SPACE PROPULSION 2024
GLASGOW, SCOTLAND | 20 – 23 MAY 2024

TOWARDS INTERPLANETARY JOURNEYS : MODELLING OF A NEP SYSTEM WITH ECOSIMPRO

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KEYWORDS: NEP system, nuclear propulsion, propulsion components, Rankine thermal conversion system, power distribution unit, EcosimPro modelling.

ABSTRACT:

Currently, nuclear reactors, for in-space applications can be used in both Nuclear Thermal Propulsion (NTP) and Nuclear Electric Propulsion (NEP) systems. In the first case, the reactor is used to heat the propellant that is then expelled through a rocket nozzle to generate thrust. While the latter allows the generation of electrical power, by means of a thermal conversion system, where heat from the reactor is transferred to a working fluid which moves a turboalternator, providing power to electric thrusters. NTP systems offers high thrust if compared to NEP, which in return are more efficient. The choice between these two systems depends on the mission requirements. The present work focuses on developing a model in EcosimPro environment for a NEP system based on a Rankine cycle thermal power conversion. The model developed aims to be used as a design tool to represent the main subsystems in an NEP system. Customs OHB components were developed and linked to those already available in EcosimPro/ESPSS library. The model is tested on a test-case scenario to showcase all the data which is capable to provide. Additional considerations on mass estimation and a comparison approach with Solar Electric Propulsion Systems (SEP) are proposed.

1. Introduction

Nuclear technology represents a valuable resource for future propulsion in-space applications. Every space mission, especially towards the edge of the solar system, involves the need of a reliable power source able to compensate for the criticalities associated to solar electric power production. To facilitate exploration of other planets, the usage of a Nuclear Electric Propulsion (NEP) system can grant increased performance. It allows for significantly reduced travel time if compared to solar electric propulsion spacecrafts, while maintaining reasonable initial mass. Shorter travel time allows for a decrease of risks related to radiation, microgravity and other problems linked to long-duration exposure in the space environment. Experience to date is still limited but great interest is seen from different companies and space agencies. Both NASA and ESA are currently studying NEP theologies for future missions. In this context, OHB is actively improving the in-house knowledge on NEP systems. A typical NEP system can be schematized into six main subsystems: nuclear reactor, electric thrusters, thermo-electric conversion system, control logic component, battery pack and power distribution unit. In simulating the overall system is therefore fundamental to being able to accurately predict how the components interacts each other to obtain the overall performances under different mission scenarios.

NEP subsystems were developed in EcosimPro environment and then integrated together in an overall system model. The overall model will allow to perform different simulations by implementing mission scenario and observing the behaviour of each component. The present work will focus on the model and the simulation environments under development used to perform a performance analysis on NEP systems. The main purpose is to model the nuclear reactor capabilities in transferring heat to a fluidic network which will allow the generation of electricity by means of a thermo-electric conversion system. Heat exchanges due to the reactor, between fluids and cooling effects by means of space radiators are taken into account. Due to its capabilities EcosimPro allows for the interconnection of these multidomain environments. ESA European Space Propulsion System Simulation (ESPSS) fluidic library provides components to describe the fluidic network of the system. These components and custom ones can be connected to an OHB custom made library called EPS (Electric Propulsion System) to allow for the definition of all the subsystems stated. The model is presented throughout Sec. 2 to 5. The results obtained are able to describe the power produced by the nuclear reactor, and its capabilities in operating an electric propulsion system during a simulated mission scenario (Sec. 6). Additionally preliminary mass estimation considerations are presented in Sec. 7. Sec. 8 presents a sample simulation to showcase the main results the current model is capable to provide. Finally future developments are discussed (Sec. 9).

2. NEP System Architecture and Modelling

A typical NEP system involves the conversion of thermal power from a nuclear reactor to electrical power, used for the whole spacecraft operability.

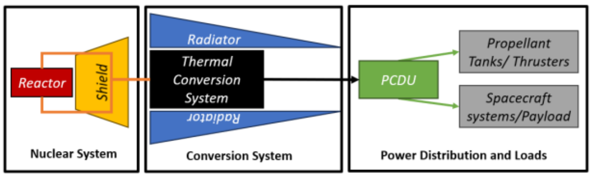

Figure 1. Schematic of a generic NEP system

A NEP typical architecture is presented in Fig. 1, here the reactor is connected to a primary fluid loop (i.e., the coolant). The primary fluid is pumped into the reactor where it heats up. The fluid exchange heat (typically in a heat exchanger) with a secondary fluid. The latter is typically used in a Bryton or Rankine cycle. As a result, the thermal power from the reactor core is used to move a turbine, which by means of an alternator, provides electric power to the power distribution unit of the spacecraft. Here power is used for operating electric thrusters as well as provide necessary power to all other spacecraft components.

Such complex system can be divided into smaller components. Given the capabilities of EcosimPro and especially of the ESPSS library, a simplified model can be defined in order to simulate the behaviour of such a system. The main idea behind this work is to develop a tool capable of providing useful information on the design of an NEP system, specifically looking at the power production/consumption of the spacecraft during a predefined mission profile. To do so the following components must be implemented and linked together in EcosimPro:

- Reactor
- Primary Fluid Loop
- Secondary Fluid Loop
- Alternator
- Power Distribution Unit
- Loads
- Backup Battery

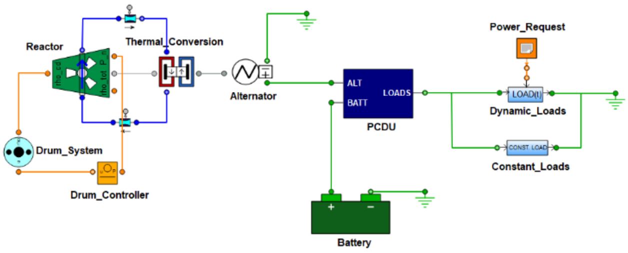

Figure 2. EcosimPro schematic of a Rankine NEP system

An overview of the full NEP model currently under development, in EcosimPro environment, is presented in Fig. 2.

3. Fluids and Materials

In order to simulate an NEP system and given the current available data from ESPSS library, additional fluids had to be introduced. Due to their properties Lithium (Li) and Potassium (K) were chose as working fluids. Li is defined as a "simplified Liquid" in order to be used in the primary fluid loop. K available data in open literature, allows for its implementation in EcosimPro as a "simplified liquid and gas". However, in order to characterize the fluid behaviour in a range of pressures and temperatures, properties were generated, allowing to treat K as a real fluid in the system secondary fluid loop. Data obtained should be still considered as an approximation, worth to be further investigated and improved. Finally, several materials, like T111, for the piping system can be considered and easily implemented to further improve the model. It should be noted that, future development should improve the quality of data related to both Li and K properties, given the current limited quantity of information available in open literature.

4. Reactor and Primary Fluid Loop

This section will describe the modelling efforts in defining the nuclear reactor system (Sec. 4.1) and the primary fluid loop (Sec. 4.2), as well as their implementation in EcosimPro.

4.1. Reactor

The reactor system is the main component of a NEP spacecraft. However, from the modelling point of view, it can be seen just as a thermal node providing heat to the primary fluid loop. Such an approach would be easily implemented in EcosimPro, but it will also give no information on the capability of the reactor in terms of thermal power production. Since one of the main purposes of this model is to understand the relationship between reactor temperature, reactivity and thermal power with the primary fluid temperature, a more advance model for the reactor system must be taken into account. At the same time, the modelling approach must allow to grant fast simulations with a level of details in line with the other components. For this reason, a similar approach as in [1] was considered for the current implementation.

The coolant temperature, Lithium in this case, is strongly dependant on the reactor fuel core temperature and vice versa. These variables are then linked to the thermal power from the reactor and consequently to its reactivity. To describe the dependence of nuclear reactor power on the reactivity change, the point reactor kinetics model with six delayed neutron groups is considered. Note that the neutronic data, used in such a model, should be generated for the specific reactor under evaluation. The total reactivity can be expressed as the sum of a feedback reactivity and the external one inserted by the control drums system, which will be described further in Sec. 4.1.1. The feedback reactivity is linked to the temperatures of the reactor fuel and cladding material which in return depends on the coolant temperature. Therefore, the reactivity equation underlines the problematic of defining the fuel temperature a priori without considering the coolant one. The usage of the point reactor kinetics model allows to consider the reactor not just as an independent thermal node but strictly linked to the coolant flow. This can be implemented in EcosimPro in different ways.

The author decided to take advantage of the ESPSS library, by implementing a “Reactor Component” using an “ABS Tube” as a base line, introducing the point reactor kinetics equations in the system, linking them to a simple heat transfer model to characterize the fuel and cladding temperature as function of the coolant one. This allows to connect the primary fluid temperature from the “ABS Tube” to all the other reactor variables. The model will integrate in time the kinetic equations allowing to describe the behaviour of the reactor main variable (thermal power, reactivity, fuel temperature) while providing the primary fluid behaviour as in a normal “ABS tube” in which heat is received from the reactor itself.

4.1.1. Drum system and Reactivity Control

The reactor reactivity is controlled by adding to the system an external control reactivity. This additional variable is influencing the reactor operation allowing for stable thermal power outputs. Typically, in NEP systems, rotating drums are used to allow the control of the reactor. The control drum shaft can be rotated to keep the reactor in safe reactivity ranges. Therefore, the reactivity from the drums system is described as function of the shaft angle of the stepper motor. The latter can be defined as function of a control voltage to the stepper motors.

In EcosimPro a custom component is defined to compute the control reactivity to be feed into the reactor. Additionally, a custom control logic could be created to allow the desired reactor operability. As an example, a simple control logic was introduced into the system by an additional component. This takes as an input the thermal power from the reactor and compared in to the one requested as a reference. The control logic then sends a voltage impulse to the drums shaft which in return provide a control reactivity signal to the reactor. With the proper logic, it is possible to control the reactor to have a stable desired thermal power production level.

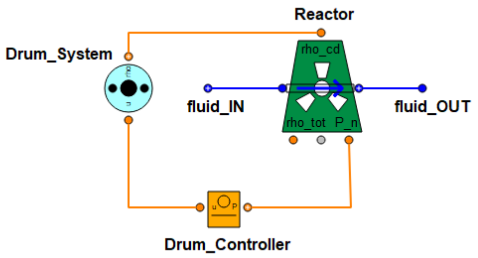

Figure 3. EcosimPro full nuclear reactor system model

The overall reactor system is showcase in Fig. 3, it consists of:

- Main reactor component where the coolant exchange heat with the fuel, following the reactor kinetics equations;
- Drums system, where the control reactivity is computed as function of the shaft rotating angle and an input voltage;
- Control component, where the reactor thermal power is compared to the desired one to formulate and provide a voltage control signal to the drums system;

4.2. Primary Fluid Loop

The primary fluid is strictly coupled to both the nuclear reactor system and the secondary fluid loop. As described in Sec. 3, Lithium was considered as the selected fluid due to its properties. Given the capabilities of EcosimPro and specifically of ESPSS library, the primary loop can be described by the usage of already available components.

The level of details is currently limited only on the inputs data for such components. Since the current work aim to provide a preliminary design tool for an NEP system, without entering in the details of a real-world system, just the following components were selected and connected together to characterize the main Lithium loop:

- A “Pump” component (from ESPSS library) to provide a pressure increase to Lithium, allowing to flow into the system. A PI controller is connected to the pump to grant a desired mass flow rate;
- A “1D-Cavity” component (from ESPSS library), which is used as a thermal node providing heat to the secondary loop;
- Reactor system described in Sec.4.1.;

Additional components like pipe and valves are taken into account to provide additional control on the Li flow. This simple schematic is capable of simulating the heat exchange between the reactor fuel, Lithium and Potassium. However, it can also be improved in further design phases, by taking advantage of already available ESPSS components, like pipes, refined pumps and valves.

5. Secondary Fluid Loop and Alternator

The secondary fluid loop is modelled with the aim of focusing on the energy production from the turbine due to the potassium heat up. A Potassium Rankine cycle in simulated in EcosimPro, taking advantage of ESPSS fluid components. Boiler and Condenser/Radiator are currently defined as thermal nodes where the fluid heats up and cools. This simplification was done mainly due to the difficulty in having detailed inputs in a preliminary design phase of such a system. However, this component, especially the Radiator/Condenser, should be further modelled with more details in future iterations of the model. The main components in the secondary fluid loop are:

- **Turbine**: grants power production to the system. It can be connected to an alternator component;
- **Alternator**: custom components, still under development, to scale the power generated by the turbine. It allows the further connection to the power distribution line (presented in Sec. 6);
- **Pump**: grant the desired pressure rise to the fluid. It is controlled by a PI controller;
- **1D-Cavity**: these components represent both the boiler and condenser/radiator. They are used as thermal nodes to simulate the heating and cooling of potassium. Specifically, the boiler is thermally connected to the primary fluid loop, while the condenser/radiator radiates into space;

The main criticality in the secondary fluid loop is the definition of pump and turbine inputs data. Further iteration of the model will need to improve the line fidelity with a real system. For example, by adding pipes and by improving the heat exchange approach.

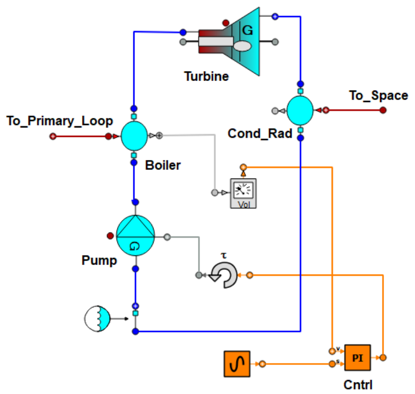

Figure 4. EcosimPro secondary fluid loop model

An overview of the secondary fluid loop system is depicted in Fig. 4.

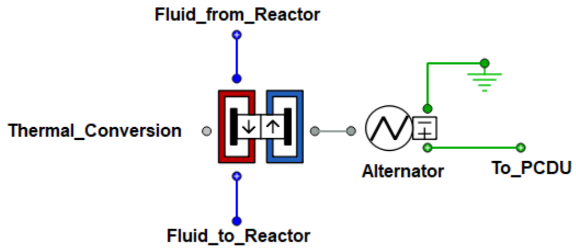

Figure 5. EcosimPro thermal conversion system model

Primary and secondary loop define the thermal conversion system showcased in Fig. 5. which is then connected to the reactor system and to the alternator. The latter is a simple component, still under development, which aims to link the thermal conversion system to the power distribution unit, described in Sec. 6.

6. Power Distribution and System Loads

In order to model both the production and distribution of electrical power, the alternator component (presented in Sec. 5) is linked to a power conditioning and distribution unit (PCDU) which will then transfer the power required to the loads. To simulate this, the electric propulsion library (EPS) developed in the EcosimPro environment at OHB, is used. Even if its detailed description is out of the scope of this paper, this section will present the main components considered that can be used to model the full system in future iteration of the model:

- **PCDU**: this component grants the connection between the power coming from the alternator, the auxiliary battery and the loads. The power coming from the alternator during normal reactor operations, flows to the loads providing the required power. In case of shutdown of the reactor the PCDU will direct power from the battery component to the loads. Moreover, the PCDU is responsible of granting the correct functioning of the battery charge/discharge;
- **Loads**: NEP system operation involves the presence of loads coming from spacecraft operating procedures, thermal conversion system pumps, thrusters etc.. All of them can be modelled either as constant or dynamic loads. In the first case a simple "Constant Load" component is requesting a pre-defined amount of power to the PCDU. In the second case, a txt file describing the loads in time is given as an input to a "Dynamic Loads" component, in order to simulate the request of the systems for

specific loads at defined time instants. This can be used to simulate the thrusters firing happening in a specific time frame during the mission;

- **Battery**: To simulate the presence of a secondary power device on board, a simplified battery model is taken into account. The main purpose is to simulate the possible shut down of the reactor and the subsequently activation of the PCDU control logic to redirect power from the auxiliary battery to the loads;

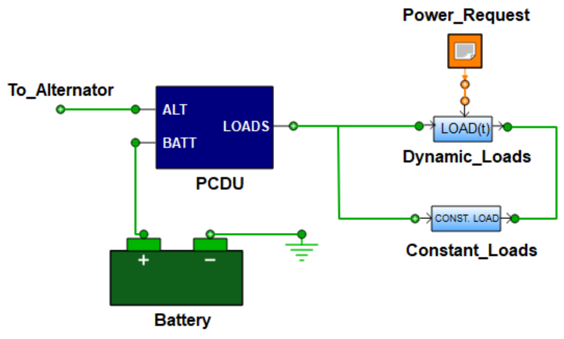

Figure 6. EcosimPro PCDU, battery and loads model

An overview of the power distribution system is depicted in Fig. 6.

6.1. NEP and SEP Comparison Approach

The full NEP model will allow to account for both the energy production and consumption of the overall system during a mission profile. It should be noted that a similar approach is already used as a designing tool in OHB heritage, specifically for solar electric propulsion (SEP) system.

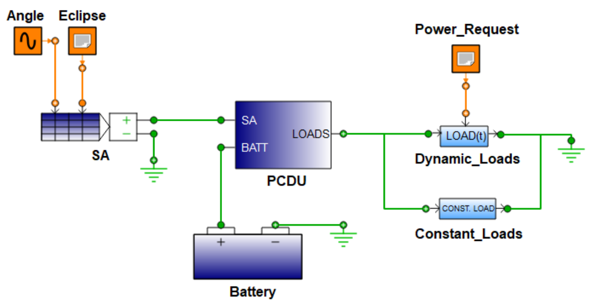

Figure 7. EcosimPro generic SEP system schematic

In those case a similar power distribution schematic is used, but an additional component needed, in order to describe the power generated from solar arrays provided to the PCDU (Fig. 7). The solar array component sense the eclipse percentage during a mission profile outputting the power production variation during the mission. This analogy allows to formulate a comparison approach between an NEP and SEP systems when considering a mission scenario.

NEP systems are usually looked at as mission enablers for specific missions in which common SEP is either not usable or not perfectly suitable. Typical analysis to decide which would be the preferred scenario involves the definition of a mission profile which underlines the total mission time and ΔV costs. These parameters are then linked to the power production of the system under consideration and the mass required by the system to sustain a certain payload mass mission scenario. Mission time, mass and power are the main variable that characterize the decision on which system to use. All these variables are assessed into both the NEP and EPS model showcased in this work:

- Mission time equals to the simulation time and is used to define at which time instants dynamic loads request power (e.g. Thrusters firing);

- Power production is supplied by either the reactor/thermal conversion system or by the solar arrays;

- Mass estimation can be done considering the batteries, reactor/thermal conversion system and solar arrays data set used in the model;

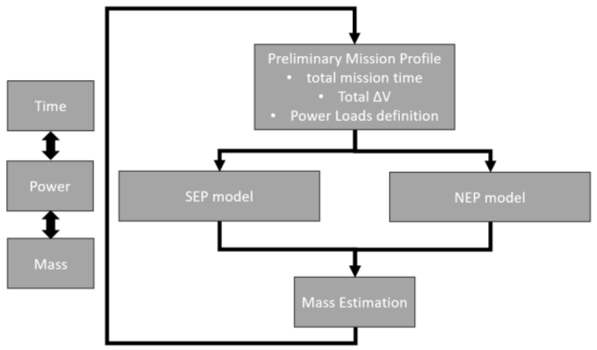

Figure 8. NEP and SEP comparison approach

Hence, the main comparison approach goes through a preliminary mission definition, the usage of both NEP and SEP model which will then output valuable data to estimate mass overall system parameters to assess the mission, to finally define the most suitable system to be used (Fig. 8).

7. Nuclear Reactor and Thermal Conversion System Mass Estimation

A mission definition, either considering a NEP or a SEP system, will always take into account the total mass of the spacecraft alongside with mission profile and requirements. However, in the current open literature, information related to mass estimation for components related to the nuclear reactor system and for the thermal conversion unit are very limited. Nevertheless, to expand the capabilities of the model as a preliminary design tool, a mass estimation approach is necessary. The mass of typical components like thruster shared with SEP system or available on the market, can be easily assessed. The most problematic mass estimation components are:

- Reactor
- Shield
- Primary fluid loop
- Secondary fluid loop
- Heat Pipe Radiator-Condenser System

A more detailed reactor and shield estimation approach is presented in [2]. However, to apply it, some geometrical data on the system is required. Unfortunately, similar models for the estimation of the thermal conversion system components, whose mass cover a relevant portion of the total spacecraft weight, are not currently available in open literature. To assess this problem and provide a rough estimation of such a system, the work from the RocketRoll consortium [3] is considered for preliminary design phases.

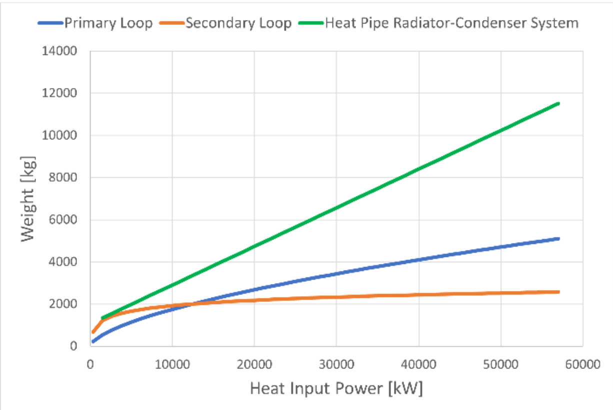

Figure 9. Mass estimation curves [3]

Functions, presented in Fig. 9, were created on the basis of similarity data from several open literature studies as well as the contribution from RocketRoll study [3]. Primary, secondary loops and heat pipe radiator-condenser system mass is estimated knowing the thermal power coming from the reactor. It must be noted that the usable range of the study developed, refers to a reactor heat power range between 350-57000 kWt thermal power for the primary and secondary loops and 498-59108 kWt for the heat pipe radiator-condenser system. Values refer to a Rankine Li-K systems. Additionally electromagnetic pumps are considered as well as turboalternator unit and a heat pipe radiator-condenser. Auxiliary cooling system mass is not considered in these functions. Naturally, due to the deviation of the data used and to the limited literature available, the results obtained should be considered as preliminary rough estimation for early design phases. Nevertheless, they easily provide a mass estimation knowing only the definition of the thermal power associated to the reactor.

8. Study Case and Model Results

In order to showcase some of the current capabilities of the model, a simple comparison between NEP and SEP in a sample mission is described in this section.

First a mission profile is selected. Mission profiles from [4] are considered. This study describes an all-electric transfer from Low Earth Orbit (LEO) to Low Mars Orbit (LMO). Different trips to Mars were analysed considering different trajectories resulting in possible scenarios with different total transfer times. Each mission scenario was then used to showcase the capabilities of different SEP and NEP system at different power levels. One of the most studied scenarios is the 601 days one way transfer to Mars.

Data	Value
Trip time	601 [days]
Mission ΔV	16.6 [km/s]
Power level range	50-15000 [kWe]
SEP LEO mass (100kWe)	24 [tons]
SEP Payload mass (100kWe)	5.2 [tons]

Table 1. Earth -Mars transfer data [4]

A 100kWe SEP system for such a mission, is characterized in terms of the total LEO mass (with a 30% margin) considering cutting edge technologies. The main mission data as well as SEP mass are reported in Tab. 1. These values are compared to one from a hypothetical 100kWe NEP system, after a rough mass estimation of its components.

The author decided to select this specific mission and to simulate a 100kWe NEP system using a Li-K potassium Rankine thermal conversion system. Such a choice is motivated due to the availability of some reliable data, related to part of the components for the reactor system and for the secondary fluid loop, in [5]. This allows to characterize the system with reasonable values to be used as inputs in the EcosimPro model. Here the system is simulated to see the power generation provided by the turbine.

Data	Value
K mass flow	0.29 [kg/s]
Li mass flow	1.37 [kg/s]
K pressure at boiler	770 [kPa]
K pressure at condenser	30 [kPa]

Table 2. Primary-Secondary fluid loop simulation data

The system is considered to operate with a 1.2MWt thermal power reactor in order to achieve the desired 100kWe electric power from the alternator. Additional data from the EcosimPro model simulation, across the primary and secondary fluid loop, are reported in Tab. 2.

The results provide power requested from the reactor as well as the one generated by the alternator. Thanks to the drum control system, a stable value of 1.2MWt thermal power its achieved, while the alternator is able to generate slightly more than 100kWe of electrical power, with the turboalternator considered. Temperature behaviour between the primary fluid (i.e. Lithium) the reactor cladding material and the fuel rods can be evaluated. In particular, the simulation reveals a temperature for the fuel rod around 1422K which translates into 1356K for the Li. Potassium line operates between 840K and 1311K.

The overall system allows to verify that the parameters especially used for the reactor and turbine, are able to achieve the desired electrical power request. The next step involves a mass estimation of the whole system. To do so, common values for all the spacecraft system not related to the thermal conversion and reactor system can be approximated from open literature models, and [4] was considered for this specific case. For the reactor system, the model from [5] was used. As already stated in Sec. 7, the critical mass estimation for the primary/secondary fluid loops and radiators, is done using the curves developed by the RocketRoll consortium [3]. Following the approach from [4], the dry mass of the system is the sum of the power sub-stem mass (reactor, shield, conversion, radiator and power conditioning) and the propulsion sub-system mass (thruster, tank and fluid system mass).

Mass	Value [kg]	Reference
Reactor	221	[5]
Shield	831	[5]
Primary loop	475	[3]
Secondary loop	1061	[3]
Radiator-Condenser	1291	[3]
Conditioning	407	[4]
Propulsion	1000	[4]
Dry mass	5286	---------------------

Table 3. NEP system mass estimation

Tab. 3 showcases the total mass estimation for the NEP system under consideration. The value obtained can be compared to the one estimated with the SEP system for this mission. The total dry mass is estimated to be around 5.3 tons. This value is similar to the one suggested by [5] for a NEP system. Moreover, a similar value is suggested for the SEP system. As expected, at 100kWe, this mission is feasible with both systems.

Further steps can be done, iterating the process describe in this section. For the mission profile selected, an increase of reactor power can be studied using the EcosimPro model and new mass estimation can be done. This would allow to make additional consideration on the mission profile, allowing to see how, for this mission profile (as depicted in [5]), the impact of an increased power level would impact the choice of either SEP or NEP system. In general SEP in more suitable for lower power levels, while NEP becomes a better choice for system with more than 1MWe power levels.

9. Conclusion and Future Development

The present work aims to be the first step in the development of a sizing and design tool for a NEP system. The main components developed could be used for all NEP system types, but further effort was done to build a model to evaluate the performances of a NEP Rankine cycle system. The custom OHB components developed in EcosimPro environment were able to deliver a first approximation for a nuclear reactor system, controller by a shaft drum approach. Additionally, the usage of ESPSS library fluidic component, allowed to connect the reactor to a fluid network representative of a Rankine System. The output of the modelling process is the capability of simulating the turbine electric power generated from the thermal power linked to a nuclear reactor system. Additionally, the custom OHB EPS library is considered as an additional tool for future iteration of the model, able to be linked to the thermal conversion system and further expand the capabilities of the model in representing the power distribution unit and loads of an NEP system during a mission scenario. Finally, a mass estimation relationship is applied for the whole thermal conversion system, thanks to the work of the RocketRoll consortium [3].

Future steps involve the improvement of the current model, targeting several components:

- Refined fluid properties (Li and K);
- Improvement of Reactor system model;
- Development of a more detailed boiler and condenser/radiator model;
- Implementation of an alternator structured model to properly link the distribution power system to the thermal one;

In parallel, further usage of the already currently available model will be analysed, with the aim of full comparison between NEP and SEP capabilities for defined mission scenarios.

10. Acknowledgments

The Authors would like to thank the members of the RocketRoll consortium [3] for the data provided as well for the support received in the writing of this paper. A special thanks to Jakub Sevecek, Head of Project Management & Procurement, Spacecraft Projects (SCPR) OHB Czechspace as well as members of the CTU in Prague, Tomáš Romsy,

R&D Engineer, Department of Energy Engineering, Faculty of Mechanical Engineering and Jan Frýbort, Nuclear Engineer, Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering.

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