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MAGNET Digital Twin Test Report
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On Wednesday March 30, 2022 the first test of a single heat pipe test article in the Microreactor Agile Non-Nuclear Experimental Testbed (MAGNET) was successfully performed. The work control for this test is LI-971 (https://inl-edms.inl.gov/pls/inl_docs/doc_3?f_doc=LI-971). This test was performed in the Systems Integration Laboratory (D100) at the Energy Systems Laboratory (ESL) building. T. J. Morton led the test, with Eric Larsen acting as the LabVIEW Human Machine Interface (HMI) subject matter expert, Cliff Loughmiller served as the Lab Space Coordinator (LSC), and Jeren Browning, Katherine Wilsdon, and Logan Browning present from the Digital Engineering department to control and manage the digital twin (DT).

Prior to beginning the experiment, a pre-job brief was held. The experiment started by running a vacuum pump to lower the oxygen partial pressure in the MAGNET environmental chamber, which was subsequently back filled with nitrogen to provide an inert test environment. Compressor frequency was varied to change flow rates through MAGNET. The test article temperature set through the HMI monitored one of three thermocouples (TC) on the core block (or “hex block”) of the test article. This TC on the core block was used as the process variable, or temperature set point, for the test article. The test article temperature was then set to 500 °C at a ramp rate of 500 °C per hour. Temperature increased at a steady rate until reaching 500 °C with no meaningful variation in temperature on the core block TCs.

Next, the temperature was set to 600 °C with a ramp rate of 100 °C per hour. From the 10 TCs located evenly along the interior thermowell of the heat pipe, only a few TCs (TC 07, TC 08, and TC 09) tracked similar temperatures to the core block that were directly under or very close in proximity to the core block. The TCs around and past the midpoint of the heat pipe did not increase much in temperature throughout the duration of this test because the operating temperature of the heat pipe was never reached. The operating temperature of the heat pipe is around 620 °C, which is when the sodium within the heat pipe begins flowing to perform heat transfer resulting in the distribution of heat along the length of the heat pipe. During the increase to 600 °C, TC 06 was expected to remain at a low temperature because this thermocouple was beyond the midpoint of the heat pipe. Instead, TC 06 diverged from the expected and rose to a similar temperature of the core block.

The temperature was then set to lower from 600 °C to 500 °C allowing the test article to cool via natural convection. The cool rate of the test article was greater than 100 °C per hour, and therefore required less time than raising the temperature from 500 to 600 °C. During this period, the DT team spent a small amount of time correcting a process in the ML Adapter, which to this point had been generating temperature predictions for each of the 10 TCs along the interior of the heat pipe. In order to cool the heat pipe, the heater power was turned off resulting in “0” values. The machine learning Jupyter Notebook read the “0” values for the core block TC as non-numerical “NA” values causing an error in the machine learning algorithms. To solve this issue, the TC data on the core block was removed before analysis by the machine learning algorithms. Then we began the DT portion of the MAGNET test.

The first step was for the LabVIEW HMI expert to switch to manual mode, which was a separate virtual instrument (VI) control system designed for operating the digital twin. The test plan specified for 1) the operators to manually set the temperature to 550 °C, 2) the temperature rises at a ramp rate of 100 °C per hour, 3) the DT predicts the temperature will go beyond this temperature threshold and then instructs LabVIEW to update the temperature set point back to 500 °C. The mechanism for interactions between the DT and LabVIEW was thoroughly documented and tested prior to the MAGNET test. The DT wrote files with a custom ".rsp" extension and a single numerical value (e.g. "500"). Once an operator switched to manual mode for the digital twin, LabVIEW began looking for these .rsp files. Once a file was found, LabVIEW would validate the file content and drop files entirely if any non-numerical content (letters or special characters) was found. Additionally, the number must fall within a range given hard minimum and maximum limits (0 and 600 °C) in LabVIEW. Once all these validation checks were passed, the operator would approve the change before LabVIEW automatically updated the temperature set point.

Unfortunately, the manual mode created in LabVIEW for digital twin operation was missing a control for the ramp rate after manually setting the temperature to 550 °C. The assumption was that the ramp rate would remain at 100 °C per hour (the agreed ramp rate for any changes above 500 °C specified in the LI). As a result, the heat pipe reached 550 °C in approximately 2 minutes 20 seconds. At this speed, the machine learning predictions of the DT were unable to predict that 550 °C would be reached before it occurred in real time. However, the DT did predict that TC 08 would exceed 550 °C and set the temperature set point to 500 °C approximately 5 minutes after the initial start. After cooling to 500 °C, the operators manually set the temperature to 450 °C. The cooling process exhibited a typical rate of decreasing in temperature that the DT could wholly predict in a timely manner. When the heater temperature reached 483 °C, the DT predicted that the TC 09 around the core block would drop below 450 °C within 10 minutes. The DT adjusted the temperature set point to 500 °C after approximately 20 minutes from the initial start.

The remainder of the test plan included raising the temperature set point back to 600 °C, adjusting compressor speed further, and then stopping power to heaters to shut down the test article. Throughout the experiment, data was periodically "sneaker-netted" from the local MAGNET ICS network to a Deep Lynx instance in the Azure cloud. With the real MAGNET sensor data in an accessible location for the Microsoft HoloLens headsets, users were able to view a 3D model of the heat pipe overlaid on the actual physical location of the heat pipe within MAGNET. The 10 TCs were shown with the latest available temperatures (from when data was last manually transferred to the Deep Lynx cloud instance).

The predictions made by the machine learning were generally very accurate, an overall accuracy number will be forthcoming. Generally, the 10-minute predictions for each TC matched very closely. When the heat pipe would move from a steady state to some increase or decrease in temperature, the first machine learning prediction after this new temperature adjustment would sometimes be wildly inaccurate, predicting high temperatures or low temperatures that were physically impossible for the heat pipe to achieve. Once the ML could identify the rate of temperature change was under normal conditions, the predictions were once again accurate. This phenomenon only occurred three times throughout the entire test. These issues can be resolved and mitigated in the future by incorporating more intelligence into controlling the asset to resolve any physically unrealistic scenarios provided by the machine learning.

An important element of this DT and LDRD has been the creation of a physics model of a single heat pipe using Sockeye, a member of the Multiphysics Object-Oriented Simulation Environment (MOOSE) framework. However, due to many uncertainties around single heat pipes and how heat may be lost, a lack of information from the heat pipe vendor, and this being the first time this specific heat pipe configuration had ever been run, the Sockeye model was not run during this test. The physics model is highly dependent on prior experimental data to build a sufficiently accurate model. Despite the data from another single heat pipe called SPHERE (Single Primary Heat Pipe Extraction and Removal Emulator), Sockeye could not provide reasonably accurate predictions in order to be incorporated into DT control decisions. The team continues to investigate the uncertainties of single heat pipes and hopes to improve this model through continued testing and validation with SPHERE.

Improvements to future MAGNET DT tests are possible by creating a MAGNET DMZ network that interfaces between the MAGNET ICS network and general INL network. With this network in place, exposure of data can be consolidated to one secure location and any input to the MAGNET ICS network can likewise be controlled and validated. This LDRD effort is working to establish this network, which would allow future tests to utilize a DT that exists in the Azure cloud and uses INL HPC resources for the intensive physics and machine learning simulations, rather than running on a single laptop connected to the MAGNET ICS network. This would allow for DT performance gains, moving from the 1-minute interval used in this test to intervals that are much closer to real-time. Additionally, the HoloLens would be able to sync with the latest real-time data, rather than a manually provided copy. Our hope is that these changes can be available in the future when the 37 heat-pipe test article is run within MAGNET.