**MAGNETIC ANALYSIS OF AN ANNULAR LINEAR INDUCTION PUMP FOR FISSION POWER SYSTEMS.** S. M. Geng[1], J. M. Niedra[2], K.A. Polzin[3], [1]NASA Glenn Research Center, Cleveland, OH 44135, [2]ASRC Aerospace Corp., Cleveland, OH 44135, [3]NASA Marshall Space Flight Center, Huntsville, AL 35812.

**Background:** Fission power systems (FPS) are being developed for use on the surface of the Moon, Mars, or other moons and planets of our solar system. FPSs are capable of providing good performance at any location, including those near the poles or other permanently shaded regions, and offer the capability to provide on-demand power at any time, even at long distances from the Sun. Fission-based systems also offer the potential for outposts, crew, and science instruments to operate in a power-rich environment.

One of the key technologies associated with the FPS is the annular linear induction pump (ALIP)[1] used to circulate the liquid-metal fluid that transports thermal energy from the nuclear reactor to the power conversion device. In 2010, an ALIP developed by the Idaho National Laboratory (INL) was tested under representative space-reactor thermal operating conditions at NASA's Marshall Space Flight Center (MSFC) to quantify the pump's performance. The measured performance was below expectations. This result motivated NASA's Glenn Research Center (GRC) to create a finite element model of the ALIP to gain a better understanding of its functionality, and to independently evaluate design variations that might have contributed to the performance shortfall.

**Introduction:** A Maxwell 3-D (symmetric to the 60˚ wedge) magnetostatic model was created of the INL ALIP pump, and is shown in Figure 1. The components modeled include the Hyperco-50 torpedo, two Hyperco-50 lamination half-stacks, twelve copper coils (85-turns per coil), and the NaK-78 fluid contained within the body of the ALIP pump discretized as 25 individual segments or slugs.

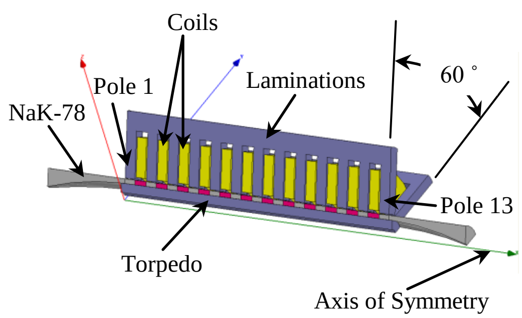


Figure 1 – 3-D Magnetostatic Model of the ALIP.

**Procedure:** The magnetostatic model was used to calculate the average magnetic flux linking each of the 25 slugs of NaK-78 fluid, for 18 time steps comprising a single complete electrical cycle. The average magnetic flux for each slug of NaK at each time step is calculated by averaging the magnetic flux normal to three cut-planes orientated as shown in Figure 2. The cut-planes are positioned at either end of the NaK slugs, and at the mid-point locations. The average magnetic flux values are then numerically differentiated to determine the induced voltages and currents in the various slugs of NaK-78 fluid. The magnetostatic model is then solved using the NaK electrical currents calculated in the previous step as input boundary conditions for the NaK elements. The magnetic forces applied to each of the 25 NaK slugs are calculated at each of the 18 time steps. The slug forces are then added to determine the net magnetic force acting on the NaK fluid within the ALIP. Finally, the 18 ALIP NaK fluid forces are averaged to determine the mean NaK fluid force over an electrical cycle.

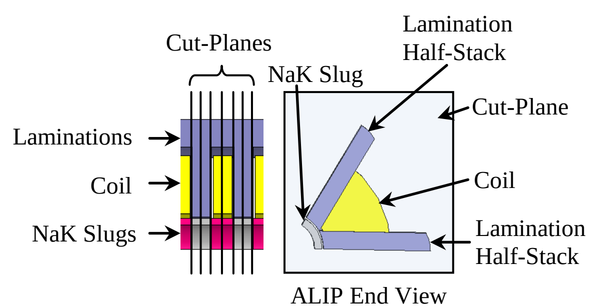


Figure 2 – Orientation of Cut-Planes used for Calculating Magnetic Flux.

**Results:** Model predictions of the net magnetic forces acting on the NaK fluid in the ALIP for various design and operating conditions are presented in Tables I and II. These predictions cannot be directly compared with the MSFC data[2] since the model is magnetostatic, and therefore the NaK fluid is stationary. It should be noted that the relative permeability of the NaK-78 fluid was estimated to be approximately 1.0, and the electrical resistivity of NaK was about 53 micro-Ohm-cm at 325 ˚C (from Ref [3]). Caution must be exercised in interpreting the results presented in this abstract since they are strongly dependant on the accuracy of the assumed NaK properties.

The results shown in Table I were generated assuming a NaK temperature of 325 ˚C, an ALIP frequency of 36 Hz, and an RMS input current of 2.47 A. These conditions were selected based on data presented in the MSFC test report[2]. The first case modeled was for an ideal ALIP, assumed to be fabricated as designed. In particular, this case assumed that the Hyperco laminations and torpedo were annealed and the ALIP input current was balanced between each of the three phases. The predicted ALIP net magnetic force at zero flow was 11.4 N for this baseline case. A number of ALIP design variations were then explored. The first design variation involved the balance between the three-phases of the ALIP input current. During the test at MSFC, it was discovered that the currents in the three phases were not equal. Phase B was always the greatest, phase A was always the smallest, and phase C fell in between. The peak phase B current was approximately 12.5 to 13.5% larger than the peak phase A current. The second case shown in Table I was generated for this current imbalance. The model predicted that the current imbalance is responsible for about a 4% drop in the net magnetic force in comparison with the baseline case. The model was then used to evaluate the impact of using a solid, rather than a hollow torpedo. In case 3, the current is once again balanced, and the predicted ALIP net magnetic force at zero flow was 12.2 N. This represents an increase in the net magnetic force of about 7%, which implies that the original hollow torpedo may be saturating for at least portions of the ALIP electrical cycle. The model was then used to evaluate the impact of using an unannealed ALIP torpedo, as presented in case 4. This had a huge negative impact on the ALIP net magnetic force. The magnetic force at zero flow was 2.9 N, about 75% below the baseline value.

The results shown in Table II were generated assuming the same NaK temperature and ALIP frequency as before, but for an RMS input current of 7.01 A. This input current value is consistent with the 40 $V_{rms}$ ALIP data presented in the MSFC test report[2]. The first case modeled assumed a balanced three-phase current. The predicted ALIP net magnetic force at zero flow was 23 N for this baseline case. The model was then used to evaluate the current imbalance issue. The same current imbalance as discussed earlier was applied to the 7.01 $A_{rms}$ input, and the result is shown in Table II, case 2. The model predicted that the current imbalance did not dramatically affect the pump performance in this case. The model was then used to predict ALIP performance at 7.01 $A_{rms}$ with an annealed torpedo. The zero flow ALIP net magnetic force increased to 54.6 N, which is a 137% increase relative to the baseline.

Table I – Summary of Results (325 ˚C NaK Temp., Input Current of 2.47 $A_{rms}$ at 36 Hz, No NaK Flow)

| **Case Description** | **Net NaK Magnetic Force (N)** | **% Diff. Rel. to Baseline (%)** |
|---|---|---|
| 1) Annealed Hollow Torpedo; Balanced Current (BASELINE) | 11.4 | - |
| 2) Annealed Hollow Torpedo; Current *Imbalance* | 10.9 | -4.4 |
| 3) Annealed *Solid* Torpedo; Balanced Current | 12.2 | +7.0 |
| 4) *Unannealed* Hollow Torpedo; Balanced Current | 2.9 | -74.6 |

Table II – Summary of Results (325 ˚C NaK Temp., Input Current of 7.01 $A_{rms}$ at 36 Hz, No NaK Flow)

| **Case Description** | **Net NaK Magnetic Force (N)** | **% Diff. Rel. to Baseline (%)** |
|---|---|---|
| 1) Unannealed Hollow Torpedo; Balanced Current; 7.01$A_{rms}$ (BASELINE) | 23.0 | - |
| 2) Unannealed Hollow Torpedo; Current *Imbalance* | 23.1 | +0.4 |
| 3) *Annealed* Hollow Torpedo; Balanced Current | 54.6 | +137.4 |

**Conclusion:** The model predictions support the present hypothesis that the magnetic properties of the torpedo may be the reason for the ALIP performance issues identified during testing at MSFC. The results indicate that if the torpedo had the expected magnetic properties, the net magnetic forces acting on the NaK fluid may have been more than double the forces experienced during the test. In addition, magnetic saturation of the torpedo might be a concern for ALIP input currents above 2.4 $A_{rms}$. It is important to note that the performance predictions are heavily dependent upon the quality of the assumed material properties used as inputs. The relative permeability of NaK is assumed, and is a key property needed for generating an accurate prediction.

**References:** [1] Adkins H. and Werner J. E. (2010) *Analysis of the Fission Surface Power Annular Linear Induction Pump Design Tools Based on Performance Test Results*, Idaho National Laboratory Technical Report INL/EXT-10-18211. [2] Polzin K. A. et al. (2010) *Performance Testing of a Prototypic Annular Linear Induction Pump for Fission Surface Power*., *NASA/TP-2010-216430*. [3] Webb J. A. (2011) *FSP Handbook for Liquid Potassium, Sodium and Eutectic Mixtures*, not yet published.