

# Design of a Mechanical NaK Pump for Fission Space Power

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Alkali liquid metal cooled fission reactor concepts are under development for spaceflight power requirements. One such concept utilizes a sodium-potassium eutectic (NaK) as the primary loop working fluid, which has specific pumping requirements. Traditionally, electromagnetic linear induction pumps have been used to provide the required flow and pressure head conditions for NaK systems but they can be limited in performance, efficiency, and number of available vendors. The objective of the project was to develop a mechanical NaK centrifugal pump that takes advantages of technology advances not available in previous liquid metal mechanical pump designs. This paper details the design, build, and performance test of a mechanical NaK pump developed at NASA Marshall Space Flight Center. The pump was designed to meet reactor cooling requirements using commercially available components modified for high temperature NaK service.

## Nomenclature

<i>A</i>	=	Amps
<i>ATC</i>	=	ALIP Test Circuit
<i>DAQ</i>	=	Data Acquisition System
<i>FTL</i>	=	Feasibility Test Loop
<i>FPS</i>	=	Fission Power Systems
<i>Hz</i>	=	Hertz
<i>kg/s</i>	=	Kilograms per second
<i>L/min</i>	=	Liters per minute
<i>mm</i>	=	Millimeter
<i>MSFC</i>	=	Marshall Space Flight Center
<i>N-m</i>	=	Newton-meter
<i>NaK</i>	=	Sodium-potassium eutectic alloy
<i>rpm</i>	=	revolutions per minute
<i>SmCo</i>	=	Samarium-Cobalt
<i>SNAP</i>	=	Space Nuclear Auxiliary Power
<i>TDU</i>	=	Technology Demonstration Unit
<i>T<sub>C</sub></i>	=	Curie Temperature
<i>T<sub>max</sub></i>	=	Maximum recommended operating temperature
<i>UHP</i>	=	Ultra-high purity
<i>UHV</i>	=	Ultra-high vacuum
<i>W</i>	=	Watts

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## I. Introduction

Space nuclear power systems using liquid alkali metal working fluids have traditionally utilized electromagnetic linear induction pumps for flow rate and head pressure requirements. Although advantageous in several respects induction pumps do have some limitations such as undesirably low efficiency (under 10%) at smaller scales, relatively high mass, and limited suppliers. Therefore, re-examination of a mechanical alkali metal pump designs for space nuclear power system needs was initiated. This paper details development at NASA Marshall Space Flight Center (MSFC) of a mechanical pump for sodium-potassium (NaK) eutectic alloy as an alternative to electromagnetic pumps to support the Fission Space Power (FSP) Technology Demonstration Unit (TDU).

## II. Mechanical Pump Development

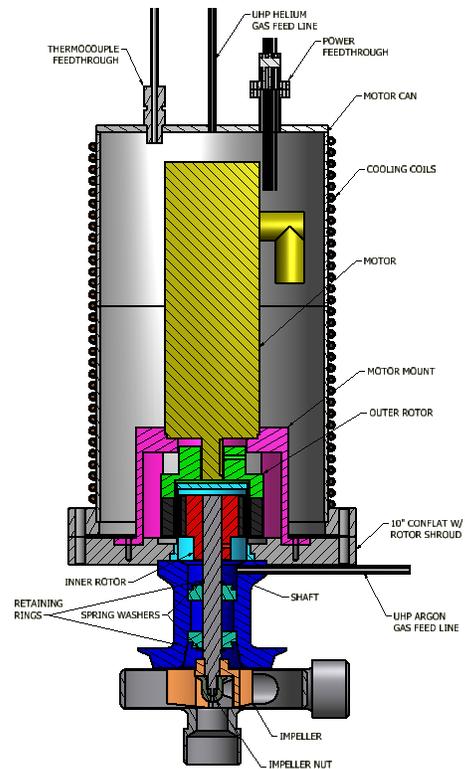
### A. Previous Mechanical NaK Pump Efforts

The application of mechanical liquid metal pumps for space nuclear power systems is not a new concept. In the mid-1960s' NASA Lewis Research Center (present day NASA Glenn) contracted the development of a mechanical NaK pump to Aerojet for the SNAP-8 program.<sup>1</sup> A significant amount of development work resulted in a pump that operated to over 50,000 hours of accumulated test time.<sup>2</sup> Initial efforts to pump liquid metals used mechanical systems; however, the corrosive nature of liquid alkali metals (particularly when containing a high concentration of dissolved oxygen, nitrogen, and carbon) made it difficult to maintain adequate integrity of seals, joints, and welds. In addition, early rotary feed-through component designs had limited performance characteristics and required numerous complicated bearings designs in order to meet performance requirements.<sup>2</sup> As a result, linear induction pumps became widely popular due to the lack of moving parts and seals required by mechanical pumps at the time.

The current mechanical pump designs are based on lessons learned from previous pump programs. The Feasibility Test Loop (FTL) is a NaK circuit currently in operation at NASA MSFC to support various liquid metal handling and characterization tests.<sup>3</sup> A commercial water pump was modified to provide head and flow-rate requirements needed for the test loop. The basic design took advantage of several modern technologies not available to the SNAP-8 pump designers and has successfully operated for several months intermittently. The FTL pump design was the basis for developing the near-flight prototypic TDU mechanical pump design.

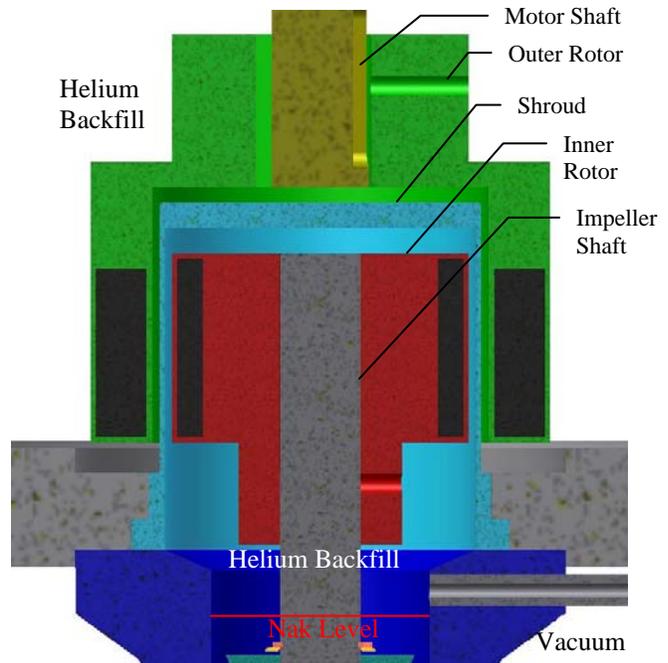
### B. Design Process

The TDU test matrix takes into account a wide range of volumetric flow rates and pressure head requirements in order to effectively demonstrate prototypic system performance at both nominal and off-nominal operating conditions. Based on the TDU requirements, the pump must be capable of operating at high temperature, in contact with the NaK working fluid, and surrounded by hard vacuum. After completion of a literature review and basic trade study a centrifugal pump (volute and 3-vane impeller) was selected based upon high efficiency (typically 55%), material specifications, and performance requirements<sup>4</sup>. The desired nominal pump requirements include handling NaK at 550 °C, a volumetric flow rate of 144 L/min (mass flow rate of 4 kg/s), a head pressure of 4 m, an ultimate efficiency of between 20-25%, operation in vacuum less than  $1 \times 10^{-3}$  Torr, and a minimal service life of approximately 1,500 hours. High-temperature, corrosive NaK limits candidate materials that can withstand the environment. Subsequently, type 316 stainless steel was selected due to its well known behavior, relatively low cost, ease of manufacturing, and ease of welding. The final pump design schematic is illustrated in Figure 1. Like the previous NaK mechanical



**Figure 1. Conceptual design of the mechanical NaK pump.**  
*The alternative mechanical NaK pump proof of concept design.*

pump designed by Bradley, the basic pump design incorporates a vertical impeller shaft that allows for the loop working fluid to act as the bearing lubricant. Several design iterations were required in order to adequately simplify the design, fabrication, and assembly methodology. Budget and schedule constraints required that a number of trade-offs be implemented that would ultimately make the prototype pump somewhat flight-like in design. For example, a vacuum-grade, high-service temperature motor was exceedingly expensive and had a long lead time. Therefore, it was decided to utilize a commercial-grade brushless stepper motor with resolver that would be housed in a motor can that is then back-filled with ultra-high purity (UHP) helium. The motor operates nominally at a rotational speed of 1750 rpm with a  $\pm 25\%$  rpm variability that is required to simulate off-nominal performance in the TDU. The motor can use an ultra-high vacuum (UHV) capable conflat seal with a copper gasket to ensure sealing while operating in a vacuum environment. The UHP atmosphere will thermally couple the motor to the can wall, which will subsequently reject heat produced during operation to a water cooled copper coil that surrounds the can. The can surface is maintained at a constant temperature by use of an external water chiller.



**Figure 2. Rare Earth Magnet Rotor Assembly.** *The outer rotor attached to the motor shaft rotates which couples to the inner shaft that turns the impeller.*

One of the key technologies that allows for fully sealed yet simplistic mechanical pump design is the 316 stainless steel clad Samarium-Cobalt (SmCo) rare-earth permanent magnet rotor assembly. The outer rotor is attached to the motor drive shaft, while the inner rotor is attached to the impeller drive shaft and the two are magnetically coupled when aligned. The rotor assembly provides up to 10 N-m of torque between the outer and inner rotors without slipping, which sufficiently provides a margin above nominal steady state operation and just below the peak motor start-up torque 11.6 N-m. The isolation barrier separating the inner and outer rotor is known as the shroud. The shroud was welded into the motor can attachment flange allowing for gas, vacuum, NaK wetted surfaces, and helium to be separated by one isolation barrier as illustrated in Figure 2. This solution eliminates the need for ferro-fluidic or cable feedthroughs that are usually required to separate the motor from the hot working fluid. The shroud houses the inner rotor, which is separated from the NaK by an UHP helium gas blanket. The helium blanket volume is controlled so that the bearings remain emersed in NaK, yet minimize viscous losses by preventing NaK from entering the narrow gap between the inner rotor and the shroud.

One possible disadvantage of using the rotor is that the maximum recommended operating temperature ( $T_{max}$ ) is limited by the high temperature demagnetization of the SmCo permanent magnets. The manufacturer  $T_{max}$  is limited to approximately 280 °C; however,  $Sm_2Co_{17}$  magnets have the highest Curie temperature and magnetization among all rare earth magnets. Numerous other  $Sm_2Co_{17}$  vendors list  $T_{max}$  as high as 350 °C; however, the nominal NaK temperature of 550 °C represents roughly 70% of the Curie Temperature ( $T_c$ ). Therefore, the rotor assembly will be designed to incorporate a longer conduction path from the NaK in addition to active external cooling of the pump housing in order to maintain the magnet temperature just below  $T_{max}$ . A simple heat transfer analysis was performed to estimate the appropriate shaft length and external cooling requirements to ensure appropriate inner rotor temperatures are maintained. The 15.875 mm shaft is centered by two stainless steel tapered roller bearings in a dual opposed configuration that are mounted within the pump housing. The bearings are submerged in NaK to act as lubricant but also prevent oxidation. The proper fluid level is maintained with a pressurized UHP helium cover gas that is dynamically controlled as a function of NaK temperature.

Early in the desing process strict tolerance control requirements were established to allow for dynamically balanced high-speed rotating components and tight fit spacing between components once assembled. It was also critical that tight tolerances be maintained in component alignment along the longitudinal axis of the entire pump assembly, while still allowing sufficient margin to accomodate thermal swelling and variation in tolerance. For example, the 1 mm gap between both the outer-rotor/shroud and the inner-rotor/shroud was of particular importance since this location would experience considerable thermal swelling while rotating at a high shaft speed.

### III. Fabrication and Performance Testing

#### A. Prototype Assembly

The mechanical NaK pump prototype was assembled once a variety of acceptance tests were applied to the majority of the components. Modifying off-the-shelf components allowed for not only a rapid design turn around time but also minimal schedule slips and significantly reduced manufacture costs. The pump body, impeller shaft, and motor mount were the only custom designed and fabricated components in the pump assembly. An iterative modification process was initiated in order to correct assembly clearance issues due to variation in manufacturing tolerance. The assembled mechanical pump and motor can is shown in Figure 3. After assembly, the motor was operated in air to maximum rotational speeds for short periods of time to verify fit checks and dynamic balancing. The motor can assembly was leaked checked and water coolant system operated. Once initial system check-out trials were completed the thermocouples were attached to several locations on the motor, pump housing, motor can, and volute in order to integrate into the instrument and control system.



**Figure 3. Mechanical NaK pump prototype.** *Left is the motor can and to the right is the motor- pump.*

#### B. Instrumentation and Control

The pump is fully instrumented to monitor and record various location temperatures, motor speed, and flow rate using the data acquisition (DAQ) system. The motor controller is used to control and measure motor shaft rotation speed and the electrical load needed to drive the motor. Pressure taps at the pump inlet and outlet coupled to pressure transducers will allow for pressure measurement across the pump, volumetric flow rate is measured with an electromagnetic flow meter, and average fluid temperature is obtained using an array of thermocouples at inlet and outlet locations. The DAQ system continuously measures and records data at a rate of 1 Hz.

#### C. Performance Test Matrix

The pressure rise across the pump, flow rate, and motor input power measurements as a function of shaft rotation speed will be used to determine the pump performance envelope. After assembly the pump will be integrated into the ALIP Test Circuit (ATC) at MSFC. The ATC is a fully instrumented flow loop that utilizes a valve that varied the flow area in order to determine flow rate and head data as a function of shaft rotational speed. The desired test matrix includes testing at shaft rotational speeds of 1300-2200 rpm (nominal 1750 rpm), temperature at 550 °C, a volumetric flow rate of 70 to 200 L/min, a head pressure of 2 to 5 m, for a cumulative service life of 1500 hours. The resulting pump curves for the volute and impeller provided by the manufacture at the desired flow rate, pump head, and shaft rotation speed resulted in an estimated efficiency of approximately 30%. Input current required to drive the motor under steady-state conditions will vary from 2.85 to 6 A, with a peak of 9 A at start-up based on provided manufacturer specifications. After the test matrix was completed a thorough data reduction process was completed. Best fit regressions were applied to the measurements in order to develop appropriate expressions for pump performance as a function of changing operating parameters.

### IV. Conclusion

Successful design and fabrication of a mechanical pump was demonstrated with performance testing to follow. Most importantly, the development of the TDU scale mechanical NaK pump demonstrated that advances in technology has allowed for additional options when liquid metal flow loops are under consideration for use, and that electromagnetic pump designs are no longer the only viable option for primary coolant flow.

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## References

<sup>1</sup>Colker, C. P. et al., "Design and Development of a Canned-Motor Pump for High Temperature NaK Service in SNAP-8," Aerojet-General Corp, NASA CR 72823, April 1971.

<sup>2</sup>Mah C.S. and Pope J.R., "Operational Experience with NaK-Lubricated Journal and Thrust Bearings for a NaK Pump-Motor Assembly", *Proceedings of the Energy 70 Conference*, Paper 709143, Vol. 1, American Nuclear Society, Hinsdale, IL, 1970.

<sup>3</sup>Bradley, D., "Sealed Mechanical Pump for High Temperature NaK," *Proceedings of Nuclear and Emerging Technologies for Space 2011*, Paper 3559, Vol. 1, American Nuclear Society, Albuquerque, NM, 2011.

<sup>4</sup>Stepanoff, A. J., "Centrifugal and Axial Flow Pumps," Second Edition, Krieger Publishing Company, Malbar, FL, 1993.

<sup>5</sup>Wilcock, D. F. and Booser, E. R., "Bearing Design and Application," First Edition, McGraw-Hill Company, York, PA, 1957.