

# DESIGN OF A NUCLEAR ELECTRIC PROPULSION (NEP) SYSTEM: FROM MISSION REQUIREMENTS TO REACTOR CONCEPT

*Pablo Rubiolo\*<sup>†</sup>, Francisco Szmandiuk\*, Nicolas Capellan\* and Martin Marone\**

*\* LPSC, Univ. Grenoble Alpes, Grenoble INP, Grenoble*

*53 Av. des Martyrs, 38000 Grenoble*

*pablo.rubiolo@lpsc.in2p3.fr – francisco.szmandiuk@lpsc.in2p3.fr*

*<sup>†</sup> Corresponding Author*

## Abstract

A comprehensive approach to the conceptual design of a Nuclear Electric Propulsion Orbital Transport Vehicle (NEP-OTV) is presented. This approach is structured into three main stages. In the first stage, mission requirements are defined based on mission objectives using a simplified NEP model. In the second stage, various alternatives for NEP subsystems are evaluated based on the mission requirements using a numerical optimization tool called PRESTO. This tool enables the selection of optimal technologies and configurations, as well as the determination of key design parameters for the NEP-OTV subsystem characteristics and operating conditions. In the third stage, the selected optimal concepts are further analyzed using detailed multiphysics simulations with a first-principles tool called NepFOAM, in order to determine precise design parameters and verify compliance with design and safety criteria. This paper provides an overview of the methodology, the numerical tools employed, and the main findings from the ongoing studies performed on Molten Salt Reactors (MSRs) and Heat Pipes Reactors (HPRs).

## 1. Introduction

Nuclear Electric Propulsion (NEP) systems can play a significant role in the coming decade in the development of New Space activities, given their capacity to provide a reliable source of energy over long durations, independent of the space environment. While the technical and regulatory challenges associated with this technology should not be underestimated, the successful deployment of NEP will ultimately depend on its ability to meet specific mission requirements while being significantly more competitive than alternative technologies such as chemical propulsion and Solar Electric Propulsion (SEP). Target missions should include both commercial opportunities and scientific exploration. Developing a successful NEP program will require the integration of mission performance, safety, and testing criteria from the earliest stages of the design process, as well as fully addressing, throughout the design phase, the complex interrelation between the various technologies employed in NEP subsystems.

A comprehensive approach to the design of such systems is being developed at the French National Center for Scientific Research (CNRS), with the support of the European Space Agency (ESA) and the French National Space Agency (CNES), and in collaboration with various international partners. The NEP design process requires multidisciplinary analysis due to the diversity of technologies involved in the different subsystems. As shown in Figure 1, the main NEP subsystems include the reactor core (comprising the fuel, reflector, coolant system, and possibly a moderator), reactor shielding, the thermal-to-electric conversion system, the radiator, the propellant tank, and the electric thrusters. As discussed in the next section, the design process must be carried out iteratively, beginning with the definition of approximate mission requirements, followed by the derivation of NEP engine specifications, and culminating with detailed multiphysics calculations to determine more precise design parameters.

The initial stage in the spacecraft design process is the definition of mission requirements, which is carried out based on the use cases identified for the proposed mission. In the case of a Nuclear Electric Propulsion (NEP) concept, suitable use cases include cargo missions to destinations such as the Moon, Mars, and regions beyond Mars. This is because cargo missions generally do not require short transit times, unlike crewed missions. Indeed, although NEP systems can provide very high specific impulse, their maximum thrust is usually very low compared to other propulsion

technologies, such as chemical rockets or Nuclear Thermal Propulsion (NTP). As electric propulsion technologies continue to advance, NEP could eventually be considered for missions that require shorter transit times.

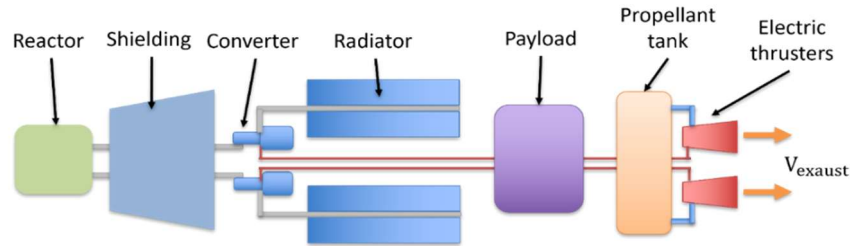


Figure 1: Main subsystems used by Nuclear Electric Propulsion (NEP) concepts.

## 2. NEP design methodology

Among the various mission requirements defined in the Mission Definition Review (MDR), four are essential for initiating the conceptual design of a Nuclear Electric Propulsion Orbital Transport Vehicle (NEP-OTV). These four key parameters are:

- (R1) Delta-V required by the mission
- (R2) Electric power needed by the Electric Propulsion (EP) subsystem (or Electric thrusters)
- (R3) Time-of-Flight (TOF)
- (R4) Payload mass

Of the four mission requirements mentioned previously, only the delta-V (R1) can be determined in a relatively straightforward manner from the mission definition, through more or less laborious orbital mechanics calculations. In contrast, the other three requirements (R2, R3, and R4) remain relatively flexible. Nevertheless, the way these three requirements are defined has a significant impact on the NEP-OTV design, as they directly influence the choice of technologies for the NEP subsystems. For example, the nuclear reactor's electric power output can be set within a relatively wide range, even when assuming the same mission parameters, payload, and time of flight (TOF). However, the choice of reactor power strongly affects the technologies used for the reactor itself, the power conversion system, the electric thrusters, and the propellant. If the reactor electric output is set to the lower end of the possible power range (i.e., on the order of tens of kilowatts), a concept based on a thermal-spectrum nuclear reactor fuelled with HALEU could be selected, coupled with Stirling conversion engines and Resistojet thrusters. Due to the low specific impulse of Resistojet engines, this NEP-OTV design would likely require a very large amount of propellant to complete the mission. On the other hand, for the same mission, if the designer explores the use of a reactor in the higher power range (e.g., several hundred kilowatts), a concept based on a fast-spectrum nuclear reactor using HALEU may be more suitable, coupled with a Brayton or potassium Rankine cycle and advanced thrusters such as Hall Effect Thrusters (HET) or Magnetoplasmadynamic Thrusters (MPD). This latter configuration would consume significantly less propellant than the former. Choosing between these two concepts requires a comparative analysis that sets the values of the reactor electric power output (R2), TOF (R3), and payload (R4) based on NEP-OTV performance, safety, and cost considerations. Unfortunately, conducting an exhaustive study of all possible design options while varying these three mission requirements is not a realistic task due to the complexity of the reactor analyses, which involve neutronics, thermal-hydraulics, thermo-mechanical simulations, and safety studies. To overcome this issue, a design methodology has been developed that incorporates specific assumptions and simplifications to constrain the problem. Firstly, to organize and define clear interfaces between the different design areas required for a NEP-OTV, the design work has been structured into five types of analysis, as illustrated in Figure 2:

- 1) "Mission Requirements Analyses"
- 2) "NEP Subsystem Analyses"
- 3) "Safety Analyses"
- 4) "Electric Propulsion System Analyses"
- 5) "Market Analyses"

The input data required and the output results produced by each of these analysis areas are highlighted in Figure 1. A detailed description of the analyses performed in each area is not provided here but can be found in [1]. The design process must be conducted iteratively, such that after each iteration, every analysis area generates a new set of output values to be used as input for the other areas in the subsequent iteration. Furthermore, the design analyses must take into account the current state of the art, lessons learned from previous space programs, compliance with the regulatory

framework applicable to NEP-OTV deployment, and, in our case, the existing industrial and research capabilities within the European Union (EU).

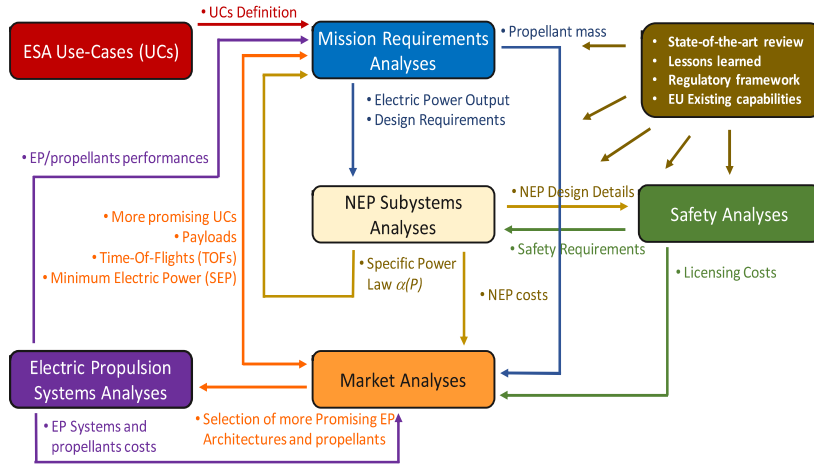


Figure 2: NEP-OTV design process organisation in five areas of analysis.

Due to the complexity of the analyses, it is necessary to minimize the number of iterations needed to converge toward a final configuration. At the same time, to successfully identify the most competitive NEP-OTV concepts, the design process must explore the impact of the various available technology options for each subsystem and identify the relevant figures of merit and constraints for comparing different design candidates. For these reasons, the design process illustrated in Figure 1 was performed according to the three stages shown in Figure 3. Each stage involves a different modelling tool, with increasing levels of detail and accuracy. The first stage enables the definition of approximate mission requirements and provides a preliminary screening of technological options for some NEP-OTV subsystems. In the second stage, a design tool called PRESTO is used to evaluate different design configurations and to estimate optimal parameter values. Based on these results, the third stage consists of performing the first full iteration of the design process described in Figure 2, focusing only on a few selected optimal configurations. In this final stage, a dedicated numerical tool called NepFOAM is employed to conduct detailed multiphysics simulations of the reactor subsystem, allowing for the determination of the NEP-OTV design parameters and operating conditions with relatively high precision. Depending on the results obtained at each stage, feedback may be used to refine the analyses in the previous stages and improve overall accuracy. The following sections describe these three stages in more detail.

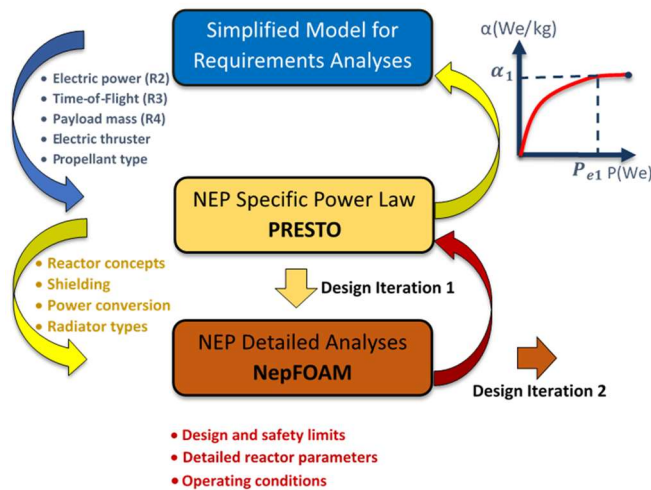


Figure 3: Implementation of the NEP-OTV design process in three stages.

### 3. First stage: Determining the approximate mission requirements for the NEP

As discussed in the previous section, at the beginning of the design process, a simplified model is required to establish approximate values for the following key mission requirements: R2, R3, and R4. These parameters, along with a preliminary selection of electric propulsion (EP) technology and propellants, must be defined before initiating the iterative design process shown in Figure 1. The simplified model used in this study was developed based on the

Tsiolkovsky rocket equation, energy conservation considerations, and an approximate NEP specific electric power law, denoted as  $\alpha(P_e)$ . This specific power law allows estimating the specific power (i.e., the power-to-mass ratio) of the NEP-OTV as a function of electric power. It can be derived from data available in the literature or, as illustrated in Figure 3, from a numerical design optimization tool such as PRESTO. The  $\alpha(P_e)$  law should be constructed by evaluating the performance of various design concepts (i.e., different technology combinations) at a given power level and selecting the maximum value achievable by the best-performing designs. Additional key input data that must be provided to the simplified NEP performance model include:

- Mission delta-V
- Time-of-flight (TOF)
- Payload mass
- Electric thruster performance (specific impulse and efficiency)
- Propellant type
- Power conversion efficiency
- Target NEP-OTV lifetime

To evaluate the performance of the NEP-OTV, the simplified NEP model uses the nuclear-to-chemical cost ratio for the selected mission as a figure of merit. This metric enables a direct comparison with the cost of chemical propulsion, and thus helps assess the potential of developing a cost-competitive NEP solution for the mission. To compute the cost ratio between the NEP-OTV and a chemical rocket, a simple Net Present Value (NPV) cost estimation model was developed based on available data for both propulsion systems. The key cost elements considered include:

- (i) For the NEP-OTV: capital costs, launch costs, and licensing costs
- (ii) For the propellant: production and launch costs
- (iii) For chemical propulsion: costs to reach LEO, GEO, the Moon, and Mars, depending on the type of launch vehicle used (non-reusable, partially reusable, or fully reusable chemical rockets)
- (iv) The applicable interest rate

Using this information, the simplified NEP performance model estimates key NEP parameters such as electric and thermal power, dry and wet mass, propellant mass, and the nuclear-to-chemical cost ratio. Further details of the simplified NEP model can be found in [2].

In our studies, the simplified NEP model is used to define approximate mission requirements and to conduct a preliminary screening of the most promising technological options for the electric propulsion subsystem and propellant type, within the context of the proposed mission. Specifically, once the mission goal is established (e.g., a cargo mission between Earth and the Moon) and the mission Delta-V is calculated using orbital mechanics, the model is employed to perform parametric studies by varying the Time-of-Flight (R3) and payload mass (R4) in order to determine the required electric power (R2). These parametric studies consider different electric thruster technologies, propellant types, and launch vehicles. The nuclear-to-chemical cost ratio is then used as a figure of merit to identify the mission profiles for which an NEP-OTV could be a competitive alternative to chemical propulsion. These mission profiles are characterized by six parameters: mission Delta-V (R1), electric power (R2), Time-of-Flight (R3), payload mass (R4), electric thruster technology, and propellant type. As illustrated in Figure 3, this information is then passed on to Stage 2, where the PRESTO tool is used to continue the screening process for other key NEP-OTV subsystems: the reactor, the shielding, the power conversion system, and the radiator. The studies conducted using this simplified model to explore various cargo missions have shown that a critical parameter for a cost competitive concept is the specific electric power of the NEP-OTV [2]. These findings suggest that, given the decreasing cost of launchers enabled by reusable technologies, the NEP concept will need to deliver specific electric powers exceeding 60 We/kg to remain competitive across a wide range of mission profiles. Meeting this target presents significant design challenges and will require a careful trade-off between maximizing specific power and ensuring robustness and reliability. Consequently, the subsequent stage of the design process is of critical importance.

#### 4. Second stage: optimal NEP-OTV design concept and specific power law

In the second stage, a large number of possible NEP-OTV design configurations are evaluated based on parameters derived from the most promising mission profiles obtained in Stage 1. Each configuration corresponds to a specific combination of reactor, shielding, power conversion, and radiator technologies. As discussed in the previous section, the optimal parameters for each of these configurations must be determined at this stage in order to maximize the specific electric power. These results are then used to down-select the most promising technological options. To

perform this analysis, a design tool called PRESTO (NEP Rocket Design Tool) is being developed by the CNRS in collaboration with the CNES. PRESTO supports the integrated design and optimization of NEP systems, enabling the identification of system configurations that optimize selected figures of merit, such as total system mass or specific electric power. As illustrated in Figure 4, PRESTO's strategy relies on metamodels obtained through interpolation of large databases containing key parameters for the NEP-OTV subsystems. These databases are generated by a Data Base Generator (DBG) algorithm, which performs numerical simulations of the various subsystems using relatively simple, single-physics models. Design optimization—whether aimed at minimizing total mass or maximizing specific power—is carried out using these metamodels, subject to user-defined constraints (e.g., minimum excess reactivity, maximum material temperature, or minimum heat pipe diameter). This comprehensive optimization methodology enables the consideration of the full complexity of NEP system design, which arises from the coupling of multiple subsystems and the interplay between various physical domains (neutronics, thermal-hydraulics, thermomechanics, and materials science). For instance, changing the fuel material may improve neutronic performance and reduce the critical mass (thus increasing specific power), but it could also reduce thermal margins. This might lower the fuel operating temperature, thereby decreasing power conversion efficiency and increasing radiator size—both of which would ultimately reduce the reactor's specific power. The PRESTO tool is currently being developed to handle a wide range of technologies, including different reactor types, power conversion systems, and radiator types. Further details on the PRESTO tool are provided in [3][4].

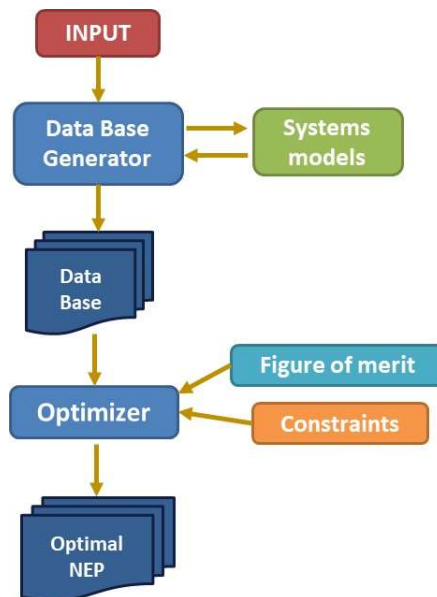


Figure 4: PRESTO workflow of optimization methodology.

PRESTO is then used to determine the most suitable NEP-OTV configurations that meet the design requirements defined in Stage 1. The resulting design parameters of these NEP-OTV configurations, such as technologies, materials, geometries, and dimensions, as well as the corresponding operating conditions (e.g., temperatures, flow rates), are subsequently used in Stage 3, which involves detailed multiphysics calculations. It is important to note that, in the present design approach, the NEP-OTV configurations selected in Stage 2 are optimized designs, specifically tailored to achieve the maximum possible specific power at the electric output defined by the mission requirements in Stage 1. This is a key aspect in making the design cost-competitive with respect to alternative technologies, as discussed in [2].

Another key use of the design optimization studies performed with PRESTO is to determine the specific power law used in Stage 1 analyses. This curve, illustrated in Figure 3, represents the maximum specific power achievable at a given electric power level, based on the consideration of multiple optimized NEP-OTV configurations. These configurations are obtained by combining various technological options available for the main subsystems (for example thermoelectric, Stirling, Brayton and potassium Rankine for the power conversion subsystem). The specific power law used in Stage 1 thus corresponds to an envelope curve, representing the theoretical upper limit of NEP-OTV performance in terms of specific power. It does not refer to any single design, and the underlying technologies will vary depending on the selected electric power. At present, the specific power law has been derived by considering only thermal and fast spectrum MSRs and fast spectrum HPRs. Additional reactor concepts will be incorporated into the analysis in future work.

### 5. Third stage: Detailed multiphysics calculations on the NEP-OTV

Once the optimal NEP-OTV configuration has been determined in Stage 2 and the design parameters (fuel type, enrichment, cladding, coolant, etc.) and operating conditions (temperature, flow rates, power density, etc.) are known, then more detailed core design studies can be carried-out. The goal of these detailed core design studies is to accurately evaluate the performance of the reactor by considering neutronics, thermal-hydraulics, and thermomechanics aspects together with first principle models. In particular, in this third stage of the design, the main objective is to check the design and safety limits with more accurate models and less approximations. This design and safety limits may include neutron flux and fluence, gamma dose, temperatures, and temperature gradients, coolant velocity, corrosion effects, feedback coefficients, etc. The Stage 3 is also devoted to other studies including transient studies for the reactor start-up operation and also accidental scenario (e.g. criticality accidents). The latter are required to confirm that the design will comply with all the safety requirements.

To perform these detailed analyses, we have developed a Multiphysics tool that can take into account the coupling between different phenomena (neutronics, thermal-hydraulics and thermomechanics) existing in a nuclear reactor. In the case of a MSR, these couplings are particularly strong. This multiphysics tool called NepFOAM is based on a numerical coupling between the codes OpenFOAM (C++ toolbox for the development of numerical solvers for continuum mechanics problems using Finite Volume Method, including Computational Fluid Dynamics) and SERPENT code. The Figure 5 illustrates the overall coupling scheme adopted in the multi-physics tool together with the main phenomena and the relevant variables that are exchanged between the different modules of the tool.

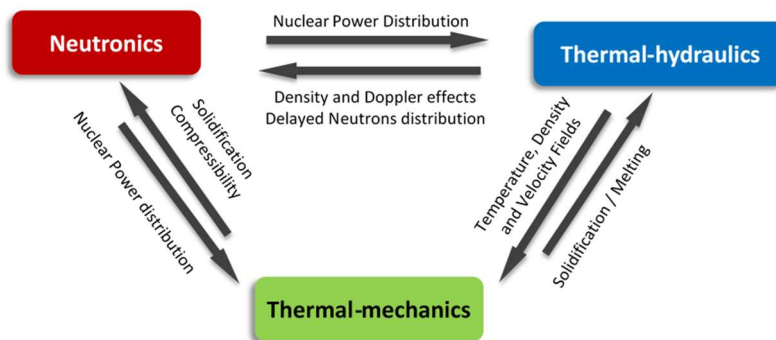


Figure 5. Multiphysics model based on a coupling between the OpenFOAM and SERPENT.

As it can be seen from Figure 5, the multi-physics tool contains three main modules: Neutronics, Thermal-hydraulics and Thermo-mechanics. During the numerical resolution, these three modules are executed in each of the regions of the reactor sequentially. A reactor region is defined in the tool according to the material properties. It can be either a solid or liquid. The coupling between the regions is ensured by the use of appropriated boundary conditions at the interface between the regions. For example, for the case of temperature or neutron flux, the appropriate boundary conditions at the interface are the continuity of the scalar field and the continuity of the current. The neutronic module can perform both steady and transient calculations. This module determines nuclear power distribution and various nuclear reactions rates. Two different solvers are available for this module: a) Deterministic  $SP_N$  approach based on a multi-group simplified spherical harmonics method (with two possible levels of discretization  $SP_1$  and  $SP_3$ ) and (b) Stochastic approach using a Monte Carlo method. Due to the small sizes (large neutron leak) and the large space heterogeneities of the material composition and the neutron spectrum of the space MSR studied in this work, only the Monte Carlo method was used. The thermal-hydraulics module solves the mass, momentum (Navier-Stokes equations if fluid) and energy balance equations in the fluid and solid regions using OpenFOAM's Computational Fluid Dynamics (CFD) algorithms for laminar or turbulent flows. The thermal-hydraulic module determines the temperature, density, velocity, delayed neutron precursors concentrations and decay heat source fields. As shown in Figure 5, these fields are transferred to the other modules to update for example the nuclear properties (e.g. neutron cross-sections) required by the neutronics module. The thermal-mechanics module is principally used to model fuel salt change of phase (melting or solidification) during transient conditions. In the present study, it was not required. A detailed discussion of the equations and approximations used by these models can be found in [5].

NepFOAM has been used to study NEP concepts based on fast-spectrum Molten Salt Reactors (MSRs) using HEU (Highly Enriched Uranium) or HALEU (High-Assay Low-Enriched Uranium) fuel. This reactor concept offers several intrinsic advantages for Nuclear Electric Propulsion (NEP), primarily due to the use of liquid fuel. An example of the results obtained from detailed studies performed with NepFOAM is presented in Figure 6, for the case of a fast-spectrum MSR design using HEU fuel enriched to 92% in uranium-235. The core cavity is filled with a molten fuel salt composed of  $\text{LiF-UF}_4$ , enclosed by cladding made of TZM alloy (Titanium-Zirconium-Molybdenum), and

surrounded by a beryllium reflector. The general layout of the core is shown in Figure 6(a), while the velocity and temperature fields of the molten salt are shown in Figures 6(b) and 6(c), respectively. These simulations were performed using a  $k-\omega$  SST RANS model for the thermal-hydraulic calculations, coupled with a Monte Carlo method for neutronics. Additional detailed results for both HEU and HALEU fast-spectrum MSR configurations are discussed in [5].

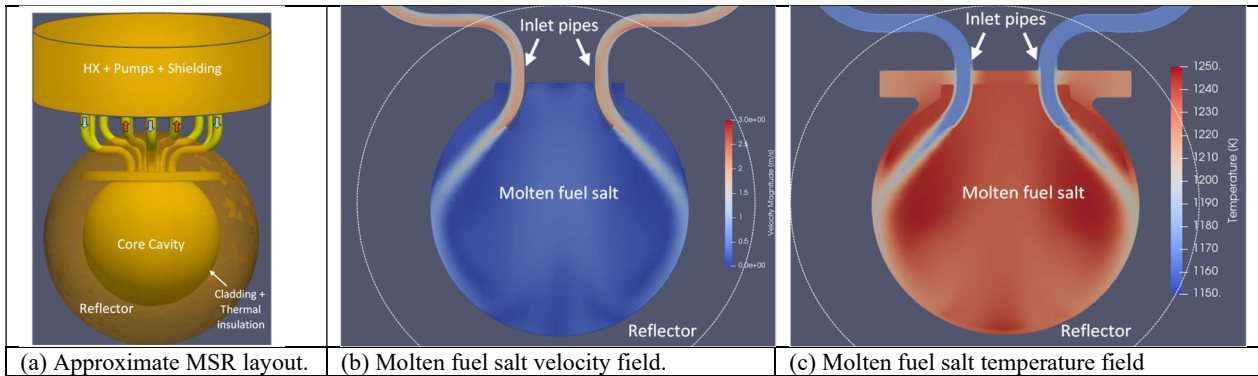


Figure 6. Multiphysics model based on a coupling between the OpenFOAM and SERPENT.

For many of the design and safety criteria, the detailed calculations performed with NepFOAM confirmed that the fast-spectrum MSR concepts met the required standards. In cases where safety margins were found to be insufficient, the analyses enabled the implementation of design modifications that restored acceptable margins without significantly compromising overall system performance, particularly in terms of specific power. Detailed design studies are now being conducted for thermal-spectrum MSRs, with the objective of comparing the performance of thermal and fast MSR concepts.

## 6. Key findings and conclusions from ongoing studies for MSRs and HPRs

A structured methodology for the conceptual design of a Nuclear Electric Propulsion (NEP) rocket has been developed, consisting of three main stages. The proposed approach enables the exploration of a large number of potential NEP design solutions capable of fulfilling a prescribed mission while keeping the overall design effort reasonable and manageable.

In the first stage, preliminary mission requirements are defined based on mission objectives, using a simplified system model. This stage allows the estimation of four key mission parameters required for the design of the NEP Orbital Transfer Vehicle (NEP-OTV): mission Delta-V (R1), electric power (R2), time of flight (R3), and payload mass (R4). Stage 1 also helps to identify the most promising electric thruster technologies and propellant types for the mission. The ongoing analyses performed with this simplified model have shown that a cost-competitive NEP cargo concept will likely require several hundred kilowatts of thermal power. Achieving a cost-effective solution will also define the acceptable range for the time of flight (TOF). Another important outcome from the studies of Stage 1 is the confirmation that maximizing the specific electric power of the NEP-OTV is essential to making the concept economically competitive in such applications.

In the second stage, the most suitable NEP-OTV configurations are identified based on the estimated mission requirements (e.g. the electric power), using the PRESTO optimization tool. For a given electric power, PRESTO can evaluate various NEP-OTV configurations by considering different reactor designs, power conversion and radiator technologies, materials, geometries, and subsystem dimensions, along with corresponding operating conditions such as temperatures and flow rates, and determine the optimal values that maximize specific power. This stage therefore enables the selection of NEP-OTV configurations that best meet the design requirements defined in Stage 1.

The selected NEP-OTV configurations, along with their optimized design and operating parameters, are then used in Stage 3, which involves detailed multiphysics calculations. In this stage, the selected concepts are further analysed using the NepFOAM simulation tool, enabling the determination of detailed design parameters and verification that both performance and safety criteria are met. The studies performed on molten salt reactor (MSR)-based concepts have shown that achieving specific electric powers beyond 60 We/kg will be challenging, but potentially feasible even for designs using HALEU fuel and delivering electric power outputs above 100 kWe, through appropriate selection of subsystem technologies. Additionally, this reactor concept presents very promising features for improving overall system performance.

## Acknowledgments

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