

ELECTROMAGNETIC PUMP FABRICATION AND PREDICTED PERFORMANCE

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Abstract – A DOE / NASA team is assessing the state-of-the-art and commercial availability of manufacturing components that may be used in a space nuclear surface power system. The Idaho National Laboratory (INL), in conjunction with Pacific Northwest National Laboratory (PNNL), is designing and building an Electromagnetic (EM) Annular Linear Induction Pump (ALIP). The operational design goals of this EM pump are: operating temperature of 800-825K, a NaK flow rate of 4.3 kg / sec, a 68 kPa pressure head and an operational lifetime of 8 years. This paper discusses the considerations in the design of the pump, aspects associated with the fabrication, and modeling predictions as to how the pump will perform under prototypic conditions.

I. INTRODUCTION

The preliminary design of a Fission Surface Power (FSP) system utilizes a liquid metal cooled fast spectrum reactor system as the primary heat source. Highly reliable, leak-proof liquid metal pumps are needed in the primary reactor coolant loop and secondary power conversion coolant loop. Desirable Liquid Metal Pump (LMP) characteristics include low mass, high efficiency, radiation tolerance and long life. The proposed FSP system operating lifetime is 8 years.

Reliability and integrity of the pump are two prime factors deemed essential for a lunar power system. The operating characteristics of the pump during both steady state and transient conditions also impact the conduct of operations of the overall system. While many of the design details that affect mass and performance of a flight system remain to be resolved, the mass flow rates, pressure parameters and lifetime parameters currently identified for the FSP are within the existing design space of LMPs that have been developed and operated. But because no ALIPs have been built for more than 15 years, it became a programmatic priority to design and fabricate an ALIP pump that could meet the FSP operational design parameters for temperature, flow rate, pressure and efficiency. Overall weight is also a factor in the system design, but is currently considered as a second order

priority at this phase (Technology Demonstration) in the program.

II. Pump Selection and Design II.A. Design Considerations

At the highest level, two basic methods may be considered to circulate the liquid metal coolant: mechanical and electromagnetic (EM) pumps. EM pumps have numerous advantages: there are no shaft seals and therefore may be totally sealed; they have no moving parts other than the liquid metal itself and therefore are free from wear and require no bearing lubrication. Because of these advantages, EM pumps have been selected for numerous liquid metal pumping applications. Mechanical pumps have been omitted from this assessment as it is desirable to avoid wear issues, mechanically induced vibrations, and sealing difficulties associated with incorporating reciprocating or rotating machinery into a liquid-metal flow system

EM pumps are generally categorized as direct current (DC) or alternating current (AC) types. Conduction pumps operate on either AC or DC current, while induction pumps, either single or polyphase, operate only on alternating current. The ALIP, sometimes called the “Einstein-Szilard” pump, was invented by Albert Einstein and Leo Szilard in 1927¹ and is slightly better than all

other polyphase type pump on an efficiency per mass basis. The ALIP design offers a duct that is a circular annulus and can be made from standard tubing or piping, adding to the duct strength and allowing for easy fabrication. The ALIP is the lightest in weight of the induction pump family and has the simplest duct design.

In EM ALIP's, a body force is produced on a conducting fluid by the interaction of an electric current and the resulting magnetic field in the fluid, with the magnetic field of the stator. This body force results in a pressure rise in the fluid as it passes from the inlet to the outlet of the ALIP. This is analogous to the familiar fundamental principal of force on a current-carrying conductor in a magnetic field, the operating principal of many common electromagnetic devices or, in general, the "motor" principal.

The ALIP operates in a manner that is similar to a polyphase induction motor. The pump contains an electromagnetic stator assembly surrounding the annular duct assembly. When power is applied to the three-phase stator winding, a traveling wave is produced in the liquid metal annulus by the magnetic field from the stator. This magnetic field induces voltage in the conducting fluid contained in the duct; as a result of this induced voltage (Lenz' Law) currents will flow in the fluid. These currents interact with the magnetic field of the stator to produce a body force on the fluid, causing it to move through the annular duct, thereby developing pressure. The pressure gradient at any point in the fluid is proportional to the magnetic field strength. The total pressure rise developed by the pump is integral of this pressure gradient over the axial length of flow passages in the pump duct.

There are several significant parameters of importance in an analytical study to determine an ALIP design. Optimizing performance requires a balance of maximum efficiency, reliability, minimum weight, and production feasibility. The most important parameters, once a set of materials and a basic concept have been selected, are: (1) fluid passage cross sectional geometry; (2) duct wall thickness and total magnetic gap; (3) power frequency; (4) duct, fluid passage and annulus diameters; (5) duct and stator length; and (6) velocity and slip (the difference in rotational speed of the fluid and the magnetic field) as determined by the interrelation between power frequency, fluid passage geometry, and duct diameter. In the design process many iterative evaluations of the parametric equations, using an ALIP design computer code licensed to PNNL, are performed to cover the multitude of combinations of these variables. Most of the design equations for electromagnetic pumps relate directly to electrical machine equations, the difference being that the armature in this case is a liquid. Design calculations for

EM pumps are beyond the scope of this paper, but can be found in references 2, 3, 4, 5, and 6 as well as others that are available.

Thin duct walls are desirable to reduce I^2R losses in the duct material, since these losses are directly proportional to duct thickness. Fluid velocity and slip are very important parameters and are established by the fluid passage cross section, power frequency, duct diameter, and pole length. Various combinations of these parameters must be investigated to determine the optimum design.

It is desirable to operate EM pumps at relatively high fluid velocities and moderate to low slip for efficient operation. Velocity, however, is limited by hydraulic loss and Net Positive Suction Head (NPSH). In addition, as slip decreases, the efficiency at the design point eventually goes through a maximum since fluid (slip) loss decreases while winding and duct I^2R loss increases with decreasing slip.

Current density directly affects the winding temperature. Current density goes through a minimum as the slip is decreased due to the load component of current, which decreases while the magnetizing component is increasing. It is desirable to select a velocity, slip, and corresponding flow passage geometry (cross section and diameter) to give peak efficiency and minimum winding current density at the design point. Since these do not occur at precisely the same point, the final design is usually a compromise between efficiency and current density factoring in hydraulic loss and NPSH. Many other things such as material selection, temperature, range, and operational longevity of pump components also have to be factored into the pump design.

The primary design trades considered in the design of the FSP pump include maximizing pump efficiency while keeping the overall size of the pump to a manageable level. Another new design consideration from earlier pump designs is that the pump has to operate in a vacuum, thus implying that the primary heat removal path is through the NaK coolant being pumped. Other considerations include successful operation at high temperature, ability of pump components to tolerate high radiation fields, and optimization of voltage, current, and frequency values to create a fairly robust design.

After several iterations matching total system current, power, weight and frequency optimization studies, a final design was established for the EM pump in July 2008.

II.B. Design Selection

The FSP EM pump selected is designed on three phase power with three circuits each containing four coil sets. The pump duct has no moving parts and no direct electrical connections to the liquid metal containing components. Pressure is developed by the interaction of the magnetic field produced by the stator and the current that flows as a result of the voltage induced in the liquid metal contained in the pump duct. Flow may be controlled by variation of the voltage supplied to the pump windings. Power input and developed pressure at a particular flow vary approximately as the square of the applied voltage. The pump for this system is designed for a nominal supply frequency of 36 Hz and a nominal supply voltage of 72 V. The electromagnetic pump is designed to supply a maximum pressure head of 68.9 kPa to liquid NaK flowing at 4.3 kg/s at approximately 800 K with an adiabatic efficiency of 15 % at nominal flow conditions. A list of the pump characteristics is found in Table I and the overall layout is featured in Figure 1.

TABLE I
 FSP Design Values

Pump Characteristics	Value
Mass	82 kg
Length	69 cm
Diameter	24 cm
Operating Temperature	800-825 K
Nominal Exit Pressure	194 kPa
Developed Head Pressure	58-68 kPa
Fluid Flow	4.0-4.3 kg/sec
Inlet / Exit pipe diameter	5.08 cm (2 in)

III. EM PUMP PERFORMANCE PREDICTIONS

A typical characteristic of space reactor system primary and secondary loops are that they require fairly high coolant mass flow rates with very low operating pressures and low head pressures being developed. The design and thus the predictions for the pump are such that the pump will be operating at its preferable slip yielding the highest efficiency at the defined steady state operating point. The pump is also designed to have a fairly broad slip-efficiency span at peak required flow. Therefore, even if the flow rate or the head pressure is a bit off-nominal, it won't substantially affect the pump performance or cause a significant loss of efficiency. The most critical design

concern is peak flow; flow rates that begin to cause or create pump cavitation will cause pump failure.

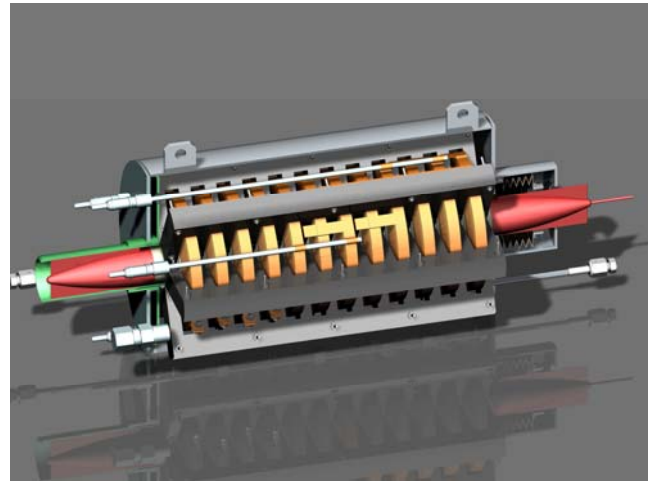


Fig. 1. Three Dimensional Drawing of ALIP

The following four figures (Figs. 2-5) provide information on the pump characteristics under the following basic conditions:

- the pump and NaK are at an operating temperature of 825 K;
- the pump is operating at a set frequency of 36 Hz;
- the pump is attached to a 5.08 cm (2 in) pipe;
- operating loop pressure as approximately 190 kPa; and
- loop pressure drop is less than 50 kPa.

Projected performance parameters featured in the Figs. 2-5 are at slips that yield maximum possible efficiency.

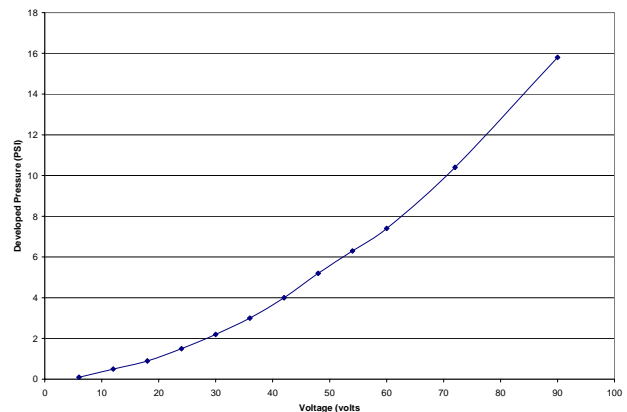


Fig. 2. ALIP Pressure vs. Voltage Performance Predictions at 36 Hz, NaK at 825 K with a 5.08 cm diameter inlet / outlet

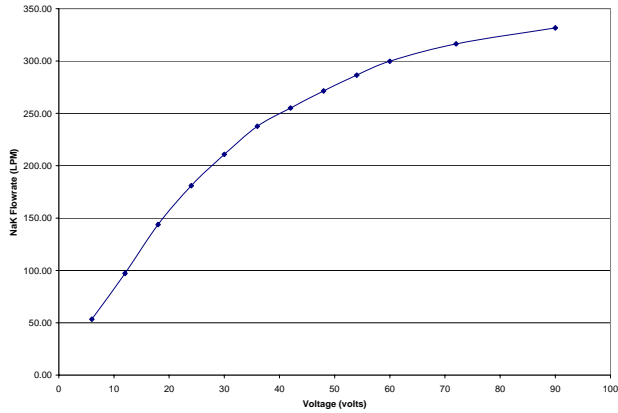


Fig. 3. ALIP Flow Rate vs. Voltage Performance Predictions at 36 Hz, NaK at 825 K with a 5.08 cm diameter inlet / outlet

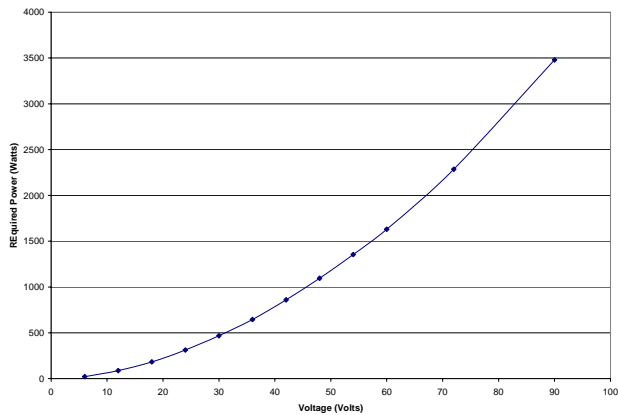


Fig. 4. ALIP Required Power vs. Voltage Performance Predictions at 36 Hz, NaK at 825 K with a 5.08 cm diameter inlet / outlet

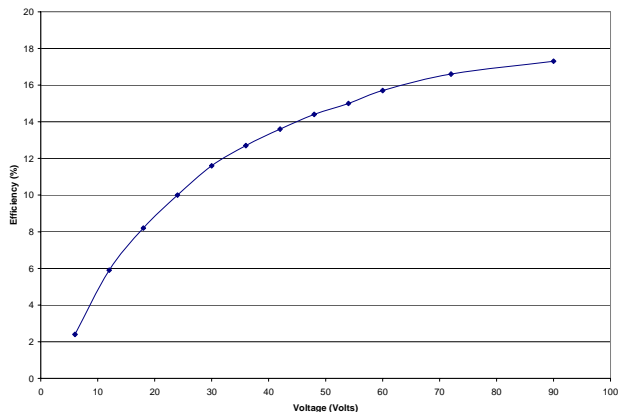


Fig. 5. ALIP Efficiency vs. Voltage Performance Predictions at 36 Hz, NaK at 825 K with a 5.08 cm diameter inlet / outlet

As can be seen from the pump prediction curves above, as the NaK flow rate approaches the desired rate of approximately 4.2 kg/sec, the pump efficiency should be greater than 16%.

IV. FABRICATION

One of the more challenging aspects associated with this effort is in identifying vendors and materials manufacturers to make the ALIP pump components. As stated earlier, no ALIP pumps have been built in the US in more than 15 years so materials or components for the pump are either not readily available or vendors no longer produce the same items as used previously. In several cases, fabrication or coating techniques have to be re-established or new process techniques developed to produce the components having the desired material characteristics or dimensions.

Because this is essentially a one-of-a-kind product, most companies are not interested in taking on the needed assembly and component fabrication processes without substantial development investment up-front. As such, assembly procedures and required assembly hardware and fixtures for the initial units will be developed utilizing INL facilities and craftsman using established laboratory quality acceptance procedures and processes. Final assembly and checkout of the pump is anticipated to be completed in the early spring of 2009. The completed pump will be shipped to NASA Marshall Space Flight Center (MSFC) where it will be installed into a NaK test loop and tested. Data from the operation of the pump in the test loop will provide the data needed to establish the actual pump performance curves.

V. CONCLUSIONS

A new design of an ALIP pump that will meet the operational performance characteristics identified for a fission surface power system has been completed. Initial modeling and analysis indicate that the pump will be able to meet all the established design requirements. Because ALIP pumps have not been built for quite some time, it has been necessary to re-establish or develop new fabrication, coating and assembly processes to make the needed materials and components. Assembly of the pump is proceeding. The pump is planned for installation and testing in a NaK test at NASA MSFC in the spring of 2009.

VI. NOMENCLATURE

EM = Electromagnetic
 ALIP = Annular Linear Induction Pump

NaK = sodium and potassium alloy
FSP = Fission Surface Power
MSFC = NASA Marshall Space Flight Center

VII. ACKNOWLEDGMENTS

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REFERENCES

1. A. EINSTEIN and L. Szilard, "Electrodynamic Movement of Fluid Metals Particularly for Refrigerating Machines," Patent Specification #303065, United Kingdom, application date: December 9, 1928, acceptance date: May 26 (1930),.
2. J. L. VERKAMP and R. G. Rhudy, "Electromagnetic Alkali Metal Pump Research Program," NASA-CR-389, National Aeronautics and Space Administration, Washington, D.C., February (1966).
3. R. S. BAKER and M. J. Tessier, *Handbook of Electromagnetic Pump Technology*, Elsevier Science Publishing, New York (1987).
4. L. R. BLAKE, "Electromagnetic Pumps for Liquid Metals," *J. Nucl. Energy B*, **1**, pp. 65-76, August (1959).
5. A. S. FENEMORE "Linear Induction Pumps for Liquid Metals," *The Engineer*, May 17 (1957).
6. D. A. WATT, "Design of Travelling Field Induction Pumps for Liquid Metals," AERE-R/M-144, Association Energy Research Establishment, Harwell, September (1957).