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PRIMARY LOOP SIMULATION OF THE SP-100 SPACE NUCLEAR REACTOR

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ABSTRACT

Between 1983 and 1992 the SP-100 space nuclear reactor development project for electric power generation in a range of 100 to 1000 kWe was conducted in the USA. Several configurations were studied to satisfy different mission objectives and power systems. In this reactor the heat is generated in a compact core and refrigerated by liquid lithium, the primary loops flow are controlled by thermoelectric electromagnetic pumps (EMTE), and thermoelectric converters produce direct current energy. To define the system operation point for an operating nominal power, it is necessary the simulation of the thermal-hydraulic components of the space nuclear reactor. In this paper the BEMTE-3 computer code is used to EMTE pump design performance evaluation to a thermal-hydraulic primary loop configuration, and comparison of the system operation points of SP-100 reactor to two thermal powers, with satisfactory results.

1. INTRODUCTION

One of the main requisites to fully reach the objectives of any space mission is an adequate power supply. To date, the main known power sources for space applications are: solar cells, chemical batteries, radioisotope thermal generators (RTG) and nuclear reactors. Each one of those has characteristics and limitations that define the choice of the system for the desired mission. In terrestrial orbit the desired power is higher than 40 kWe and for the deep space missions the requirements are above 20 kWe, nuclear reactor is the best possible solution for electricity generation, like shown in Fig. 1 [1].

The TERRA project aims the development of equipment and systems based on the application of fast micro-reactor technology for generating electricity in space and special land applications. The TERRA project is being conducted at the Institute for Advanced Studies (IEAv) [2]. Among the several types of reactors being considered, one that is suitable is the SP-100 from the 80's. Previously, in another Brazilian case study (RESPA Project) the SP-100 was also considered as a study option [3].

In the electromagnetic thermoelectric pump (EMTE) the current is generated by thermoelectric convertors that transform the temperature difference imposed over its terminals into electric current. This electric current circulates around the magneto made of the Hiperco-27, generating the magnetic field that is conducted by the magneto itself. The interaction of the current and the magnetic field generates the desired magnetic force that pumps the liquid lithium in the primary fluid loops. In this way the EMTE pump controls the working metallic fluid flow as a function of the reactor thermal power. This is the process that is simulated by the BEMTE-3 program [4]. In this paper the BEMTE-3 is used to EMTE pump design performance evaluation to a thermal-hydraulic primary loop configuration, and comparison of the system operation points of SP-100 reactor to two thermal powers.

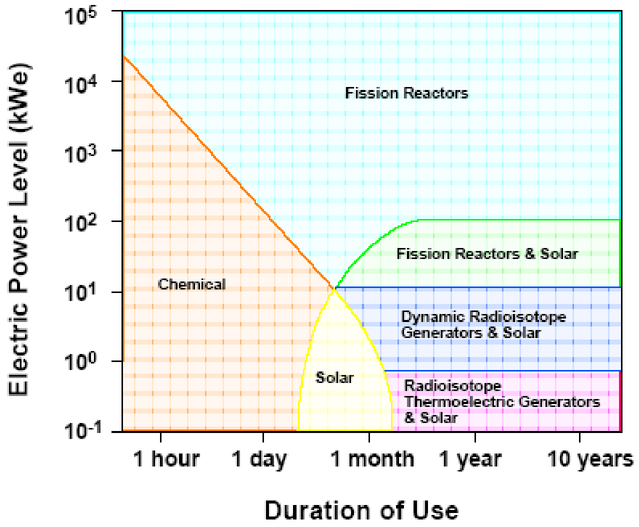

Figure 1. Application range of energy sources in space.

2. BEMTE-3 PROGRAM

The simulation of a space nuclear reactor of the SP-100 type requires the operation knowledge for the thermo electric convertors, electrical circuits, magnetic field, cooling loops, heat exchangers and heat pipe radiators, all related to the pump operation as a function of the nuclear reactor power. In this way, one may to relate the operation point for the nuclear reactor and the pump operation. The BEMTE-3 performs all types of electromagnetic pumps calculation by, interactively, solving the system equations. It takes into consideration the pressure losses in the flow loops as defined by the design and the geometry of the system (Reynolds' number function), calculates the necessary pump flow rate and correlates that with the nuclear reactor thermal power. The BEMTE-3 program is a PC version of the BEMTE computer code (FORTRAN version) developed in the 90's [3].

The BEMTE-3 program models the thermo electric convertor through a calculation of the temperature distribution in each of the thermo-electric elements. For that, it solves the heat conduction differential equation, obtaining the values for the internal resistance and the Seebeck tension generated by the thermo electrical convertors as a function geometric data, conversion parameters and the temperature difference imposed over its terminals, which in turn is a function of the reactor thermal power. After that, the electric current that circulates in the EMTE pump channels is calculated. The program then proceeds to calculate the magnetic field generated as a function of the electric current and the dynamic head produced by the EM pump, which is obtained by the magnetic field interaction with the electric current in each channel, according to the equations developed by Barnes and Blake [5, 6].

3. EMTE PUMP

The structural scheme used for the EMTE pumps eliminates the need for permanent magnets for the generation of the magnetic field, allowing them to be compact and so considerably reducing the its total weight. This scheme uses Hiperco-27 as ferromagnetic material, which has a high Curie temperature (about 1240 K). The magnet is used on approximated S form, and the channels for the tubes of the fluid to be pumped are between the magnet legs. Coupled thermoelectric converters are used for generation of the electric current that goes through the fluid channels and conductive plates, closing the electric circuit, involving the central part of the S type magnet and inducing, therefore, a magnetic field. The interaction between the magnetic field and the electric current produces the force to control the working fluid flow loop. The operation scheme of the EMTE pump of the SP-100 reactor can be seen in detail in Fig. 2 and 3 [7]. Table 1 shows the SP-100 EMTE pump data simulated [8].

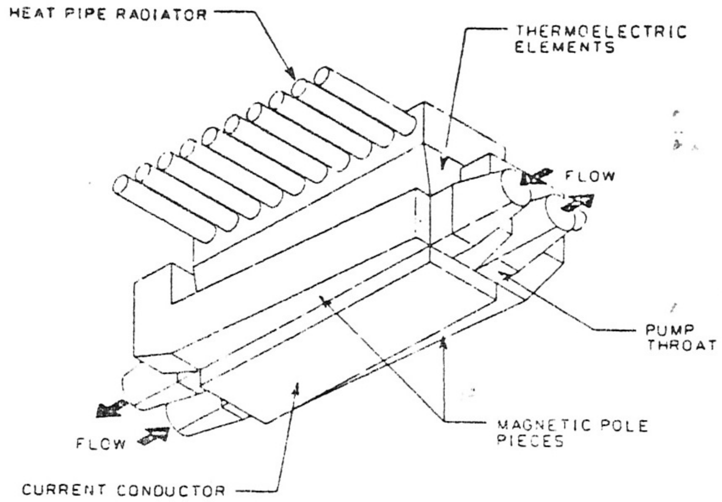

Figure 2. EMTE pump simulated.

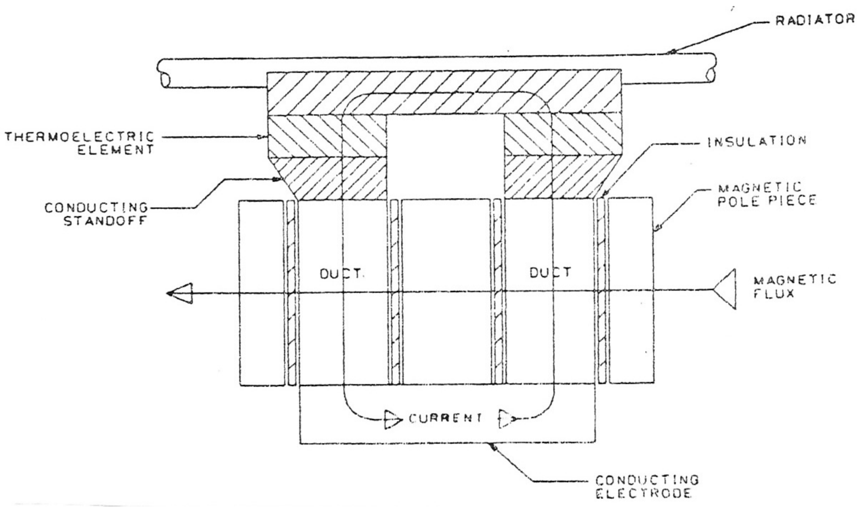

Figure 3. Cross section of the EMTE pump.

Table 1. SP-100 EMTE pump parameters

Duct width	1.784 cm
Primary duct height	2.676 cm
Active pump length	25.4 cm
Duct wall thickness	0.076 cm
Thermoelectric length	0.30 cm
Thermoelectric material	SiGe/GaP
Magnet width	1.148 cm
Magnet height	7.41 cm
Magnet material	Hyperco-27
Magnet Curie point	1240 K

4. SP-100 PRIMARY LOOP SIMULATION

The SP-100 space reactor for electricity generation in the range of 100 to 1000 kWe was developed, in the USA, between 1983 and 1992. In this concept heat generated in the core of a compact fast reactor is extracted by lithium flow. This heat is transferred through closed loops to a set of thermoelectric convertors that produce electric energy. The flow of lithium loops is maintained by electromagnetic thermoelectric pumps. These types of pumps are highly suitable for pumping liquid metal coolants (such as lithium) in a high power density reactor core. These pumps have high reliability and low maintenance needs, because they have no moving parts and because of which make them, desirable item for space systems.

Figure 4 shows the primary loop configuration studied of the SP-100 nuclear space reactor system [9]. In Table 2 some of the main characteristics of the SP-100 are presented [8]. Figure 5 presents schematically the thermal hydraulic balance of plant for the SP-100 space reactor. The reactor core is cooled by the primary loops, and the excess heat is radiated to space. The EMTE pump controls and maintains the lithium flow in primary loop.

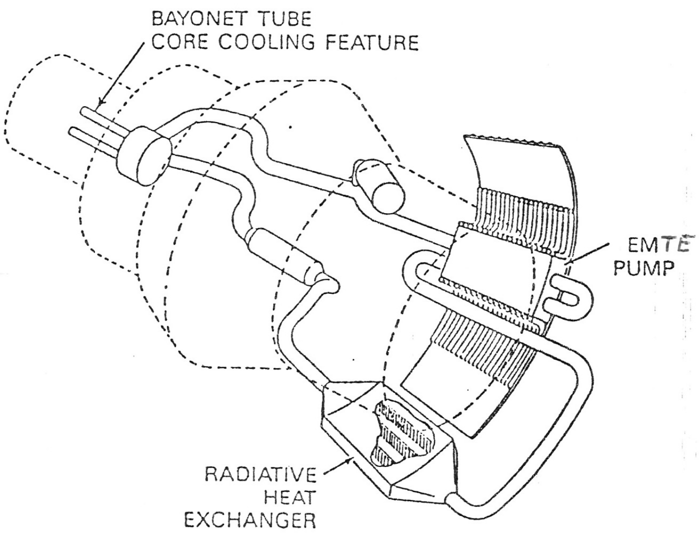

Figure 4. SP-100 Primary loop simulated.

Table 2. SP-100 main Project characteristics

Objective	Electric generation
Project start	1983
Nominal power range	100 a 1000 kWe
Nuclear reactor type	Liquid metal fast reactor
Electric generation system	Thermoelectric conversion
Heat rejection system	Heat pipe
Reactor main fluid coolant	Lithium
Main flow drive	EMTE pump

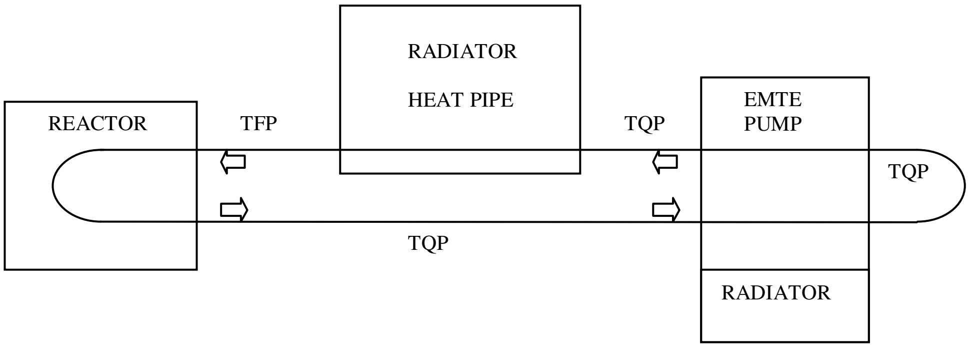

Figure 5. Thermal hydraulic balance of SP-100 simulated.

4.1. EMTE Pump Temperature Difference

BEMTE-3 gets the hot primary reactor temperatures TQP (hot – core outlet temperature) as function of the thermal power reactor for loop (Pot), TFP (cold – core inlet temperature) here TFP is assumed to be equal to 1000 K, mass flow rate (m), and specific heat of liquid lithium (Cp), by Eq. 1

$$Pot = m\, Cp\, (TQP - TFP) \quad . \qquad (1)$$

Considering Fig. 3 and 5, it may be noted that the temperature difference imposed on the poles of the thermo-electric element is caused by the difference between the hot primary fluid and the pump radiator temperatures (TQP-TR). Here TR is assumed to be equal to 500 K.

Figure 6 presents the simulated temperature difference (TQP-TR) as function of the primary lithium mass flow rate, for two thermal powers reactor for loop (400 kW – black points and 800 kW – blue points). Note that as the lower the flow rate is, the greater is the temperature difference imposed on the thermo elements terminals.

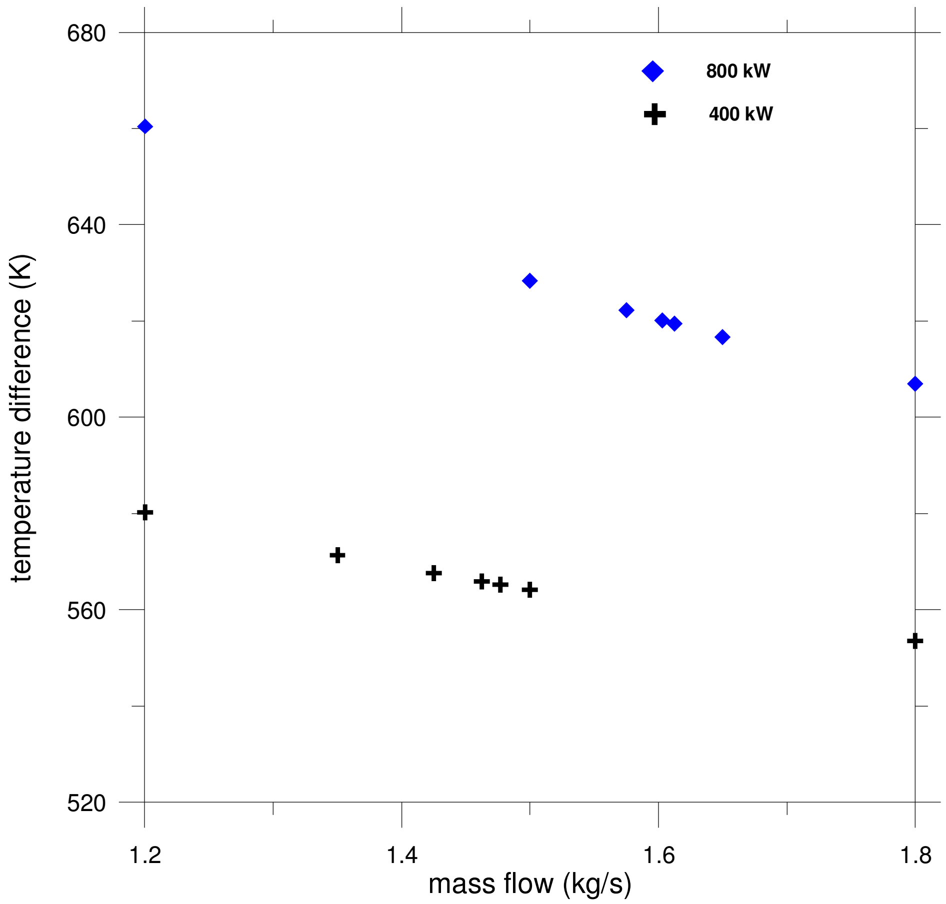

Figure 6. EMTE pump temperature difference.

4.2. EMTE Pump Generated Electric Power

The thermo-electric elements in the EMTE pump generate the electric current as a function of their electric properties (Seebeck, Thomson, etc.), geometric design data and temperature difference imposed over them. The P type thermo-electric element generate electric current in the same direction to the heat (hot temperature to cold temperature) and the N type thermo-electric element generate electric current in the opposite direction to the heat (cold temperature to hot temperature)

Considering Fig. 3 and 5, it may be noted that the temperature difference is caused by the difference between the hot primary fluid and the pump radiator temperatures (TQP-TR). The total electric current is the summation of the independent electric current generated by each of the two thermo elements (P and N thermo-electric elements).

Figure 7 presents the electric current as function of the temperature difference (TQP-TR), for two thermal reactor powers for loop (400 kW – black points and 800 kW – blue points). Note that if the imposed temperature difference over the thermo elements increases, the generated current increases, too.

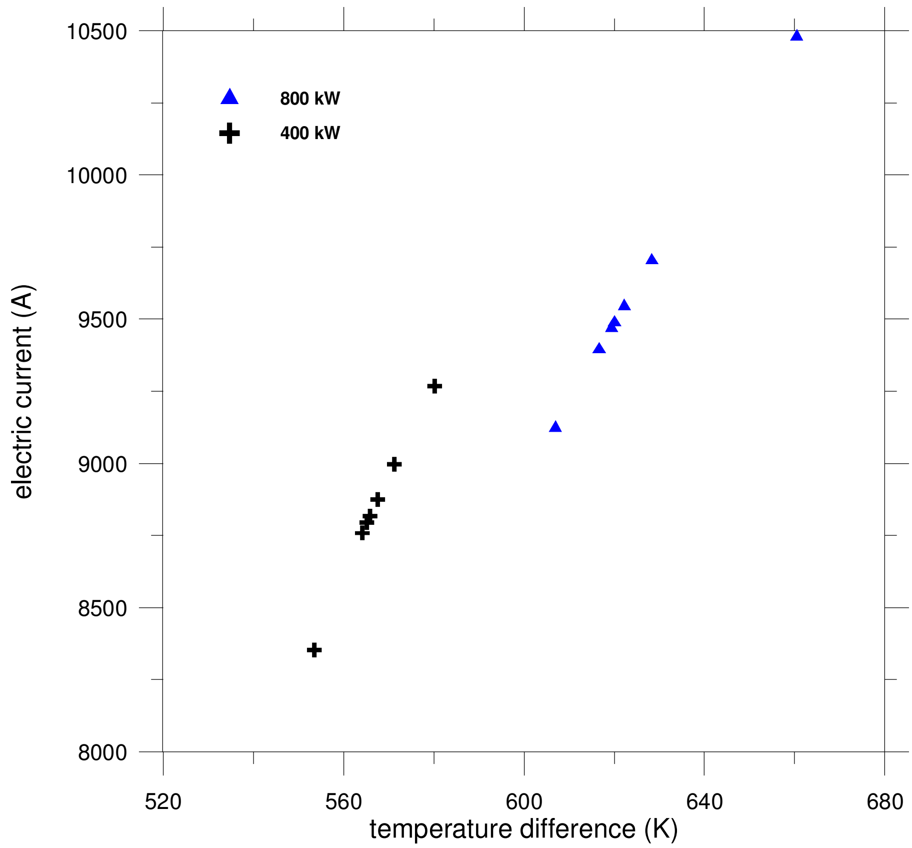

Figure 7. EMTE pump electrical current.

4.3. EMTE Pump Magnetic Field

As the EMTE pump geometries are rectangular Maxwell's equations can be simplified, while maintaining reliability [3]. In the BEMTE-3 program the magnetic field (B) generated by the EMTE pump is obtained by the field equation, Eq. 2

$$B = \frac{u N_{esp} I}{2d} \quad . \qquad (2)$$

Where, u is the vacuum magnetic permeability (here it is assumed to be equal to the air), N_{esp} is the number of coil turns (which for S type EMTE pump is equal to 1), I is the field current (which for this simulation is the total generated current), and d is the duct width.

By Eq. 2 it is clear that the magnetic field is a function of the generated electric current and the geometric parameters designed in the S type EMTE pump. Also some experimentally obtained correction factors are included in this simulation [10].

Figure 8 presents the simulation results for the magnetic field plotted as a function of the pump electric current. Note that then the generated current increases, the magnetic field in the EMTE pump increases, too.

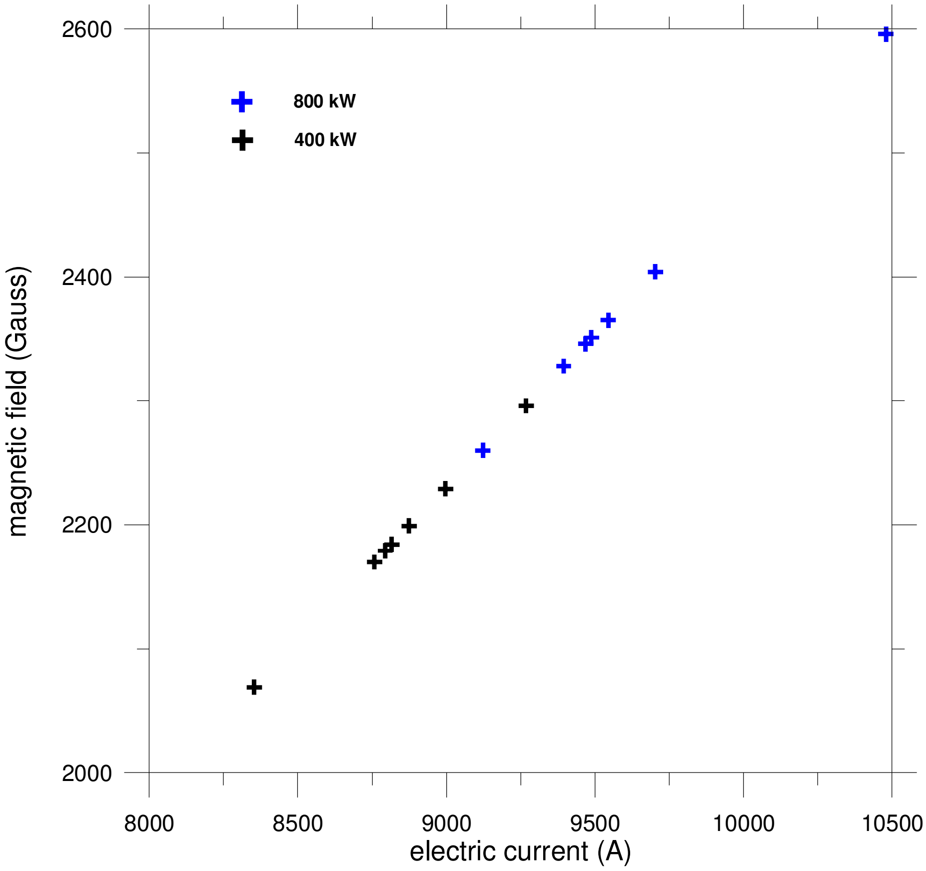

Figure 8. EMTE pump magnetic field.

4.4. System Operating Points

The system thermal hydraulic operating points are produced by the BEMTE-3 program. First, the force resulting from the interaction between magnetic field and main electric current is obtained by Eq. 3. Where, F is the force, B is the magnetic field, and I_e is the useful electric current which depends on the electric current generated by the thermo-electric elements and liquid lithium mass flow rate. For this S type EMTE pump, d is the channel width, and b is the channel height of the primary. The pump head (P) is defined by Eq. 4

$$F = BI_e b \quad , \tag{3}$$

$$P = F/(db) \quad . \tag{4}$$

Figure 9 shows the load curve of the SP-100 primary loop, for a tube length of 10 m and a medium diameter of 1.91 cm (continuous line), and EMTE pump head as function of the primary lithium mass flow rate, for two thermal powers reactor for loop (400 kW – black points and 800 kW – blue points). The intersection of these curves with the pump dynamic high points as a function of the mass flow determine the operation points of the system, namely 1.48 kg/s to 400 kW and 1.603 kg/s to 800 kW. In all, the BEMTE-3 program was considered to produce satisfactory results [3].

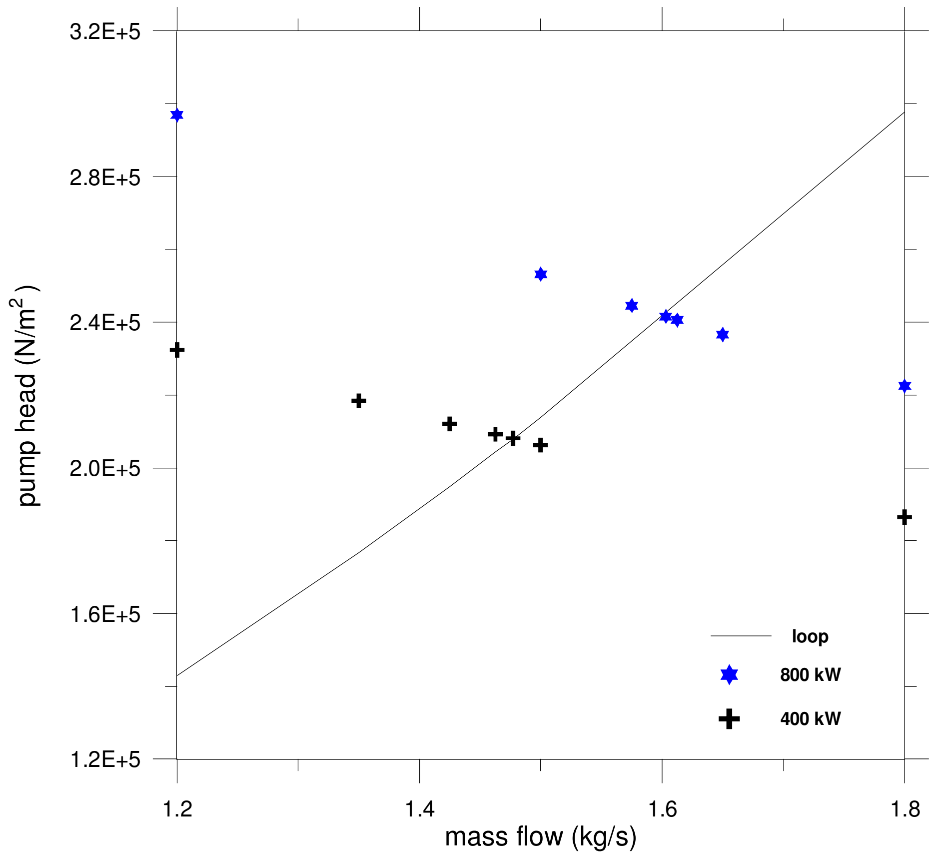

Figure 9. EMTE pump curve for the SP-100 primary loop.

5. CONCLUSIONS

The SP-100 project of space nuclear reactors can be used for electric power generation in a range of 100 to 1000 kWe. There are several configurations to satisfy different mission objectives and power systems.

Without moving parts and thus with high reliability, the electromagnetic pump may control and pump an electrically and thermally conductivity fluid flow in a closed loop. That characteristic makes the electromagnetic pump highly desirable to be used in a system that will not undergo maintenance during its useful life, such as the ones intended to operate in space.

In the electromagnetic thermoelectric pump the current is generated by thermoelectric convertors that transform the temperature difference imposed over its terminals in to electric current. This electric current circulates around the S type magneto made of the Hiperco-27, generating the magnetic field that is conducted by the magneto itself. The interaction of the produced current and the magnetic field generates the desired magnetic force that pumps the liquid lithium in the primary loop (in this specific case). In this way the EMTE pump controls the working metallic fluid flow as a function of the reactor thermal power. This is the process that is simulated by the BEMTE-3 program, with satisfactory results.

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