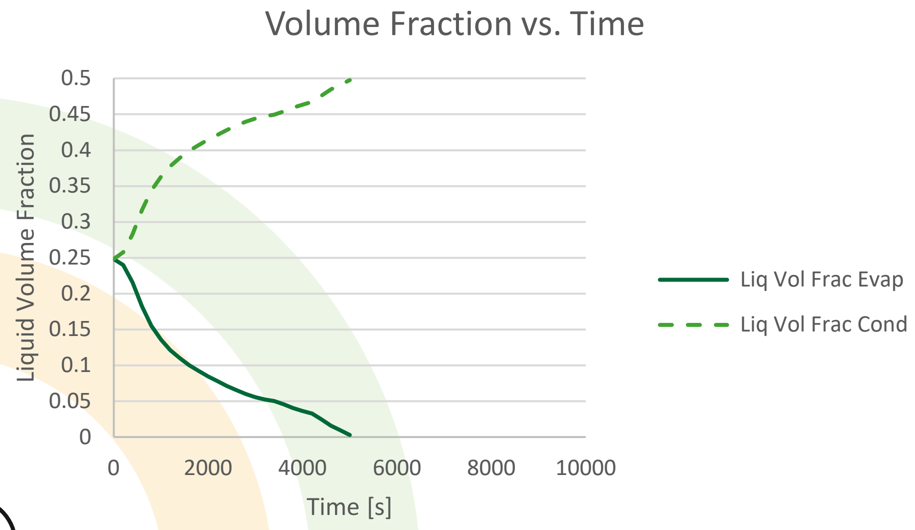


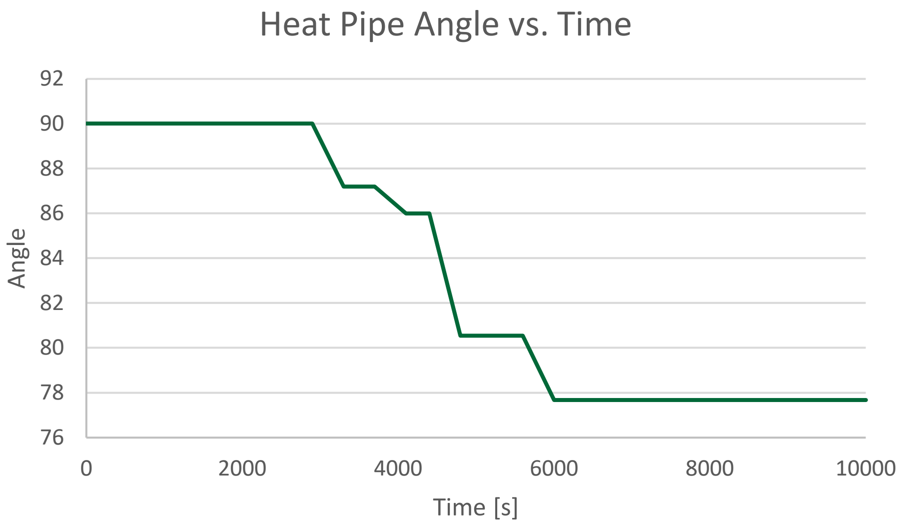


Small Angles can Impact Failure

- We ran two identical transients (shown to the right and below), except in the one on the right the heat pipe was rotated upward 20 degrees over an hour (shown in lower right).
- Below we see the one that didn't move had a dry out event in the evaporator (no liquid) at about 5000 seconds.
- The one that did move shown on the top right ran to steady state (10,000 seconds) with a low, but nonzero, liquid volume fraction







Validation Experiments

- Because transient heat pipe analysis for high reliability and high consequence applications is immature, the models need to have uncertainty reduced.
- Uncertainty is reduced by gathering large amounts of high quality experimental data that scales to the application space.
- We need the equivalent nondimensional numbers similar to Reynolds, Prandtl, and Nusselt to describe the entire heat pipe because of the unique wick designs.
- Nondimensional analysis comes from analyzing conservation laws which are the basis for transient heat pipe modeling.
- The transient heat pipe model is needed to design transient validation experiments.

Conclusions

- In a heat pipe-based microreactor, the heat pipe plays the role of the primary cooling system in a traditional BWR.
- Capturing the dynamics of the heat pipe requires capturing the physics inside of the heat pipe.
- Timing of safety and security transients depends on the dynamics of the heat pipe.
- Knowledge of the dynamics of the heat pipe may reveal possible sabotage targets.
- Heat pipe dynamics will impact sabotage consequences.

Future Work

- Finish Work on Micro-Reactors (with heat pipes) and Sodium Fast Reactors.
- The work will be generic (will apply to more than one reactor design).
- This will allow vulnerabilities to be designed out of the reactor or minimized by operating procedures.
- This results in cost savings over back-fitting changes in the design to minimize the vulnerability.
- Move to other advanced reactor designs and determine if a generic security analysis approach is appropriate.