



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DEPARTMENT OF INDUSTRIAL ENGINEERING - DIN

**MASTER'S DEGREE PROGRAMME IN
MECHANICAL ENGINEERING
CURRICULUM – FLUID MACHINERY**

**DEVELOPMENT OF A PLANT LAYOUT
AND SIMULATION FOR A POWER
CIRCUIT FOR NEW-GENERATION
NUCLEAR REACTORS**

Master's Thesis in Turbomachinery

Supervisor

Prof. Antonio Peretto

Presented by

Piergiorgio Sicuranza

Co-supervisor

Eng. Stefano La Rovere

Prof. Andrea De Pascale

Prof. Lisa Branchini

March 2026 Session

Academic Year 2024/2025



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DEPARTMENT OF INDUSTRIAL ENGINEERING - DIN

MASTER'S DEGREE PROGRAMME IN
MECHANICAL ENGINEERING
CURRICULUM – FLUID MACHINERY

DEVELOPMENT OF PLANT LAYOUT AND SIMULATION FOR POWER CIRCUITS IN NEW-GENERATION NUCLEAR REACTORS

Master's Thesis in Turbomachinery

Supervisor

Prof. Antonio Peretto

Presented by

Piergiorgio Sicuranza

Co-supervisor

Eng. Stefano La Rovere

Prof. Andrea De Pascale

Prof. Lisa Branchini

March 2026 Session

Academic Year 2024/2025

ABSTRACT

This thesis analyses the relationship between next-generation modular nuclear reactors and energy conversion systems, with particular reference to the Balance of Plant (BoP) and Brayton-cycle modelling. After outlining the energy context and the role of nuclear power in a low-carbon mix, the work develops a benchmark of the main SMR and MMR concepts, used to select three representative case studies: AMR, eVinci and OTRERA 300.

The methodological approach treats the reactor as a characterised heat source, defined by thermal power, hot-side temperature, heat-transfer fluid and interface constraints. On this basis, the BoP is the object of analysis. Thermo-fluid dynamic modelling was carried out in THERMOFLEX through a reverse-engineering procedure in which pressure ratio is the key parametric variable, while working-fluid mass flow rate is determined iteratively according to source constraints.

For AMR, a multi-fluid analysis was performed using air, helium, nitrogen and CO₂, comparing simple and recuperated layouts. Results show a strong sensitivity to working fluid: helium gives the highest net efficiencies, air and nitrogen show intermediate and stable behaviour, whereas CO₂, though less favourable in the simple cycle, shows significant potential in the recuperated one. For eVinci, modelled as an open-air Brayton cycle, net efficiency increases with pressure ratio, while the recuperator is mainly beneficial at low PR values. For OTRERA 300, modelled as a closed nitrogen Brayton cycle, internal heat recovery is advantageous across the PR range, with maximum performance in a recuperated configuration at intermediate PR.

Overall, the thesis shows that BoP performance depends not only on source thermal level, but also on working fluid, cycle structure and internal heat recovery. Its main contribution lies in defining a coherent methodological framework for interpreting the relationship between reactor concept and conversion-system performance.

Table of Contents

Chapter 1 – Energy landscape, advanced nuclear power, and SMR/MMR benchmarking.....	9
1.1 Global energy landscape and electricity generation.....	9
1.2 The role of nuclear power in the energy system.....	10
1.2.1 Why nuclear power is relevant to electricity generation.....	10
1.2.2 Strengths and main challenges.....	11
1.2.3 The role of nuclear power in the low-carbon mix.....	11
1.3 SMRs and MMRs: technological and industrial interest.....	12
1.3.1 Definition of SMRs and MMRs.....	12
1.3.2 Differences compared to conventional reactors.....	13
1.3.3 Reasons for the growing interest.....	15
1.3.4 State of development and diversity of the technological landscape.....	15
1.4 General structure and types of nuclear reactors.....	15
1.4.1 Main components of a nuclear power plant.....	15
1.4.2 Core, fuel, moderator and coolant.....	17
1.4.3 Main reactor families relevant to SMRs/MMRs.....	18
1.4.4 Reactor parameters of interest for the comparative analysis.....	23
1.5 Construction of the SMR/MMR benchmark.....	25
1.5.1 Sources used and inclusion criteria.....	25
1.5.2 Structure of the Excel table and field dictionary.....	26
1.5.3 Data normalisation and inconsistency management.....	27
1.5.4 Usefulness of the benchmark for case study selection.....	28
Chapter 2 – Balance of Plant, Brayton cycle and thermofluid dynamic model setup.....	29
2.1 From the reactor to the Balance of Plant.....	29
2.2 Conversion cycles for nuclear applications and the choice of Brayton.....	29
2.3 The Brayton cycle for nuclear applications: operation, configurations and key parameters.....	31
2.3.1 Simple cycle and physical significance of heating.....	31
2.3.2 Open, closed and recovered configurations.....	31

2.4 Model setup and reverse engineering procedure.....	34
2.4.1 Data imposed on the source side.....	34
2.4.2 BoP-side variables and iterative procedure.....	34
2.5 Implementation in THERMOFLEX and criteria for interpreting results.....	36
Chapter 3 – Case studies and simulation setup.....	37
3.1 Case study selection criteria.....	37
3.2 Common methodological framework for the simulations.....	37
3.2.1 Common simulation assumptions.....	37
3.2.2 Calculation procedure and monitored parameters.....	38
3.3 AMR case study.....	39
3.3.1 Concept profile and reactor data.....	39
3.3.2 Simulation setup for the AMR case.....	40
3.4 eVinci case study.....	41
3.4.1 Concept profile and reactor data.....	41
3.4.2 Simulation setup for the eVinci case.....	42
3.5 OTRERA 300 case study.....	43
3.5.1 Concept profile and reactor data.....	43
3.5.2 Simulation setup for the OTRERA 300 case.....	44
3.6 Summary of the simulation campaign and link to the results chapter.....	45
Chapter 4 – Simulation results and technical discussion.....	47
4.1 Criteria for interpreting the results.....	47
4.2 Results of the AMR case.....	48
4.2.1 Variation in net efficiency with changes in working fluid and pressure ratio.....	48
4.2.2 Role of the recuperator in the AMR case.....	52
4.2.3 Summary of the AMR case.....	52
4.3 Results of the eVinci case.....	53
4.3.1 Net efficiency and pressure ratio trends.....	53
4.3.2 Resulting mass flow rate and cycle structure.....	54
4.3.3 Summary of the eVinci case.....	55

4.4 Results of the OTRERA 300 case.....	56
4.4.1 Net efficiency trend in the closed nitrogen Brayton cycle.....	56
4.4.2 Characteristic temperatures and resulting mass flow rate.....	58
4.4.3 Summary of the OTRERA 300 case.....	58
4.5 Cross-cutting discussion of the results.....	59
4.6 Final application considerations.....	60
Conclusions:.....	61
Appendix A – List of acronyms.....	64
Appendix B – Dataset structure (Excel) and methodology.....	67
References:.....	81

Chapter 1 – Energy landscape, advanced nuclear power, and SMR/MMR benchmarking

1.1 Global energy landscape and electricity generation

The global energy system is undergoing a phase of transformation in which three needs are increasingly overlapping: rising electricity demand, the need to reduce climate-altering emissions, and the maintenance of security of supply. In this context, electricity is taking on an increasingly central role in decarbonisation processes, since the electrification of end uses is one of the main levers for reducing the direct use of fossil fuels in the residential, industrial, and transport sectors [1], [2].

According to the International Energy Agency (IEA), global electricity demand grew by 4.3% in 2024 and is expected to increase at a rate of around 4% per year over the 2025–2027 period. The largest share of this growth is attributed to emerging and developing economies, particularly China, India, and Southeast Asia, whilst in advanced countries electricity demand is rising again due to the proliferation of data centres, the electrification of end uses, and increasing cooling requirements [2].

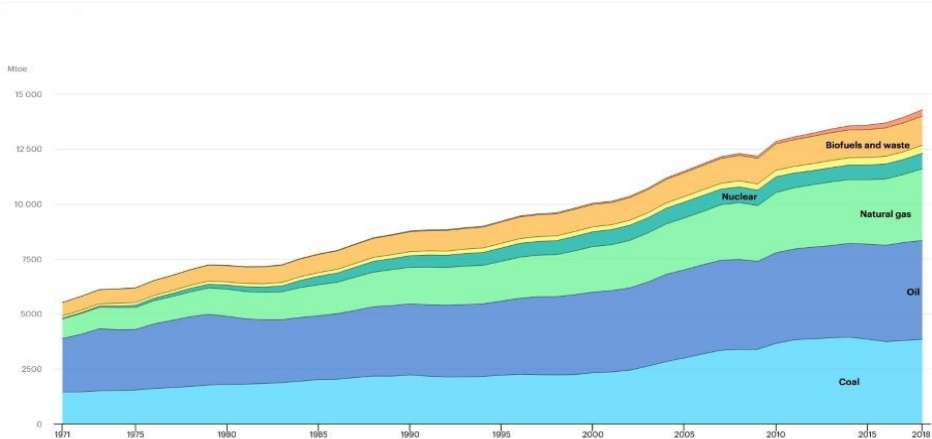


Figure 1 : Evolution of global energy consumption by primary source over the period 1970–2018. Source: IEA, World Energy Balances, 2020

The increase in electricity generation from non-dispatchable renewable sources, particularly wind and solar power, is an essential element of the energy transition process; however, the growing penetration of these sources makes the availability of resources capable of providing dispatchable power, system inertia and grid stability support even more critical. Given rising electricity demand and increasingly electrified energy systems, the issue of energy security therefore concerns not only the quantity of energy available, but also the quality of the electricity service and the continuity of supply [1], [2].

In this context, nuclear power continues to represent a technology of strategic interest. The 2025 IEA report highlights how the sector is entering a new phase of political and industrial focus, driven by energy security needs, climate targets and the growth in electricity demand [1].

The renewed interest in this source stems not only from its low emissions intensity throughout the life cycle, but also from its ability to provide baseload power and contribute to the robustness of the electricity system in scenarios with high penetration of renewable sources. Building on this general overview, this chapter introduces the role of nuclear power in the electricity mix, the growing interest in SMRs and MMRs, and the approach taken to develop a comparative benchmark useful for the subsequent selection of case studies.

1.2 The role of nuclear power in the energy system

1.2.1 Why nuclear power is relevant to electricity generation

In the context of the energy transition, nuclear power continues to be a key technology for electricity generation thanks to its ability to provide programmable power, high availability and low direct carbon dioxide emissions during operation. According to **the IEA**, nuclear generation is set to reach a new all-time high in 2025, and nuclear power is now the world's second-largest source of low-emission electricity after hydropower; however, its significance stems not only from its quantitative contribution to electricity generation, but also from the systemic characteristics that distinguish it from other low-carbon options. In particular, nuclear power plants are capable of delivering power continuously, reducing dependence on weather conditions and contributing to the stability of the electricity system in contexts characterised by the growing penetration of non-dispatchable renewable sources.

From an energy-industrial perspective, nuclear power is therefore a suitable technology for providing baseload generation and, in principle, also flexibility services within defined operational limits. Its role is particularly significant in systems that simultaneously pursue the three objectives listed at the beginning of this chapter; indeed, the IEA highlights how nuclear power can strengthen energy security precisely at a time when rising electricity demand requires reliable, low-emission capacity.

In this paper, this significance is considered specifically from the perspective of electricity generation. Nuclear power is therefore not introduced as a general energy policy issue, but as a high-energy-density heat source that enables the study of advanced conversion configurations, in particular using the Brayton cycle. From this perspective, the reactor is not the primary focus of plant optimisation, but rather the system that defines the framework and boundary conditions within which the Balance of Plant (**BoP**) can be configured and analysed [1], [2].

1.2.2 Strengths and main challenges

The main strengths of nuclear power relate first and foremost to **operational continuity**, the **high capacity factor** (defined as the ratio of the energy actually produced over a period to the maximum theoretical energy producible at rated power) typically associated with such plants, the **reduced land footprint** per unit of energy produced, and the very **low emissions profile** during operation. Added to this is the potential to contribute to the diversification of the electricity mix, reducing exposure to geopolitical shocks and fossil fuel price fluctuations. In system terms, nuclear power therefore offers a form of low-carbon generation that is not dependent on the daily or seasonal variability of renewable resources.

Alongside these elements, well-known challenges remain. The first concerns the initial investment costs, which are generally very high, and the difficulty of keeping construction times and the risk of cost overruns under control in large-scale projects. The IEA highlights that the main obstacles to the rapid expansion of nuclear power are precisely costs, project risks, access to finance and regulatory uncertainty [1].

A second critical issue concerns the complexity of the regulatory, safety and social acceptance frameworks. Nuclear technology requires very high standards of design, operation, spent fuel management and radioactive waste treatment. These aspects do not negate the importance of nuclear power in the low-carbon mix, but they strongly influence the timing, costs and methods of its deployment. IAEA and NEA documents show that the development of new modular solutions is closely linked not only to technological innovation, but also to credible pathways for licensing, supply chains and fuel availability [1], [2].

From a technical perspective, it is also necessary to distinguish between the theoretical potential of advanced technologies and their actual level of industrial maturity. A significant proportion of **SMR** and **MMR** concepts are still in pre-commercial or demonstration phases, which implies that the available data may be heterogeneous, incomplete or, in any case, not perfectly consistent across different sources. This observation is particularly important for the comparative benchmark developed in this thesis, as it requires caution in the normalisation of data and the subsequent selection of case studies. It follows that nuclear power cannot be treated as a one-size-fits-all solution but, from an engineering perspective, must be considered as one of the most viable options available for low-carbon electricity generation, characterised by significant systemic advantages but also by stringent technical and economic constraints. It is precisely this balance between potential and limitations that justifies an analytical approach based on physical parameters, expected performance, technological maturity and plant compatibility [1], [3].

1.2.3 The role of nuclear power in the low-carbon mix

Within the low-emission electricity mix, nuclear power occupies a unique position: unlike non-dispatchable renewable sources, it can contribute in a stable manner to load coverage; compared to fossil fuels with CO₂ capture, however, it presents a different profile in terms of maturity, infrastructure requirements and supply chain challenges. From this perspective, its

role is not to fully replace other low-carbon technologies, but to integrate with them within diversified energy portfolios [1], [2].

For the purposes of this thesis, the positioning of nuclear power within the low-carbon mix is significant primarily as a methodological premise for the subsequent case studies. Interest in SMRs and MMRs does not, in fact, stem from an abstract assessment of the technology, but from the possibility that such systems offer conditions of temperature, size and interface that make the analysis of the energy conversion system meaningful.

1.3 SMRs and MMRs: technological and industrial interest

1.3.1 Definition of SMRs and MMRs

The acronym **SMR** stands for *Small Modular Reactors*, i.e. nuclear reactors that are smaller in size than conventional plants and designed according to principles of modularisation, standardisation and serial manufacture of components or subsystems. In **IAEA** literature, the category of small and medium-sized modular reactors encompasses a wide range of solutions, differing in terms of power, coolant, neutron spectrum, fuel configuration and intended application.

In this paper, the term SMR is used in a functional sense to refer to small reactors below 300 MWe [3] designed for power generation and characterised by greater modularity than large traditional nuclear plants. This modularity may refer both to factory-built modules and to the possibility of use in multi-module configurations on site.

The term **MMR**, on the other hand, refers to *Micro Modular Reactors* or, more generally, to microreactors. These are systems with even lower power output, typically below 10 MWe [3], designed for decentralised applications, remote sites, isolated loads or specific energy requirements, often with a strong emphasis on compactness, long fuel autonomy, simplified plant design and reduced on-site operational interventions. The most recent **IAEA** documents treat **MRs** as part of the advanced landscape with potential use not only for electricity but also for process heat and other energy applications; however, in this paper the focus remains on conversion to electrical power.

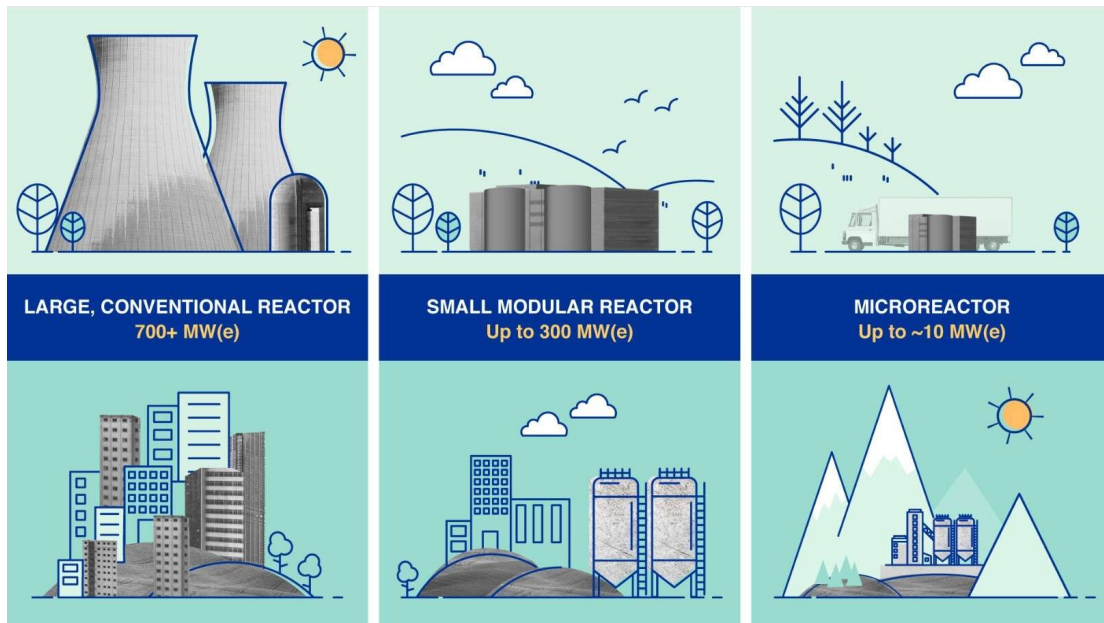


Figure 2 : Classification of Modular Reactors – Source: Greenreport, 2025

From a classification perspective, **SMRs** and **MMRs** () do not constitute a single technological family, but rather a collection of diverse solutions. These include light-water reactors of an evolutionary design, sodium- or lead-cooled fast reactors, high-temperature gas-cooled systems, as well as other advanced architectures. It follows that interest in these technologies cannot be reduced to size alone: rather, it concerns the combination of size, design philosophy, safety characteristics, site requirements and integration with specific energy conversion schemes.

1.3.2 Differences compared to conventional reactors

Compared to conventional large-scale reactors, SMRs/MMRs are distinguished first and foremost by their lower unit power, which can substantially alter the plant design challenges. Lower thermal power, in fact, entails different scales for components, heat exchangers, turbomachinery, plant layouts and strategies for integrating the fuel source with the conversion system. A second difference concerns the design philosophy. Many SMR concepts are developed with the aim of increasing standardisation, reducing on-site construction complexity and improving industrial replicability. In principle, this should allow for greater control over costs and timelines compared to the ‘site-specific’ construction typical of large reactors, although this advantage remains to be fully demonstrated on a commercial scale for many technologies still under development.

In terms of safety, numerous SMR/MMR projects emphasise the use of passive systems, lower fuel inventories, greater integration of the vessel or primary circuit, and configurations that simplify certain safety functions. Here too, however, the expected improvement in safety does not stem solely from a reduction in size, but from the overall design of the system and its effective regulatory validation.

A fourth difference lies in the greater technological diversity of the SMR/MMR landscape. Whilst the global conventional nuclear fleet has historically been dominated by light-water reactors, the advanced modular segment encompasses very different technological families, with vastly differing outlet temperatures, pressures, coolants and thermal interfaces. This aspect is of particular interest for a thesis focused on the Balance of Plant, as it directly influences the choice of power cycle, working fluid and thermodynamic constraints on the hot-end side [3]-[5].

The growing interest in SMRs and MMRs stems from the convergence of energy, industrial and strategic factors.

- From an energy perspective, these reactors are seen as potential tools for expanding the supply of programmable low-carbon electricity in a context of rising demand and the progressive decarbonisation of electricity systems [1]-[3].
- From an industrial perspective, modularisation promises greater production scalability and a reduction in barriers to entry compared to large-scale plants, at least for certain markets and applications [1]-[3].
- Strategically, these systems may be suitable for smaller-scale electricity grids, remote sites, dedicated industrial areas, or contexts where the construction of a conventional nuclear plant would be excessive in terms of installed capacity, initial investment or logistical complexity [3], [5], [8].

Attribute	Subattribute	Benefits
Operational flexibility	Maneuverability	Load following
	Compatibility with hybrid energy systems and poly-generation	Economic operation with increasing penetration of intermittent generation, alternative missions
	Diversified fuel use	Economics and security of the fuel supply
	Island operation	System resiliency, remote power, micro-grid, emergency-power applications
Deployment flexibility	Scalability	Ability to deploy at scale needed
	Siting	Ability to deploy where needed
	Constructability	Ability to deploy on schedule and on budget
Product flexibility	Electricity	Reliable, dispatchable power supply
	Process heat	Reliable, dispatchable process-heat supply
	Radioisotopes	Unique or high demand isotope supply

Figure 3 : Advanced Reactors Benefits – Source: Handbook of Generation IV Nuclear Reactors, 2023

Figure 3 summarises the main attributes associated with advanced reactors and highlights how modularity, flexibility, safety and potential energy integration are recurring elements in their value proposition.

Within the scope of this thesis, the primary focus lies in the possibility of combining these heat sources with conversion schemes that are more targeted and better suited to the available temperature range. In particular, certain gas- or liquid-metal-cooled technologies make the study of direct or indirect Brayton cycles particularly relevant.

1.3.3 Reasons for the growing interest

1.3.4 State of development and diversity of the technological landscape

The contemporary **SMR/MMR** landscape is broad and highly heterogeneous. **The IAEA** reports the existence of over 80 SMR projects at various stages of maturity, whilst **NEA** documentation shows that the paths to deployment depend on a variety of factors: licensing, fuel, supply chain, siting, financing and industrial capacity [1]-[3].

Not all projects are, in fact, at the same stage of development. Some are based on technologies relatively close to those of light-water reactors and follow more evolutionary paths; others, however, incorporate more radical choices, such as unconventional coolants, fast neutron spectra or higher operating temperatures, with interesting prospects but more uncertain industrial maturity. This heterogeneity makes a rigorous selection of case studies essential and justifies the construction of a structured benchmark. The nature of the primary coolant, the available temperature range, the operating pressure, the nominal thermal power and the maturity of the concept all influence the definition of the interface between the reactor and the BoP. From this perspective, the classification and comparison of reactors serve not only to organise the SMR/MMR landscape, but above all to identify representative heat sources to be incorporated into the thermo-fluid dynamic model developed in the following chapters.

In conclusion, technological and industrial interest in SMRs and MMRs depends on the potential for these systems to offer new combinations of plant scale, modularity, safety, useful temperatures and integration with advanced conversion cycles. On this basis, the remainder of this chapter examines the plant design aspects of the main reactor families and the benchmark used for selecting the case studies.

1.4 General structure and types of nuclear reactors

1.4.1 Main components of a nuclear power plant

From an engineering perspective, a nuclear power plant for electricity generation can be described as the integration of two main functional blocks: the **nuclear heat generation and transfer system** and the **conventional energy conversion system**. In commonly used terminology, these two blocks correspond respectively to the **Nuclear Island** and the **Balance of Plant (BoP)**. This distinction is widely used in technical and plant engineering literature because it allows the systems directly involved in thermal power generation and nuclear

safety functions to be separated from those responsible for converting thermal energy into useful electrical power and managing the plant's auxiliary services [7], [9].

The **Nuclear Island** comprises all the structures, components and systems directly connected to the generation of heat through fission, its removal from the core and the fulfilment of the main safety functions. This includes the reactor, the core, the primary vessel, the internal structures, the control and shutdown mechanisms, the cooling circuits, any interface heat exchangers present within the nuclear block, as well as the physical barriers and systems intended for the containment of radioactive materials [7], [9]. In many design contexts, the technical core of the Nuclear Island largely coincides with the **Nuclear Steam Supply System (NSSS)**, that is, the set of systems that generate nuclear heat and make it available to the conversion system. The handbook on fourth-generation reactors explicitly highlights the distinction between the requirements of **the nuclear island** and those of **the power generation plant**, emphasising that the separation between the nuclear side and the conventional side is also a design criterion, not merely a descriptive one [7].

The **Balance of Plant**, on the other hand, comprises the set of systems that receive thermal energy at the interface with the nuclear island and convert it into electrical energy, as well as the auxiliary and service systems necessary for the operation of the conventional plant. In a traditional Rankine cycle-based nuclear power plant, the BoP typically includes a steam turbine, electric generator, condenser, feedwater pumps, regenerative heaters, condensate extraction systems, cooling systems, electrical power systems and plant utilities. In different configurations, such as those based on the Brayton cycle, it instead comprises compressors, a turbine, a recuperator, hot-side and cold-side heat exchangers, working fluid lines, control devices and all the subsystems necessary to complete the conversion cycle [10]-[12].

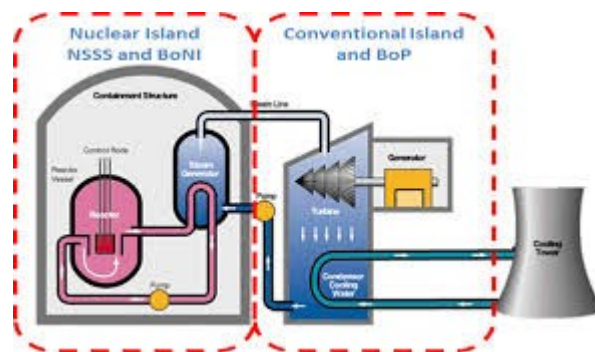


Figure4 : Example of a Nuclear Island and Balance of Plants – Source: Delta Mobrey

This functional division also applies to **SMRs and MMRs**, but in modular systems it may take on less distinct physical configurations. Many SMR designs, in fact, adopt solutions involving high integration of the primary system, with a reduction in external piping, a limitation on the number of large separate components and, in several cases, the placement of multiple NSSS elements within a single compact configuration [5], [6], [8]. The **ARIS** catalogue and **IAEA** reports show, for example, numerous integrated designs in which the

core, steam generators, pressuriser and other primary components are highly compacted compared to traditional layouts [5], [6]. In such cases, whilst the separation between the nuclear and conventional parts remains conceptually distinct, it becomes even more important to precisely identify the **thermal interface point** between the two blocks, i.e. the point at which the heat removed from the reactor is made available to the conversion cycle.

1.4.2 Core, fuel, moderator and coolant

Within the Nuclear Island, certain subsystems play a central role because they define the reactor's architecture and directly influence the conditions under which heat can be transferred to the conventional system.

The **core** constitutes the subsystem in which the controlled fission reaction takes place and in which the plant's thermal power is generated. From a plant engineering perspective, it should not be viewed as an isolated element, but as a closely integrated assembly of fuel, internal structures, coolant flow channels and reactivity control devices. The core is, in fact, the point at which neutron phenomena, heat production and the thermohydraulic removal of the generated power are coupled, and for this reason it represents the central element of reactor design [7], [9].

Nuclear fuel is the fissile or fertile-fissile material in which the nuclear reaction takes place. Its form, composition and configuration depend on the reactor technology and have a substantial impact on power density, burn-up, thermal limits, transient behaviour and heat removal methods. In light-water reactors, uranium oxide-based ceramic fuels in structured fuel elements predominate; in advanced systems, different solutions appear, such as metallic fuels, carbides, nitrides or TRISO particles in gas-cooled high-temperature reactors [7], [8]. Although a comprehensive discussion of the fuel would require a detailed examination of neutronics and the fuel cycle, in this work it is particularly relevant as it determines the permissible temperatures in the core, the power distribution and, indirectly, the characteristics of the heat that can be transferred to the conversion system.

The moderator is the material which, in thermal-spectrum reactors, serves to slow down the neutrons produced by fission to energies at which the probability of further fission becomes more favourable. It is therefore essential to distinguish between thermal reactors and fast reactors: in the former, the moderator is an integral part of the system's physics, whilst in the latter it is deliberately avoided to maintain a high-energy neutron spectrum. This distinction has a direct impact on the fuel, coolant, power density and plant configuration [7], [9].

Among the fundamental components of the nuclear system, the **coolant** is the one of greatest interest for the purposes of this thesis. It is, in fact, the medium through which the heat generated in the core is extracted and transported to the outside of the core and, subsequently, to the conversion system. The choice of coolant directly influences:

- the achievable temperature level;
- the operating pressure of the primary circuit;
- the heat removal capacity;

- the configuration of the heat exchangers;
- the possible need for intermediate circuits;
- compatibility with the downstream conversion cycle.

In conventional light-water reactors, the coolant and moderator are generally the same, namely light water, with high pressure levels and limited temperatures compared to many advanced technologies. In high-temperature gas-cooled reactors, the coolant is typically helium (though, as will be seen, there are several possible choices and viable options in this area), which allows for significantly higher outlet temperatures and makes coupling with Brayton cycles particularly attractive [7], [12]. In sodium- or lead-cooled fast reactors, the coolant is a liquid metal, characterised by thermohydraulic behaviour very different from that of water or gases, and by specific interface constraints with the conversion system [7]. Finally, in molten salt reactors, the fluid itself can play multiple roles and make the definition of the boundary between the nuclear zone, heat transport and energy conversion more complex [7].

In plant engineering terms, the **core–fuel–coolant** triad therefore defines the physical and functional heart of the nuclear system, whilst the presence or absence of **a moderator**, and thus the reactor’s neutron spectrum, distinguishes profoundly different families. For the purposes of this discussion, these elements are considered not to develop an exhaustive discussion of nuclear engineering, but because they determine the architecture of the nuclear part and the conditions under which heat can be transferred to conventional systems.

1.4.3 Main reactor families relevant to SMRs/MMRs

The SMR and MMR landscape is characterised by considerable technological heterogeneity. Unlike the currently dominant nuclear fleet, which is heavily concentrated on light-water reactors, the modular and advanced sector comprises families that are very different in terms of neutron spectrum, coolant type, temperature level, plant architecture and potentially associated conversion system [3], [5]–[8].

No.	System	Neutron spectrum	Coolant	Outlet T ($^{\circ}\text{C}$)	Fuel cycle	Size (MW_{el})
1	VHTR	Thermal	Helium	900–1000	Open	250-300
2	GFR	Fast	Helium	850	Closed	1200
3	SFR	Fast	Sodium	500-550	Closed	50-150 300-1500 600-1500
4	LFR	Fast	Lead	480-570	Closed	20-18 300-1200 600-1000
5	MSR	Thermal/Fast	Chloride or fluoride salts	700-800	Closed	300-1000
6	SCWR	Thermal/Fast	Water	510-625	Open/closed	300-700 1000-1500

Figure 5 : Overview of Gen IV Systems - Source: Handbook of Generation IV nuclear reactors

- Light Water Reactors (LWR): these include configurations derived from or evolved from traditional PWRs and BWRs and represent, even within the SMR landscape, the development path closest to the industrial experience gained in commercial nuclear power. These are generally thermal spectrum systems, in which water typically serves as both coolant and moderator. From an engineering perspective, they are in line with the technology currently dominant in the global nuclear fleet and are therefore favoured in terms of technological familiarity, the supply chain and licensability. However, it is precisely the coolant and the typical operating conditions of LWRs that place this family at significantly lower thermal levels compared to many Generation IV solutions; consequently, the interface with the conventional system remains, in most cases, naturally associated with Rankine cycles, whilst interest in high-temperature cycles is more limited [5], [6], [8].
- High-Temperature Gas-Cooled Reactors (HTGRs) and Very High-Temperature Reactors (VHTRs): these are helium-cooled, graphite-moderated reactors using all-ceramic fuel, with a strong emphasis on the retention of fission products within the fuel and the ability to operate at temperatures significantly higher than those of LWRs. HTGRs typically operate at coolant outlet temperatures of around 750–850 $^{\circ}\text{C}$, whilst the VHTR represents an evolution towards temperatures approaching 950–1000 $^{\circ}\text{C}$, with more stringent requirements on structural materials. These conditions make this family particularly attractive for energy conversion: the handbook and Yan’s paper highlight its strong compatibility with direct or indirect helium Brayton cycles and, more generally, with high-temperature applications [7], [12].

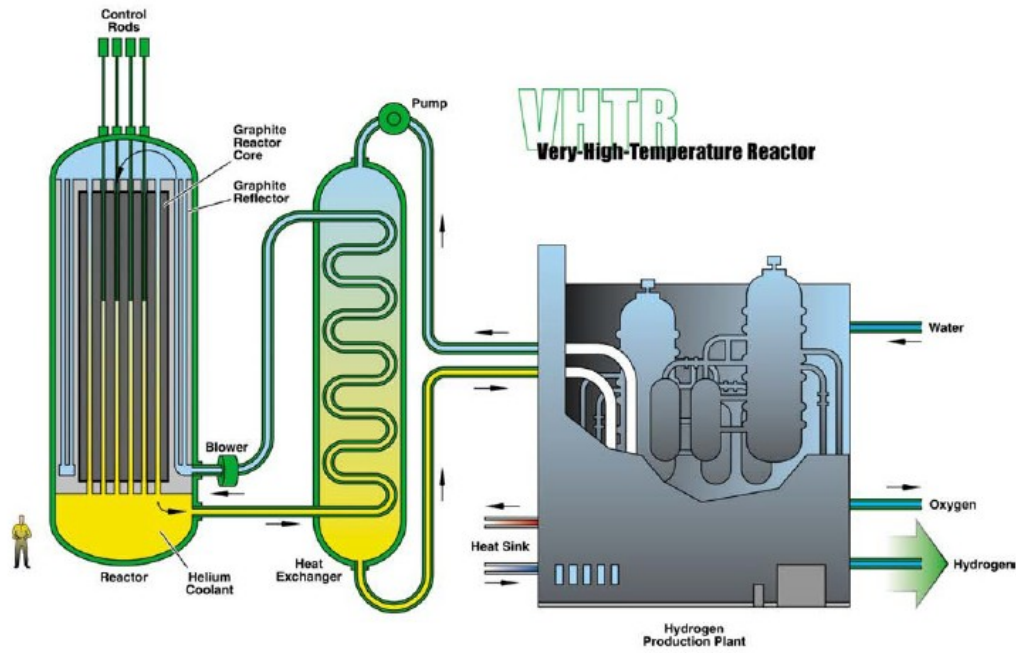


Figure6 : Very-High-Temperature Reactor (VHTR) - Source: GIF

- Sodium-cooled Fast Reactors (SFR): these are fast reactors cooled by liquid sodium. In this case, the defining feature is not only the coolant, but the entire system configuration: these are fast-spectrum reactors, without a moderator, designed with a closed fuel cycle in mind, with the possibility of utilising plutonium and minor actinides. From a thermo-fluid dynamic perspective, sodium exhibits excellent heat transfer properties and allows operation at typical temperatures in the range of 500–550 °C with very low pressures in the primary circuit. However, sodium’s high chemical reactivity with water and air imposes specific safety constraints and decisively influences the design of the connection to the conventional system, which generally takes place via a chain comprising a sodium primary circuit, an intermediate heat exchanger, an intermediate circuit, and only subsequently the conversion system [7].

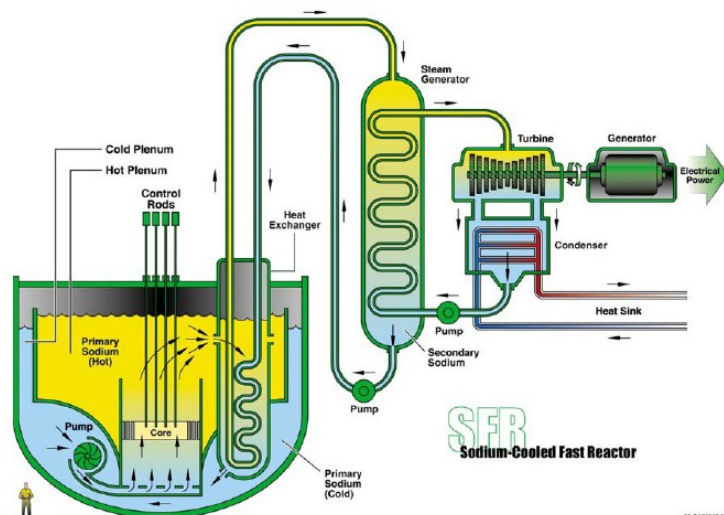


Figure7 : Sodium-cooled Fast Reactor (SFR) - Source: GIF

- Lead-cooled Fast Reactors (LFR): these are fast reactors cooled by lead or a lead-bismuth alloy. These systems also operate in the fast spectrum and share with SFRs an interest in advanced fuel cycles, but they differ markedly in terms of the properties of the coolant. Lead and lead-bismuth, in fact, allow for low-pressure operation combined with relatively high temperatures and exhibit much lower chemical reactivity than sodium when in contact with water and air. This has direct implications for plant design: in various LFR configurations, it may be possible to eliminate the intermediate loop typical of sodium systems, precisely because the coolant does not present the same chemical criticality when in contact with the secondary circuit. This family is therefore of particular interest for comparisons where one wishes to distinguish the effect of the thermal level from that of the interface architecture with the BoP [7].

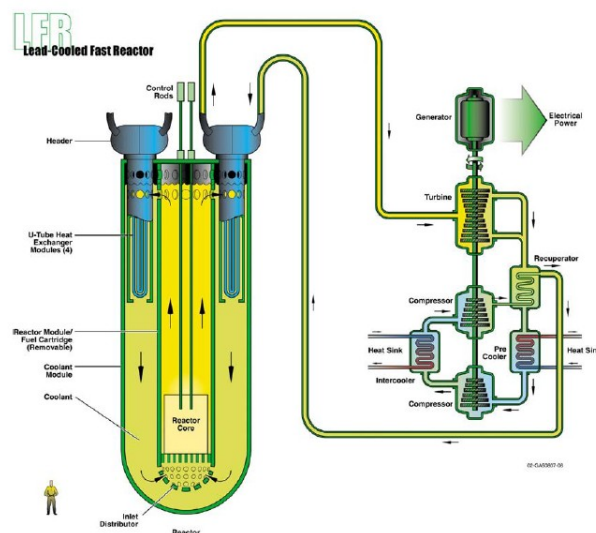


Figure8 : Lead-cooled Fast Reactor (LFR) -
Source: GIF

- Gas-cooled Fast Reactors (GFR): combine a fast spectrum with helium cooling, with typical temperatures up to around 850 °C and natural compatibility with direct or indirect Brayton cycles; from a conceptual standpoint, they represent one of the most interesting families for high-efficiency conversion systems, although they are less mature from an industrial perspective [7].

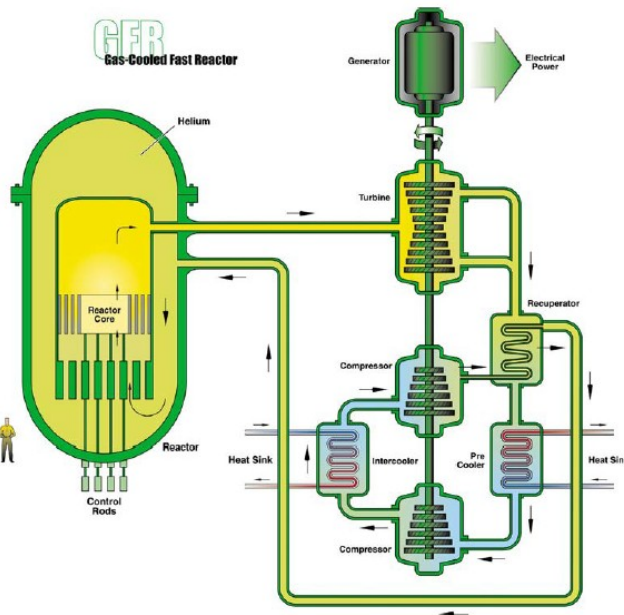


Figure9 : Gas-cooled Fast Reactor (GFR) - Source: GIF

- Molten Salt Reactors (MSR): these include both thermal and fast configurations and use fluoride or chloride salts as coolants, sometimes also as the medium hosting the fuel. The handbook associates these systems with typical outlet temperatures in the range of 700–800 °C and highlights their low operating pressure, limited vapour pressure and wide conceptual variety, which makes standardisation of the interface between the reactor, heat transport and conversion system less straightforward [7].

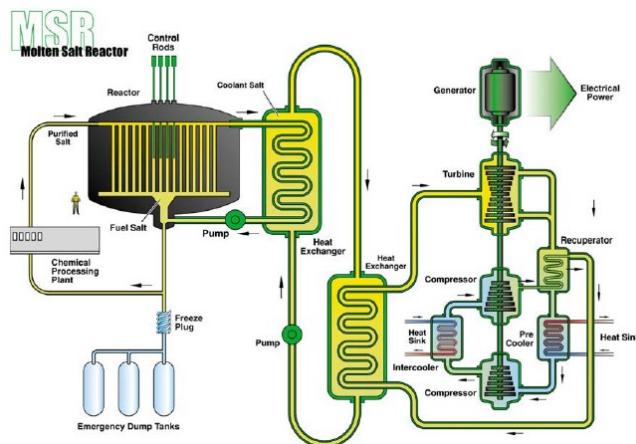


Figure10 : Molten Salt Reactor (MSR) - Source: GIF

- Supercritical Water-cooled Reactors (SCWR): these constitute the only water-cooled family within the GIF and are based on the use of supercritical water, with very high pressures and temperatures that can reach approximately 510–625 °C; from the perspective of the power cycle, this family is naturally linked to an evolution of the supercritical Rankine cycle, rather than to gaseous Brayton cycles [7].

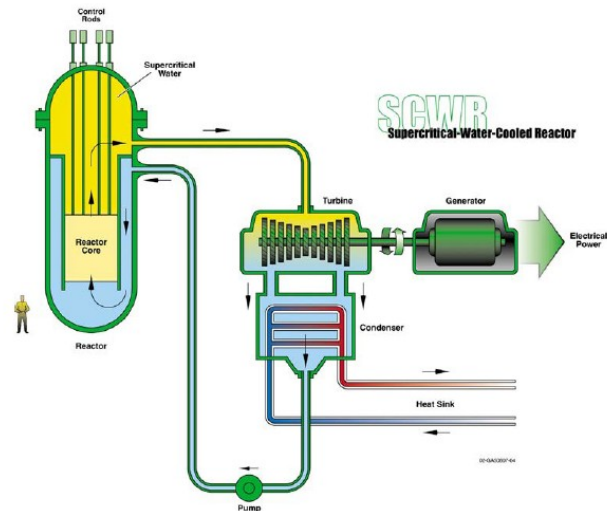


Figure 11 : Supercritical Water-cooled Reactor (SCWR) - Source: GIF

In comparative terms, the classification of reactor families serves primarily to highlight that, behind the general acronym SMR/MMR, there are technologies that differ profoundly in terms of:

- available temperature range;
- nature of the coolant;
- the need for one or more intermediate circuits;
- compatibility with Rankine, Brayton or other configurations;
- the manner in which the nuclear component interfaces with the conversion system.

This point is crucial to avoid an overly generalised view of the sector. To speak of SMRs or MMRs as if they were a single technology would in fact be misleading: from an energy and plant engineering perspective, the challenges posed by a light-water reactor are fundamentally different from those posed by an HTGR, an SFR or an LFR.

1.4.4 Reactor parameters of interest for the comparative analysis

To develop a comparative analysis useful for the purposes of this thesis, it is not necessary to consider the entire set of parameters normally used in detailed nuclear design. Instead, it is appropriate to identify a subset of parameters capable of describing the reactor in terms that are significant from an energy and plant engineering perspective, so as to be able to compare different technologies according to criteria consistent with the objective of the work.

The first parameter of interest is the **nominal thermal power**. This represents the level of energy made available by the nuclear system and forms the basis for any analysis of the conversion system's design. Thermal power is also necessary to correctly interpret the relationship between reactor size, expected electrical power and the plant's overall architecture. In modular reactors, this parameter takes on particular significance, because one

of the main differences compared to large conventional plants lies precisely in the smaller unit size of the module.

Alongside thermal power, a second fundamental parameter is the **nominal electrical power** stated in the design. Although this value cannot be directly transferred from one concept to another without caution, it provides a concise indication of the overall performance level associated with the conversion configuration envisaged by the designer. It should be noted, however, that the electrical power stated in the technical data sheets depends on the type of cycle adopted, the assumed efficiencies and the nominal conditions considered; it is therefore purely indicative and cannot be used as an absolute figure without taking the design context into account, a point that will be utilised as design flexibility for the plant [3], [5], [6], [7], [8].

Of particular importance is the **temperature of the hot fluid** associated with the reactor. In reality, this parameter requires clarification: there is not always a single ‘reactor temperature’ that is unambiguously significant for the conversion system. A distinction must in fact be made between:

- the temperature at the core outlet;
- the coolant temperature in the primary circuit;
- temperature at the inlet of the interface heat exchanger;
- the temperature actually available to the conventional side after any intermediate stages and heat losses.

This distinction is essential, because reactors formally characterised by high temperatures may subsequently make values effectively lower than these available to the conversion system due to the presence of intermediate circuits, thermal drops in the heat exchangers or other plant constraints [7]. For a thesis focusing on the relationship between the reactor and the power cycle, it is therefore not sufficient to know the maximum temperature in the core; it is necessary to understand what thermal level is actually accessible to the conventional system.

A further parameter of great importance is the **type of coolant**, together with the associated **architecture of the heat transport circuits**. The coolant is in fact not merely a technical fluid, but a factor that profoundly influences the plant design. Water, helium, sodium, lead or molten salts entail different levels of temperature, pressure, heat capacity, conductivity, thermal inertia and safety constraints. Added to this is the different configuration of the connection between the nuclear and conventional parts:

- in some cases, heat transfer to the cycle is direct;
- in other cases, an intermediate circuit is required;
- in yet others, the transfer chain may be organised across multiple levels.

This aspect is crucial for understanding the extent to which conditions on the reactor side subsequently affect the layout and performance of the conversion cycle [7], [9].

The **operating pressure of the primary system** is also a significant parameter, as it helps define the technological constraints, the robustness of the components, the configuration of

the heat exchangers and, indirectly, the management of the interface with the conventional side. High-pressure gas reactors, supercritical water systems, pressurised water reactors and liquid metal reactors operate under very different conditions, and these differences are reflected both in the design of the nuclear power plant and in the form of the connection to the conversion system [7], [9].

In addition to strictly thermo-fluidodynamic parameters, quantities and information of a more general nature may also be useful for comparative analysis, such as:

- type of neutron spectrum;
- presence or absence of a moderator;
- vessel, loop or pool configuration;
- planned number of modules;
- stage of development and technological maturity;
- availability of project data.

These elements do not directly affect the cycle's energy balances, but are important when selecting representative and technically meaningful case studies. The NEA Dashboard, for example, clearly shows how the assessment of SMR projects depends not only on nominal power or temperature parameters, but also on factors such as industrial development, fuel availability, supply chain, licensing and overall readiness [3].

In summary, the parameters of interest for comparative analysis are those that allow for a coherent description of:

- the **energy scale** of the system;
- the **thermal level** of the available power;
- the **nature of the heat transfer fluid**;
- the **structure of the interface** between the nuclear and conventional parts;
- the **degree of maturity and technical clarity** of the concept.

It is these data that enable, in the subsequent work, the transition from the classification of reactors to the selection of case studies and the subsequent analysis of the conversion system.

1.5 Construction of the SMR/MMR benchmark

1.5.1 Sources used and inclusion criteria

The construction of the SMR/MMR benchmark (Appendix B) constitutes an essential methodological step in this work, as it allows a broad and heterogeneous technological landscape to be transformed into an ordered set of comparable data, useful for the selection of case studies. The benchmark is not intended as an exhaustive catalogue of all existing or

proposed reactor concepts, but as a tool to support comparative analysis, aimed at organising the most relevant information from an energy and plant engineering perspective and making the link between reactor characteristics and possible configurations of the conversion system clear.

The main sources used for this activity are the most authoritative and up-to-date institutional and technical-scientific documents on the subject. In particular, the NEA Small Modular Reactor Dashboard [3] serves as a fundamental reference for assessing the progress of projects, their level of maturity, and the key industrial and regulatory aspects associated with SMR development. The volume Nuclear Power Reactors in the World [4] provides an overview of the global nuclear sector, which is useful for situating the SMR/MMR sector within the broader context of nuclear power generation. The report Small Modular Reactors: Advances in SMR Developments 2024 [5] provides an essential comparative basis for classifying technologies, whilst the ARIS Small Modular Reactor Technology Catalogue [6] is particularly useful for finding technical and descriptive project data. These are complemented by the Handbook of Generation IV Nuclear Reactors [7] and the chapter dedicated to the state of development of SMRs and S&MRs [8], which allow reactors to be interpreted not merely as isolated technical specifications, but as expressions of reactor families with specific implications in terms of thermodynamics and plant design.

The inclusion criteria for the benchmark were defined in line with the objective of the study. Firstly, priority was given to reactors for which a minimum set of technical data useful for describing the plant layout was available: nominal thermal power, reference electrical power, reactor family, coolant type, and sufficient information on the thermal conditions of the hot side or the heat transfer architecture. Secondly, an effort was made to ensure the benchmark was representative of the main technological families, so as not to limit the comparison solely to concepts closest to light-water reactors, but also to include advanced systems potentially relevant to conversion schemes other than the traditional Rankine cycle. Thirdly, importance was attached to the technical clarity of the design, avoiding basing the comparison on concepts for which the publicly available documentation was excessively incomplete or contradictory.

A benchmark constructed using these criteria does not therefore claim to provide an absolute ranking of the best technologies, but rather to establish a methodologically controlled basis from which to identify representative reactors useful for the study of the BoP. At this stage of the thesis, its main function is therefore to organise a complex technological landscape and to provide a robust foundation for the subsequent selection of case studies.

1.5.2 Structure of the Excel table and field dictionary

The Excel table used as a benchmark was constructed with a focus on technical comparability and subsequent modelling utility. For each reactor or concept included, it collects a set of descriptive and quantitative fields selected for their relevance to the thesis's objective. The spreadsheet therefore does not serve a purely archival purpose, but aims to collect and organise the information that is truly significant for the transition from the analysis of the reactor side to that of the conversion system.

The fundamental fields can be grouped into several macro-categories. A first category comprises general identification data, such as reactor name, developer, country of origin, technology family, type of neutron spectrum and development status. A second category concerns nominal size and performance parameters, in particular thermal power, electrical power and the expected number of modules. A third category comprises thermo-fluidodynamic and interface parameters, such as primary coolant, hot-end temperature, the presence of an intermediate circuit where applicable, and the associated energy conversion technology. Finally, a fourth category gathers information regarding the project's maturity and its industrial viability, for example licensing status, the presence of demonstrators, proximity to commercialisation, and the apparent robustness of the supply chain [3], [5]-[8].

This organisation allows each concept to be situated within the SMR/MMR landscape and, at the same time, highlights the variables that most significantly affect the interface with the conversion system.

For the purposes of this thesis, thermal power plays a primary role, as it constitutes the baseline reference for any subsequent analysis of the power circuit. The declared nominal electrical power, whilst useful as a summary indicator, must instead be interpreted with caution, as it depends on the type of cycle adopted, the assumed efficiencies and the nominal conditions considered by the designer.

Particular attention has been paid to the thermo-fluidodynamic interface parameters, as these allow us to describe not only reactor technology in the strict sense, but also the nature of the connection between the nuclear power plant and the conventional system. For a thesis focused on BoP modelling, these data are in many cases more useful than other traditional reactor parameters.

To ensure clarity and reproducibility, the table has been accompanied by a field dictionary, i.e. a concise yet unambiguous description of the meaning of each column. This step is particularly important when combining different sources, which may use terms that are not perfectly interchangeable or refer to quantities that are only apparently equivalent.

In the context of this thesis, the field dictionary performs an essential methodological function: it makes transparent the way in which reactor data are reinterpreted in terms of energy and plant engineering and prepares the subsequent transfer to the BoP simulation model.

1.5.3 Data normalisation and inconsistency management

One of the most delicate aspects in constructing the benchmark concerns data normalisation. SMR/MMR projects are described by different sources, compiled for different purposes and at time stages that do not always coincide; consequently, the available information may be inconsistent, incomplete or seemingly contradictory [3], [5], [6], [8].

Standardisation therefore requires the definition of explicit rules. Firstly, it is necessary to establish which source takes precedence in the event of discrepancies regarding the same parameter. In general, for project classification, development status and overall context, the most recent institutional documents constitute the primary reference; for more specific

technical parameters, specialist catalogues and handbook entries may prove more informative, provided they are read in line with the general framework [3], [5]–[8].

Secondly, quantities must be reported in a uniform format, using consistent units and standardised terminology. Thermal and electrical power must be expressed in clearly defined units; temperatures, pressures and efficiencies must be expressed in accordance with common conventions; any range values or differing nominal conditions must be accompanied by explanatory notes.

When relevant information is unavailable or presents ambiguities that cannot be resolved with reasonable reliability, the methodologically correct approach is not to arbitrarily fill the gap, but to indicate the absence of the data, note the uncertainty, or exclude that parameter from direct comparison. For the purposes of this thesis, the objective is not to maximise the amount of data in the spreadsheet, but to ensure that the data used are sufficiently robust to support the selection of case studies and the subsequent modelling of the BoP.

1.5.4 Usefulness of the benchmark for case study selection

The main function of the benchmark is to provide a rational basis for selecting the case studies to be analysed in the following chapters. In an extremely varied landscape, the choice of reactors to be modelled cannot be left to purely descriptive criteria or narrative convenience; it must instead be based on parameters and considerations consistent with the objectives of the work.

From this perspective, the benchmark allows for the identification of configurations that are simultaneously technically comprehensible, sufficiently documented and significant for the purposes of energy conversion. The selection need not necessarily favour the most mature projects in an absolute sense, but rather those best suited to representing different classes of thermo-fluidodynamic problems, i.e. different temperature levels, different coolants and different heat transfer structures.

The benchmark also fulfils a second, less obvious but equally important function: it allows the transition from the overview of the reactor landscape to the selection of a limited number of case studies to be justified transparently. In this sense, it constitutes the methodological bridge between the classification of reactors and the subsequent analysis of the conversion system.

Chapter 2 – Balance of Plant, Brayton cycle and thermofluid dynamic model setup

2.1 From the reactor to the Balance of Plant

Following the overview of the SMR/MMR landscape provided in Chapter 1, the focus shifts from the strictly reactor-related aspects to the energy conversion system, namely the Balance of Plant (**BoP**). In the case of a nuclear power plant, this term refers to **the set of subsystems that convert the thermal power** made available by the source **into net electrical power**: the thermodynamic cycle, turbomachinery, main heat exchangers, cooling systems, heat recovery systems and essential auxiliaries.

In this work, the BoP is not treated as an ancillary section of the plant, but as the primary focus of engineering analysis. The aim of the thesis is not, in fact, to compare the selected reactors in terms of neutronics, licensing or detailed safety, but rather to understand how different nuclear heat sources influence the architecture and performance of the conversion system. From this perspective, the reactor is not treated as a complete design object, but as a heat source characterised by a limited set of interface parameters: available thermal power, hot-end temperature level, nature of the heat transfer fluid, and the main plant constraints associated with heat transfer [3], [7], [9]; these interface parameters are, in turn, associated with the dependent parameters on the BoP side.

This schematisation constitutes a deliberate simplification of the physical problem, but not a trivialisation of it; indeed, it allows us to isolate the quantities that are actually relevant to the power cycle, thereby avoiding extending the analysis to issues which, whilst fundamental to the overall design of a nuclear plant, lie outside the scope of this study. In other words, the Nuclear Island is treated as a heat source characterised by physical and design constraints that act as boundary conditions, whilst the Balance of Plant is studied as a space for configuration and performance analysis.

This approach is particularly suited to the current landscape of advanced reactors and thus the technologies envisaged in SMRs, where concepts that differ significantly in terms of coolant, neutron spectrum, temperature range, size and application purposes coexist [3], [5], [6]. In such a heterogeneous context, an analysis focused exclusively on reactor classification is insufficient to clarify the plant-level consequences of their differences. It is therefore more effective to frame the problem in terms of the relationship between the heat source and the conversion cycle, that is, the way in which the reactor side imposes boundary conditions on the conventional side.

2.2 Conversion cycles for nuclear applications and the choice of Brayton

The conversion of thermal power into electrical power requires the use of a thermodynamic cycle. In the nuclear sector, the historical benchmark is the **Rankine steam cycle**, widely used

in light water reactors (LWRs) and, more generally, in systems where the available temperature, technological maturity and plant configuration favour the use of steam turbines; indeed, the majority of reactors included in the benchmark still employ a conversion cycle utilising a steam turbine. The Rankine cycle therefore serves as a natural point of comparison for any discussion of energy conversion in the nuclear sector [7], [10].

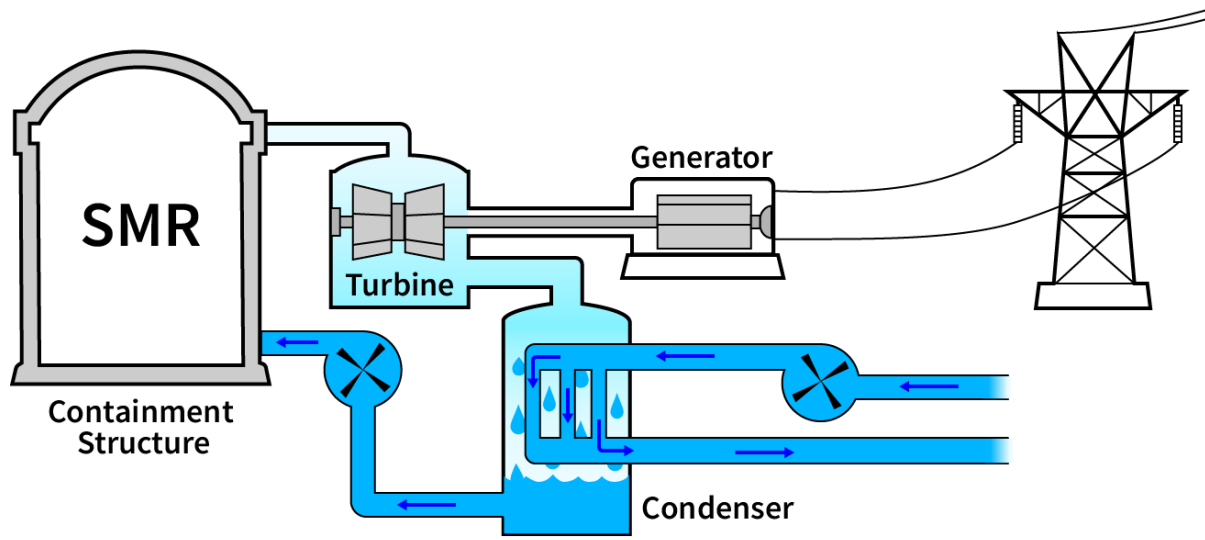


Figure12 : SMR coupled with a Rankine energy conversion system - Source: Stanford Energy, Understand Energy Learning Hub, 2025

An example of a non-water-cooled system that nevertheless employs a Rankine cycle is **the HTR-PM** (Table B.2), a helium-cooled high-temperature modular reactor, in which the reactor heat is transferred to an indirect steam cycle for the production of electricity.

The shift towards advanced and modular reactors has, however, reignited interest in Brayton cycles in open or closed, direct or indirect configurations, sometimes with heat recovery. This interest is linked primarily to three aspects:

1. **Temperature:** The potential to achieve higher thermal levels, making the use of gas turbines and recuperative systems more attractive.
2. **Flexibility:** The second is the greater plant flexibility that the Brayton cycle can offer in certain modular concepts, especially where heat transfer occurs via gas circuits, heat pipes or compact heat exchangers.
3. **Transparency:** The third aspect concerns the analytical clarity of the cycle itself, which is particularly useful in a study aiming to investigate the role of variables such as pressure ratio, mass flow rate of the working fluid and heat recovery [7], [11], [12].

Compared with nuclear power plants currently in operation, which are predominantly based on steam Rankine cycles, the adoption of a Brayton cycle introduces several significant differences in the configuration of the Balance of Plant. In conventional systems, the water-steam circuit requires components such as steam generators, multistage steam turbines, a condenser, and associated feedwater systems. In the Brayton case, by contrast, energy

conversion takes place through a gaseous circuit composed mainly of a compressor, a turbine, a source-side heat exchanger, and, in many configurations, a recuperator.

This architecture changes the role of the Balance of Plant within the nuclear power plant: whereas in Rankine-based systems the conversion cycle is relatively standardized and only weakly sensitive to the specific reactor technology, in Brayton cycles the thermal conditions imposed by the source—particularly the available temperature level and the heat-transfer fluid—directly affect both the configuration and the performance of the cycle. From this perspective, the study of the Balance of Plant assumes a central role in the analysis of the energy architectures associated with advanced reactors.

The choice of the Brayton cycle in this work does not therefore imply a claim of superiority over the Rankine cycle; rather, it stems from a desire to broaden the range of commercially available technologies and focuses on the consistency between the thesis objectives and the nature of the selected case studies. In all case studies, the Brayton cycle allows for a transparent analysis of the relationship between the thermal level of the source, the BoP configuration and the achievable performance.

2.3 The Brayton cycle for nuclear applications: operation, configurations and key parameters

2.3.1 Simple cycle and physical significance of heating

In its simplest form, the Brayton cycle consists of four transformations (ideal or real depending on the type of assessment being carried out), corresponding to the four characteristic states of the working fluid.

Referring to Figure 14 for the non-regenerative cycle, in section 1–2 the fluid is compressed by the compressor, with an increase in pressure and temperature. In section 2–3 it absorbs heat from the heat source and reaches the maximum temperature of the cycle. In section 3–4 the fluid expands in the turbine, producing useful work. Finally, in section 4–1, it transfers heat to the cooling system, returning to its initial conditions.

In the classic case of industrial gas turbines, the heating in the 2–3 section occurs through combustion. In the cases studied here, however, this enthalpy increase is achieved without combustion, through heat exchange with a nuclear source or its equivalent representation. This aspect must be explicitly borne in mind when interpreting the cycle: from a thermodynamic perspective, the heating stage remains present, but its physical significance lies in heat transfer via an interface component rather than a direct input of chemical energy.

2.3.2 Open, closed and recovered configurations

For the indirect closed cycles considered in this thesis, but which are nevertheless included in some of the benchmark solutions, the working fluid remains confined within the power circuit and exchanges heat with the hot side via a heat exchanger. This is the approach adopted for **AMR** and **OTRERA 300**. In the open-loop case, however, the working fluid does not recirculate within a completely closed circuit; in the configuration adopted here for **eVinci**, the air is compressed, heated indirectly by the equivalent heat source and subsequently

expanded, following an open Brayton cycle logic consistent with the concept documentation [6].

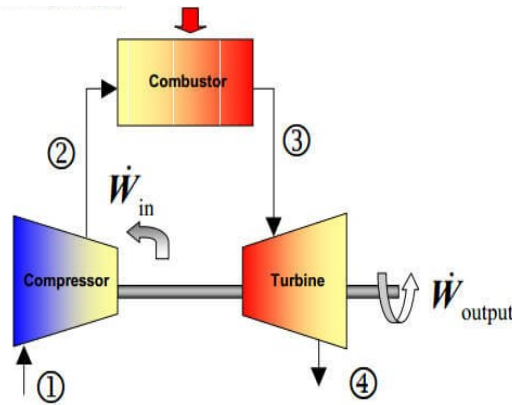


Figure13 : Brayton Cycle scheme

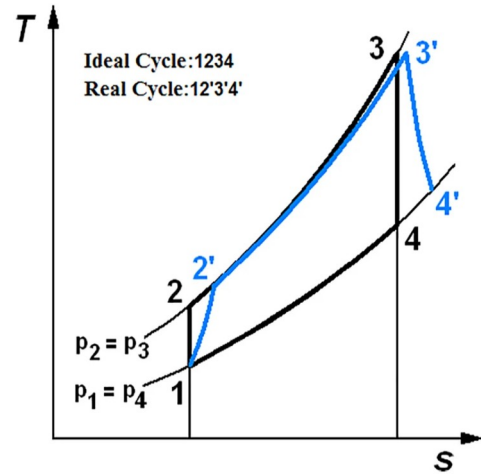


Figure14 : T-s Brayton Cycle Diagram

A particularly important configuration is the **regenerative cycle**. In this configuration, the fluid leaving the turbine transfers part of its enthalpy to the compressed fluid leaving the compressor, thereby reducing the heat that must be supplied by the external source to reach the turbine inlet temperature. The regenerator can be particularly advantageous when the turbine outlet temperature remains sufficiently high compared to the compressor outlet temperature.

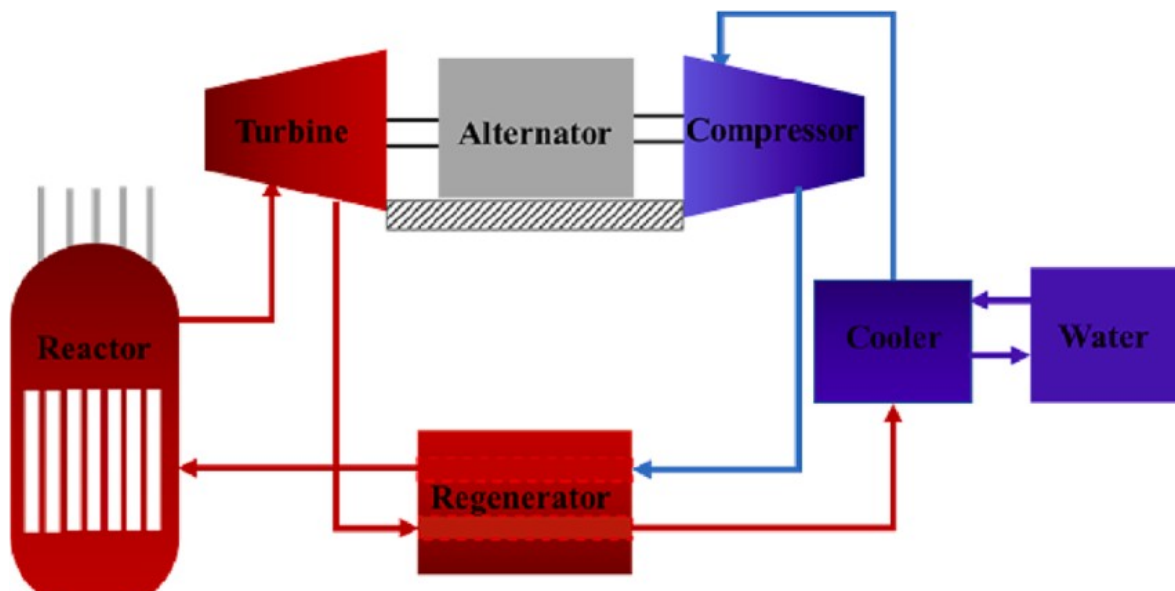


Figure15 : Regenerated Brayton Cycle scheme

The following **minimum thermodynamic criterion** will therefore be adopted as a necessary condition for evaluating the introduction of the regenerator:

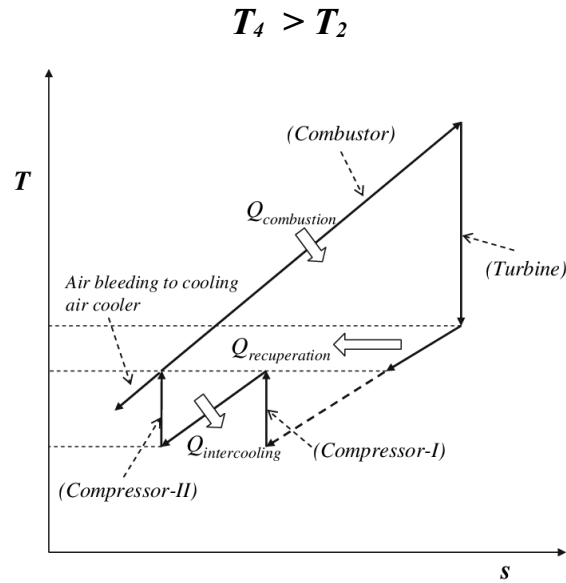


Figure16 : Regenerated T-s Brayton Cycle Diagram

From a descriptive point of view, the cycle can be usefully represented either by a process flow diagram or by a T–s diagram (Figure 14-16), in which compression, heating, expansion and cooling are clearly evident. In the actual diagram, the irreversibilities of the turbomachinery and heat exchangers manifest themselves through an increase in entropy and a deviation from ideal behaviour.

The parameters governing the cycle’s behaviour in this study are primarily the pressure ratio, the minimum cycle temperature T_1 , the maximum temperature T_3 which affects the TIT, the mass flow rate of the working fluid, the efficiencies of the turbomachinery, and the temperature differences available in the heat exchangers. In particular, the **pressure ratio** directly affects the compression work, the expansion work and the intermediate temperatures of the cycle; it therefore constitutes the main parametric variable of the analysis.

$$PR = p_2 / p_1$$

The behaviour of the compressor and turbine can be expressed, as a first approximation, through the following specific enthalpy drops:

$$w_c = h_2 - h_1$$

$$w_t = h_3 - h_4$$

where w_c is the specific work absorbed by the compressor and w_t is the specific work produced by the turbine [10], [11]. In terms of isentropic efficiencies, the following relationships can also be invoked:

$$\eta_c = (h_{2s} - h_1) / (h_2 - h_1)$$

$$\eta_t = (h_3 - h_4) / (h_3 - h_{4s})$$

If the fluid is treated, as a first approximation, as an ideal gas with γ approximately constant, the isentropic temperatures can be related to the pressure ratio by equations of the form:

$$T_{2s} = T_1 \cdot PR^{(\gamma-1)/\gamma}$$

In this study, however, the final calculation of the properties is delegated to the thermo-fluid dynamic model implemented in THERMOFLEX, which allows the fluids used and their respective thermophysical properties to be treated in a manner more closely aligned with the actual conditions of the cycle [13].

The working fluids analysed are selected based on their relevance to the case studies and the parametric nature of the problem:

- For AMR, the reference fluid consistent with the concept is air, but the analysis is also extended to helium (He), nitrogen (N_2) and carbon dioxide (CO_2), in order to evaluate the influence of the working fluid for a given heat source;
- For eVinci, the working fluid is air, as it is an open Brayton cycle;
- For OTRERA 300, the working fluid is nitrogen, consistent with the closed Brayton nitrogen cycle associated with the concept [6].

2.4 Model setup and reverse engineering procedure

2.4.1 Data imposed on the source side

The approach adopted in this thesis is based on a clear separation between data imposed on the source side and variables solved on the BoP side. For each case study, the reactor is linked to a heat source characterised by the following minimum parameters: nominal thermal power $Q_{th,nom}$, hot-side inlet temperature at the heat exchanger $T_{hot,in}$, hot-side outlet temperature $T_{hot,out}$, hot-side fluid and, by derivation, source-side mass flow rate. These quantities define the energy and thermal framework within which the conversion cycle can operate.

The source-side energy balance is expressed by:

$$\dot{Q}_{th} = \dot{m}_{hot} \cdot (h_{hot,in} - h_{hot,out})$$

or, when it is acceptable to assume a constant average specific heat within the temperature range under consideration:

$$\dot{Q}_{th} \approx \dot{m}_{hot} \cdot c_{p,hot} \cdot (T_{hot,in} - T_{hot,out})$$

These relationships do not describe the entire reactor system, but only the heat exchange section relevant for coupling with the BoP. They allow the calculation of a hot-side mass flow rate consistent with the available thermal power and the assigned temperature difference.

2.4.2 BoP-side variables and iterative procedure

On the cycle side, the quantities of greatest interest are the mass flow rate of the working fluid, p_1 , p_2 , T_1 , T_2 , T_3 , T_4 , the net power and the net efficiency. The net cycle power can be expressed, in summary form, by the following relationship:

$$\dot{W}_{net} = \dot{m}_{wf} \cdot [(h3 - h4) - (h2 - h1)]$$

whilst the definition of net efficiency adopted in this study is:

$$\eta_{net} = P_{el,net} / Q_{th,nom}$$

This latter quantity represents the ratio between the net electrical power obtained from the model and the nominal thermal power made available by the source. This definition is preferred to THERMOFLEX's internal indicator 'Plant net electric efficiency (LHV)', as the latter is designed for combustion plants and is not directly representative of the cases discussed here, in which the cycle is powered by an external thermal source [13].

Common simulation assumptions are kept as constant as possible across the case studies to ensure methodological comparability. In particular, a minimum **thermal pinch** of 10 °C in the hot-side heat exchanger, an ambient temperature T_{amb} of 15 °C and a compressor inlet temperature of:

$$T1 = 25 \text{ °C}$$

Furthermore, the simulations consider pressure drops of 1% in each heat exchanger and heat losses of 1% of the transferred power. Once the heat source has been assigned, the maximum cycle temperature is initially constrained by the hot-side pinch according to a relationship of the form:

$$T3 \approx T_{hot,in} - \Delta T_{pp}$$

Once a pressure ratio value has been set, the model determines the corresponding compressor outlet temperature and, more generally, the state levels compatible with the assumptions made.

The most important methodological point, however, concerns the **mass flow rate of the working fluid**. This is not treated as a second independent variable to be freely explored; on the contrary, for each value of the pressure ratio, the mass flow rate is determined iteratively so as to simultaneously respect the level of thermal power transferable from the source, the maximum temperature imposed on the hot side, and the cycle's energy balances. It is therefore a reverse engineering procedure: one does not start from an arbitrary flow rate to observe how much power is absorbed, but from an assigned heat source to determine which flow rate is physically compatible with it.

This approach is consistent with the physical meaning of the problem. In the architectures under consideration, the conversion system does not, in fact, have unlimited freedom: it must adapt to the constraints imposed by the source, and not the other way round. For this reason, the pressure ratio will be treated as the main parametric variable in the following, whilst the mass flow rate of the working fluid will be treated as a derived quantity.

2.5 Implementation in THERMOFLEX and criteria for interpreting results

The numerical model is implemented in THERMOFLEX, which is used as a simulation environment for the Balance of Plant only and not for the entire nuclear plant [13]. The software allows the Brayton cycle to be modelled, mass and energy balances to be closed, and the main performance outputs to be returned; however, in this work it does not replace thermodynamic reasoning, but serves as the tool for its numerical implementation. The relationships outlined in the previous sections therefore remain essential for interpreting the physical significance of the convergence points and for verifying their plausibility.

The simulation procedure can be summarised as follows. For each case study, $Q_{th,nom}$, $T_{hot,in}$, $T_{hot,out}$ and the hot-side fluid are first assigned. The source-side mass flow rate consistent with the available heat exchange is then derived. Subsequently, the common cycle-side assumptions are imposed, a pressure ratio value is set, and the mass flow rate of the working fluid is adjusted iteratively until the temperature and power constraints are satisfied. Once the model has converged, the net power, characteristic temperatures, resulting flow rate and any potential benefit of the recuperator are determined.

The recuperator is not introduced a priori, but only when the thermal hierarchy of the cycle justifies it. In particular, the simple configuration is solved first; then it is checked whether $T_4 > T_2$. If this condition is satisfied by a sufficient margin, the cycle is recalculated in the recuperated configuration, whilst keeping the set of main constraints unchanged. The recuperator is therefore treated as a possibility conditioned by the thermal structure of the operating point, and not as an automatic choice.

A further aspect to be monitored concerns the relationship between numerical convergence and physical plausibility. A formally convergent point is not, in fact, necessarily a useful point from an engineering perspective. It must be verified that it is consistent with the thermal level of the source, with the logic of the iterative procedure and with the cycle structure. In this study, the results are therefore interpreted not as a mere output of the software, but as the outcomes of a constrained physical problem, in which each point must be interpreted in light of the relationship between the heat source, the plant configuration and the simulation parameters.

This chapter has thus defined the methodological framework of the entire study. Having redefined the reactor as a characterised heat source, the reasons for choosing the Brayton cycle were outlined, the configurations of interest were introduced, and the procedure for simulating the BoP was clarified. On this basis, the following chapter can present the case studies and translate the reactor data into input data for the model, leaving the discussion of the performance results to Chapter 4.

Chapter 3 – Case studies and simulation setup

3.1 Case study selection criteria

The selection of case studies was based on the benchmark developed in Chapter 1 and subsequently refined by consulting IAEA/ARIS, NEA, and Handbook documentation [3], [5], [6], [7]. The aim is not to compare three reactors as homogeneous alternatives nor to identify a ‘best concept’ in an absolute sense; rather, the three cases are taken as representative heat sources, differing in size, technology, heat transfer structure and thermal level, with the aim of analysing how these differences are reflected in the configuration and performance of the Balance of Plant.

There are four main selection criteria:

1. Availability of sufficient data to describe the heat source in terms useful for BoP modelling.
2. Representativeness of different technologies and sizes, so as to cover more than one family of thermo-fluid dynamic problems.
3. The presence of temperature and power conditions compatible with a Brayton cycle study.
4. Clarity of the connection between the reactor side and the conversion side, i.e. the possibility of reducing the concept to a relatively compact set of interface data.

On this basis, three cases were selected: **the Advanced Micro Reactor (AMR)**, representative of a high-temperature HTGR microreactor; the **Westinghouse eVinci**, representative of a heat-pipe microreactor with an air conversion system; and **OTRERA 300**, representative of a larger-scale SFR concept, for which the reference documentation explicitly refers to a closed nitrogen Brayton cycle [6].

The three cases should therefore not be viewed as direct competitors, but as examples of different ways in which a nuclear source can be integrated into the conversion system.

3.2 Common methodological framework for the simulations

3.2.1 Common simulation assumptions

Despite the diversity of the concepts considered, the simulation campaign is built on a common methodological framework. In all cases, the reactor is reduced to a heat source characterised by nominal thermal power, hot-side temperature at the inlet and outlet of the heat exchange interface, hot-side fluid, and main operational constraints.

Starting from this representation, the BoP model is constructed in THERMOFLEX, defining the Brayton cycle consistent with the specific case and applying a uniform calculation procedure.

The common assumptions adopted in this study are as follows:

- $\xi_Q = 0.01$, i.e. heat losses of 1% per heat exchanger,
- $\xi_p = 0.01$, i.e. relative pressure drop of 1% per heat exchanger,
- minimum thermal pinch of 10 °C,
- ambient temperature of 15 °C and
- compressor inlet temperature of 25 °C.

These assumptions do not cover the full scope of the actual design problem, but they provide a controlled comparative basis, sufficient to study the influence of the pressure ratio, the resulting mass flow rate and the presence of the heat recovery unit.

3.2.2 Calculation procedure and monitored parameters

From a procedural point of view, for each case, the heat source is first defined; the mass flow rate on the hot side is then calculated in accordance with the available temperature difference; subsequently, the Brayton cycle is set up, a pressure ratio is assigned, and the mass flow rate of the working fluid required to satisfy the problem's energy and thermal constraints is determined iteratively. The parameters monitored are the mass flow rate of the working fluid, the characteristic temperatures of the cycle, the net power obtained, verification of the condition $T_4 > T_2$ and the net efficiency calculated ex post as the ratio of net electrical power to the nominal thermal power of the source.

The distinction between source data, assumed data and derived data is methodologically important. The reactor parameters listed in catalogues are not mechanically transposed into the simulation model; they are reworked to establish boundary conditions consistent with the objectives of the thesis. In particular, the presence of heat pipes, intermediate circuits or significant reactor-side integration requires, in some cases, an equivalent representation of the heat source. This step is not an arbitrary imposition, but a stated simplification necessary to maintain the focus on the Balance of Plant.

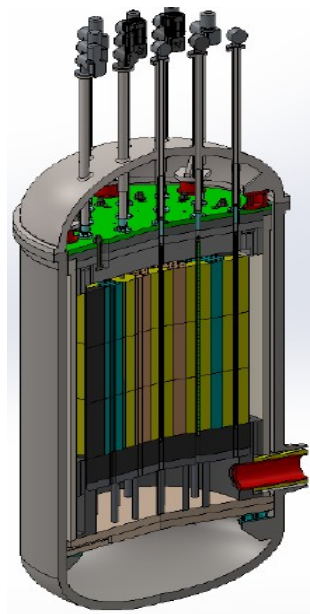
Table 3.1 – Common simulation assumptions and conventions adopted

Parameter	Symbol	Value
Heat losses for heat exchanger	ξ_Q	0.01
Relative pressure drop for heat exchanger	ξ_p	0.01
Minimum thermal pinch	ΔT_{pp}	10 °C
Ambient temperature	T_{amb}	15 °C
Compressor inlet temperature	T_1	25 °C
Net efficiency adopted	η_{net}	$P_{el,net} / Q_{th,nom}$
Criterion for selecting the heat recovery unit	$T_4 > T_2$	verified on a case-by-case basis

3.3 AMR case study

3.3.1 Concept profile and reactor data

The Advanced Micro Reactor (AMR) is a South African concept belonging to the family of high-temperature reactors, classified in the IAEA catalogue as an advanced prismatic HTR. The system uses helium as a coolant and graphite as a moderator, whilst the fuel is of the TRISO type, inserted into SiC tubes; the reference configuration also involves the use of a Heat Pipe Heat Exchanger (HPHE) for heat transfer to a secondary circuit containing air. Overall, it is therefore a small-scale concept but characterised by a high thermal level, a feature that makes it particularly interesting in the context of a study focused on the Balance of Plant and possible Brayton architectures [6].



*Figure 17 : AMR Reactor
Core - Source: SMR
Catalogue 2024,
ARIS/IAEA*

According to the reference documentation, the AMR has a power output of 10 MW_{th} and 3 MWe, with primary and secondary NSSS pressures of 4 and 1 MPa respectively, and a core coolant temperature ranging from 450 °C at the inlet to 750 °C at the outlet. These characteristics place the system among the high-temperature microreactors of greatest interest for flexible applications, in both single-module and multi-module configurations, with potential uses for grid power supply, isolated consumers and process heat.

For the purposes of this thesis, the interest of the AMR case lies not only in the reactor technology itself, but above all in the clarity with which the concept allows one to understand the transition from the reactor side to the conversion side. The presence of a high-temperature heat source and a clearly identifiable heat exchange interface makes the case particularly

suitable for being traced back to the concept of a characterised heat source, upon which the power cycle modelling can then be based.

This profile makes it particularly interesting for a study focused on the relationship between the heat source and the BoP: on the one hand, it is a small-scale system; on the other, the available temperature level is relatively high, making it natural to focus on Brayton architectures.

3.3.2 Simulation setup for the AMR case

In this work, the AMR is taken as the reference case to fully set up the simulation procedure. The heat source is described by assuming, as a first approximation, that the outlet and return temperatures of the core coincide with the hot-side temperatures at the inlet and outlet of the interface heat exchanger. The following are therefore adopted as source-side constraints: $Q_{th,nom} = 10 \text{ MW}_{th}$, $T_{hot,in} = 750 \text{ }^{\circ}\text{C}$ and $T_{hot,out} = 450 \text{ }^{\circ}\text{C}$. On this basis, the primary-side mass flow rate consistent with the available temperature difference is derived.

As regards the power cycle, the reference fluid that is physically most consistent with the concept documentation is air, since the ARIS data sheet explicitly refers to a secondary circuit containing air [6]. However, once the heat source has been defined, the same procedure is extended to helium, nitrogen and CO_2 , in order to evaluate, in a parametric manner, the role of the working fluid under the same thermal constraints on the reactor side. This extension does not aim to faithfully reproduce the original AMR design in all its plant engineering choices, but represents a controlled expansion of the BoP analysis scope.

The parametric sweep for the AMR is conducted for pressure ratios $PR = 6, 8, 10, 12$ and 14 . For each working fluid and for each pressure ratio value, the cycle is first solved in a simple configuration. Subsequently, the condition $T_4 > T_2$ is verified; when this is satisfied with a sufficient margin, the recuperator is introduced and the cycle is recalculated in the recuperated configuration. The parameters of interest are the mass flow rate of the working fluid, the outlet temperatures from the compressor and turbine, the net power and the net efficiency.

Table 3.2 – Reactor data and BoP input data for the AMR case

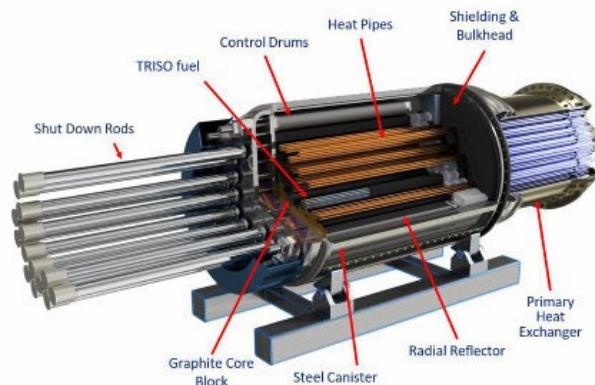
Parameter	Symbol	Value
Nominal thermal power of the reactor	$Q_{th,nom}$	10 MW _{th}
Nominal electrical power of the reactor	$P_{el,nom}$	3 MWe
Primary fluid	–	Helium
Core inlet temperature	$T_{in,core}$	450 °C
Core outlet temperature	$T_{out,core}$	750 °C

Parameter	Symbol	Value
Hot side temperature at the cycle inlet	$T_{hot,in}$	750 °C
Hot side temperature at the cycle outlet	$T_{hot,out}$	450 °C
Working fluids analysed in the BoP	–	Air, He, N2, CO2
Pressure ratios investigated	PR	6, 8, 10, 12, 14
Cycle configurations considered	–	single / recovered

3.4 eVinci case study

3.4.1 Concept profile and reactor data

The second case study is Westinghouse’s **eVinci** microreactor, representative of **heat-pipe** technology for decentralised energy applications. In the benchmark developed in this thesis and in the reference literature, the concept appears as a scalable platform in the range of **1–15 MWe** and **3–45 MWth**, with a reference configuration of **15 MWe** and **45 MWth**. From a plant engineering perspective, the most distinctive feature is the use of heat pipes to transfer heat from the core to the conversion system, without the need for a traditional convective primary circuit.



*Figure 18 : eVinci Westinghouse reactor core
- Source: Westinghouse Nuclear*

This distinguishes eVinci from both the AMR and OTRERA 300, making it a particularly useful case for verifying the robustness of the methodology adopted in the thesis.

The interest of the eVinci case lies not only in the system’s compact size, but above all in the possibility of studying the Balance of Plant based on an **equivalent heat source** attributable

to a heat-pipe concept. In the available documentation, in fact, the system is associated with a high thermal level, with **core outlet temperatures of 750 °C**, and an **open-air Brayton-type** conversion configuration. In this way, the case study introduces, compared to the AMR, a substantial difference not only in reactor technology but also in the nature of the connection between the heat source and the power cycle.

For the purposes of this work, eVinci is therefore treated as a case study for an **open-air Brayton cycle**, without multi-fluid extension. The simulation procedure remains the same as that adopted for the other cases: the heat source is assigned, the **pressure ratio** is varied within the selected range, and the mass flow rate of the working fluid required to satisfy the energy constraints of the problem is determined iteratively. In this case too, the recuperator is considered only when the thermal hierarchy of the cycle permits it. The significance of the eVinci case, within the overall framework of the thesis, therefore lies in extending the BoP analysis to a high-temperature heat-pipe microreactor, whilst maintaining the general methodological approach unchanged.

3.4.2 Simulation setup for the eVinci case

For the purposes of this work, eVinci is therefore reduced to an equivalent heat source, described using the same minimum parameters employed for the other cases: transferable thermal power, hot-side inlet temperature at the interface, hot-side outlet temperature, and equivalent mass flow rate on the source side. This operation represents a methodological translation necessary to place the case within a framework of analysis comparable to the others.

In the model adopted here, eVinci is studied as an open-cycle air Brayton engine. A multi-fluid campaign is therefore not carried out: the working fluid is exclusively air, and the pressure ratio sweep is conducted at values of $PR = 6, 8, 10, 12$ and 14 . In this case too, the simulation logic remains unchanged. The equivalent heat source is specified, the pressure ratio is assigned, the air mass flow rate required to satisfy the problem's energy constraints is derived iteratively, and, where thermodynamically justified, the potential introduction of a heat recovery unit is evaluated.

The eVinci case is particularly useful because it demonstrates how the method adopted in this thesis can also be extended to concepts in which the reactor side does not take the classic form of a primary circuit with a convective coolant. It therefore constitutes an important test bed for the robustness of the procedure: starting from an equivalent heat source consistent with the physics of the concept, the BoP is nevertheless analysed in terms of pressure ratio, resulting mass flow rate, heat recovery and net efficiency.

Table 3.3 – Reactor data and BoP input data for the eVinci case

Parameter	Symbol	Value
Electrical power of the concept	$P_{el,nom}$	1–15 MWe (15 MWe reference)
Thermal power of the concept	$Q_{th,nom}$	3–45 MWth (45 MWth reference)
Reactor technology	–	Heat-pipe microreactor
Core outlet temperature	$T_{out,core}$	750 °C
Fluid / heat transfer medium	–	Sodium heat pipes
Working fluid on the cycle side	–	Air
BoP configuration adopted	–	Open Brayton
Pressure ratios investigated	PR	6, 8, 10, 12, 14
Cycle configurations considered	–	single / recovered

3.5 OTRERA 300 case study

3.5.1 Concept profile and reactor data

The third case study is **OTRERA 300**, a French concept belonging to the family of **sodium-cooled fast reactors** and classified in the IAEA catalogue as **an SMR / SFR**. Compared to the two previous microreactors, OTRERA 300 represents a significant step up in scale, as the reference documentation indicates a power output of **300 MWth / 110 MWe**. From a technological perspective, the reactor uses **sodium** as a coolant and operates with a core coolant temperature ranging from **400 °C at the inlet** to **550 °C at the outlet**. The same documentation also explicitly refers to a **closed Brayton nitrogen cycle** as the power conversion system, making the connection between the reactor side and the BoP side particularly direct.

The OTRERA 300 case is of dual interest. On the one hand, it allows the analysis to be extended to a significantly larger scale than AMR and eVinci; on the other, it represents a case in which the relationship between the heat source and the conversion system is already clearly evident in the source material. The available documentation indeed highlights the concept's intended use for the production of **decarbonised electricity and heat** for industrial users, with installation near industrial sites and the potential to utilise the cycle's residual heat. In this sense, OTRERA 300 constitutes a particularly useful case for studying the BoP not only as an electricity generation system, but also as a potential hub for thermo-industrial integration.

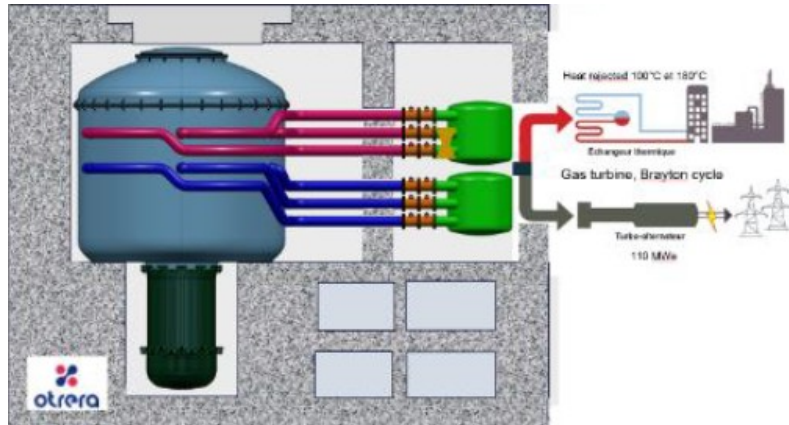


Figure19 : OTRERA reactor plants - Source: SMR Catalogue 2024

In this study, OTRERA 300 is therefore taken as a case study for a **nitrogen-cooled closed Brayton cycle**, consistent with the configuration described in the sources. Unlike the AMR, there is no multi-fluid campaign here: the use of nitrogen is not an exploratory choice added retrospectively, but a direct consequence of the selected concept. The heat source is therefore modelled, taking the nominal thermal power and the hot-end thermal level as the main constraints, whilst the parametric analysis is conducted for **pressure ratios of 2, 3 and 4**, first in a simple configuration and subsequently, where permitted by the cycle's thermal hierarchy, in a recovered configuration.

3.5.2 Simulation setup for the OTRERA 300 case

In the model, $Q_{th,nom} = 300 \text{ MW}_{th}$, $T_{hot,in} = 550 \text{ °C}$, $T_{hot,out} = 400 \text{ °C}$ and the cycle working fluid as N_2 are therefore set. In this case, the use of nitrogen is not an additional parametric choice made retrospectively, but derives directly from the conversion system referenced in the sources [6]. The parametric sweep is limited to $PR = 2, 3$ and 4 , in line with the investigation range selected for the OTRERA case and with the different cycle structure compared to the previous microreactors.

For OTRERA too, the cycle is first solved in simple configuration and subsequently, when the condition $T_4 > T_2$ is verified with a sufficient margin, in recovered configuration. The observed variables remain the same: mass flow rate of the working fluid, characteristic temperatures, net power and net efficiency. However, compared to AMR and eVinci, OTRERA exhibits a more direct relationship between reactor data and conversion data, as the reference concept already explicitly refers to a nitrogen Brayton cycle. For this reason, the case is particularly useful for verifying the consistency of the adopted methodology.

Its interest therefore lies not only in its larger scale, but in the fact that it allows the procedure to be tested on a concept in which the reactor side and the BoP side are more closely coupled. Whilst for eVinci the main challenge is to rigorously construct an equivalent source, and whilst for AMR it is useful to distinguish between a secondary system consistent with the concept and an extended multi-fluid analysis, for OTRERA the central methodological issue lies primarily in clarifying that the representation via a characterised heat source is a

controlled simplification of the actual concept, adopted to maintain consistency in the comparison between the case studies.

Table 3.4 – Reactor data and BoP input data for the OTRERA 300 case

Parameter	Symbol	Value
Nominal thermal power of the reactor	$Q_{th,nom}$	300 MW _{th}
Nominal electrical power of the reactor	$P_{el,nom}$	110 MWe
Primary coolant	–	Sodium
Core inlet temperature	$T_{in,core}$	400 °C
Core outlet temperature	$T_{out,core}$	550 °C
Hot side temperature assumed at the cycle inlet	$T_{hot,in}$	550 °C
Hot side temperature at the cycle outlet	$T_{hot,out}$	400 °C
Working fluid on the cycle side	–	N ₂
Pressure ratios investigated	PR	2, 3, 4
Cycle configurations considered	–	simple / recovered

3.6 Summary of the simulation campaign and link to the results chapter

The setup of the three case studies allows for the construction of a coherent simulation campaign despite the presence of very different concepts. For AMR, the procedure is applied to four different working fluids of the power cycle, with a pressure ratio sweep between 6 and 14. For eVinci, the same logic is applied to an open-cycle Brayton engine using air, again with a sweep between 6 and 14. Finally, for OTRERA 300, the working fluid is fixed as nitrogen and the analysis focuses on lower pressure ratios of 2, 3 and 4. In all cases, the recovered configuration is considered only when the thermal hierarchy of the cycle justifies its introduction.

The purpose of this chapter has not been to discuss performance results in the strict sense, but to present the case studies, clarify the nature of the data used and justify the transition from reactor-level information to the boundary conditions of the Balance of Plant. From this

perspective, the chapter serves as a link between the methodological framework defined in Chapter 2 and the analysis of results developed in Chapter 4.

The following chapter will therefore be devoted to the presentation and technical interpretation of the simulation outputs. In particular, we will discuss the trend in net efficiency as the pressure ratio varies, the resulting mass flow rate required by the cycle, the role of the recuperator at points where $T_4 > T_2$ and, in the case of the AMR, the influence of the working fluid on BoP performance. The comparison that emerges will not concern the absolute superiority of one reactor over another, but the different behaviour of the conversion system in the presence of different source constraints.

Chapter 4 – Simulation results and technical discussion

4.1 Criteria for interpreting the results

This chapter compiles and discusses the results of the simulations carried out on the three case studies introduced in Chapter 3: **AMR**, **eVinci** and **OTRERA 300**. In line with the methodological approach adopted, the analysis is not intended to compare the three reactor concepts as homogeneous or directly competing solutions, but rather to study how different nuclear heat sources influence the behaviour of the Brayton cycle on the Balance of Plant side. From this perspective, the results should be interpreted as the response of the conversion system to a given set of thermal, fluid-dynamic and plant-related constraints.

The main variables considered in the analysis are the mass flow rate of the working fluid resulting from the iterative procedure, the compressor outlet temperature T_2 , the turbine outlet temperature T_4 , the net electrical power obtained, and the net cycle efficiency, calculated according to the following equation:

$$\eta_{net} = P_{el,net} / Q_{th,nom}$$

As already explained in the previous chapters, the PR constitutes the main parametric variable, whilst the mass flow rate is not freely set but is derived iteratively to make the cycle compatible with the assigned heat source. It follows that the interpretation of the results must focus not only on the trend of the efficiency but also on the way in which the cycle modifies its operating state as the pressure ratio varies.

A further criterion for interpretation concerns the recuperator. In all simulations, it is not introduced a priori, but only at points where the thermal hierarchy of the cycle permits it, i.e. when the temperature of the fluid leaving the turbine remains higher than that of the fluid leaving the compressor. The presence of recuperative configurations must therefore be interpreted as an expression of an effectively exploitable thermal margin and not as an automatic architectural choice. In general, two outcomes are expected: on the one hand, an improvement in net performance in cases where a significant portion of the turbine's residual heat can be recovered; on the other, a gradual reduction in this advantage as the pressure ratio increases, when the rise in T_2 tends to reduce the recovery margin.

4.2 Results of the AMR case

The plant layout to be considered in this discussion, shown in the Thermoflex workspace, is illustrated in Figures 20 and 21 in classic and regenerative configurations, for air with a PR of 8:

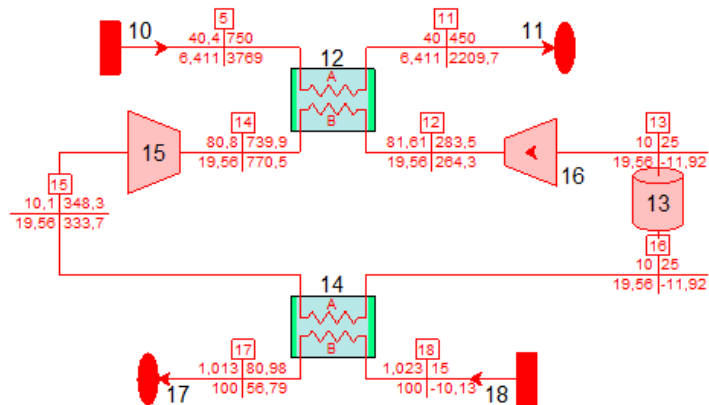


Figure20 : Thermoflex AMR Brayton cycle scheme – Air PR 8

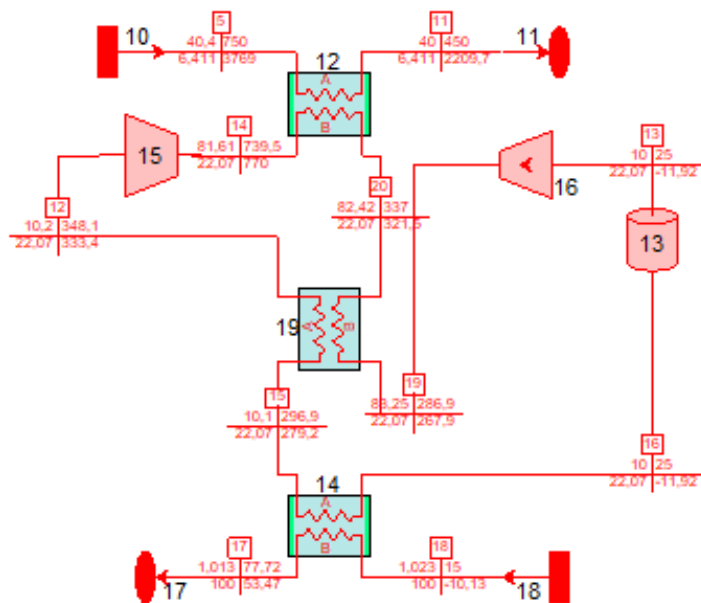


Figure21 : Thermoflex AMR Brayton cycle scheme – Air PR 8 Regenerated

4.2.1 Variation in net efficiency with changes in working fluid and pressure ratio

The AMR case provides the most comprehensive parametric test bed, as, for a given thermal source, it allows for the comparison of four different working fluids in the power cycle: air, helium, nitrogen and CO₂. This scope is methodologically significant because it allows the role of the fluid's properties on the BoP response to be isolated, whilst keeping the nominal

thermal power of the case study and the hot-side temperature level constant. Furthermore, the AMR is particularly well-suited to this type of analysis as the reference documentation associates the concept with a high temperature level, equal to 750 °C at the core outlet, and an air-cooled secondary circuit via a heat pipe heat exchanger, making the transition from the reactor side to the conversion side particularly clear.

Table 4.1 – Summary results of the AMR case

Fluid	PR	Recuperator	\dot{m}_{wf} [kg/s]	T compressor outlet [°C]	T turbine outlet [°C]	Net power [kW]	η_{net} [%]
Air	6	No	17.83	236.3	393.5	2704.3	27.0
Air	6	Yes	24.33	239.5	255.1	3622.0	36.2
Air	8	No	19.56	283.6	348.8	2950.7	29.5
Air	8	Yes	22.07	267.9	296.9	3253.0	32.5
Air	10	No	21.29	322.7	315.1	3090.0	30.9
Air	12	No	23.06	356.5	289.2	3161.0	31.6
Air	14	No	24.91	386.4	268.0	3,184.0	31.8
Helium	6	No	3,254	154.8	258.8	5,642.0	56.4
Helium	6	Yes	3.867	156.2	166.5	6686.0	66.9
Helium	8	No	3,370	175.0	206.5	6,381.0	63.8
Helium	8	Yes	3,502	176.5	186.5	6,608.0	66.1
Helium	10	No	3,472	191.7	169.5	6,927.0	69.3
Helium	12	No	3.566	206.1	141.9	7,357.0	73.6
Helium	14	No	3,655	219.0	119.1	7,713.0	77.1
Nitrogen	6	No	18.15	255.2	389.1	2,693.9	26.9
Nitrogen	6	Yes	23.76	243.3	271.7	3,455.0	34.6
Nitrogen	8	No	20.07	304.6	343.7	2922.3	29.2

Fluid	PR	Recuperator	\dot{m}_{wf} [kg/s]	T compressor outlet [°C]	T turbine outlet [°C]	Net power [kW]	η_{net} [%]
Nitrogen	8	Yes	21.42	297.2	308.2	3041.0	30.4
Nitrogen	10	No	22.04	345.7	310.3	3039.0	30.4
Nitrogen	12	No	24.11	381.3	284.0	3084.0	30.8
Nitrogen	14	No	26.30	412.7	262.8	3,074.0	30.7
CO ₂	6	No	15.24	185.3	511.1	2010.8	20.1
CO ₂	6	Yes	30.70	126.1	219.1	3,749.0	37.5
CO ₂	8	No	15.91	215.9	477.8	2267.9	22.7
CO ₂	8	Yes	26.91	153.0	245.6	3,801.7	38.0
CO ₂	10	No	16.52	240.8	452.4	2,454.0	24.5
CO ₂	10	Yes	25.14	175.2	265.0	3,698.0	37.0
CO ₂	12	No	17.08	261.9	431.9	2596.2	26.0
CO ₂	14	No	17.60	280.4	414.9	2709.2	27.1

Analysis of the simulated points shows, first and foremost, that the behaviour of the cycle is strongly dependent on the working fluid. In the case of air, the simple cycle shows a progressive increase in net efficiency from point **air6** to point **air14**, i.e. from approximately 27.0% to approximately 31.8%. The trend is upward but tends to flatten out at higher pressure ratios, indicating a gradual reduction in the marginal benefit associated with the increase in pressure. The introduction of the recuperator produces a net improvement at low pressure ratios: efficiency rises from **air6** to **air6Rec** to around 36.2%, whilst in the transition from **air8** to **air8Rec** it reaches around 32.5%. This indicates that, for air, the recuperator is particularly effective in the lower portion of the PR range, whilst its benefit diminishes as the compressor outlet temperature increases.

A behaviour similar in many respects is observed in the case of nitrogen. The simple cycle moves from point **N₂6** to point **N₂14**, i.e. from approximately 26.9% to approximately 30.7–30.8%, with a moderate increase followed by a substantial plateau. Here too, the recuperator proves particularly advantageous at low PRs: efficiency rises from **N₂6** to **N₂6Rec** to around

34.6% and from **N₂8** to **N₂8Rec** to around 30.4%, whilst at higher values the increase diminishes to the point of becoming negligible. Air and nitrogen therefore show a qualitatively similar response, with limited numerical differences and a clear sensitivity of the recuperator under low compression ratio conditions.

The behaviour of CO₂, on the other hand, is more complex. In the simple cycle, it yields the lowest net efficiency values of the entire AMR set, with an increase from point **CO₂6** to point **CO₂14**, i.e. from approximately 20.1% to approximately 27.1%. However, in the case of CO₂ specifically, the recuperator produces the greatest relative increases: points **CO₂6Rec**, **CO₂8Rec** and **CO₂10Rec** reach approximately 37.5%, 38.0% and 37.0% respectively. The difference between the simple and recovered cycles is therefore very marked. This result suggests that, in the adopted model, CO₂ penalises performance in the simple configuration, but simultaneously leaves a very substantial amount of recoverable heat available downstream of the turbine, making the recovered configuration decidedly more favourable.

The helium case is the one that, across the AMR results, yields the highest net efficiency values. The simple cycle increases from point **He6** to point **He14**, i.e. from approximately 56.4% to approximately 77.1%, with a clearly rising trend throughout the entire investigated range. The recuperator provides a further improvement at low PRs, bringing points **He6Rec** and **He8Rec** to approximately 66.9% and 66.1% respectively. Beyond these points, only simple configurations appear in the set of results adopted. Within the model and the assumptions adopted, helium therefore emerges as the working fluid that provides the most favourable balance between compression work and expansion work, resulting in the highest levels of net power and efficiency.

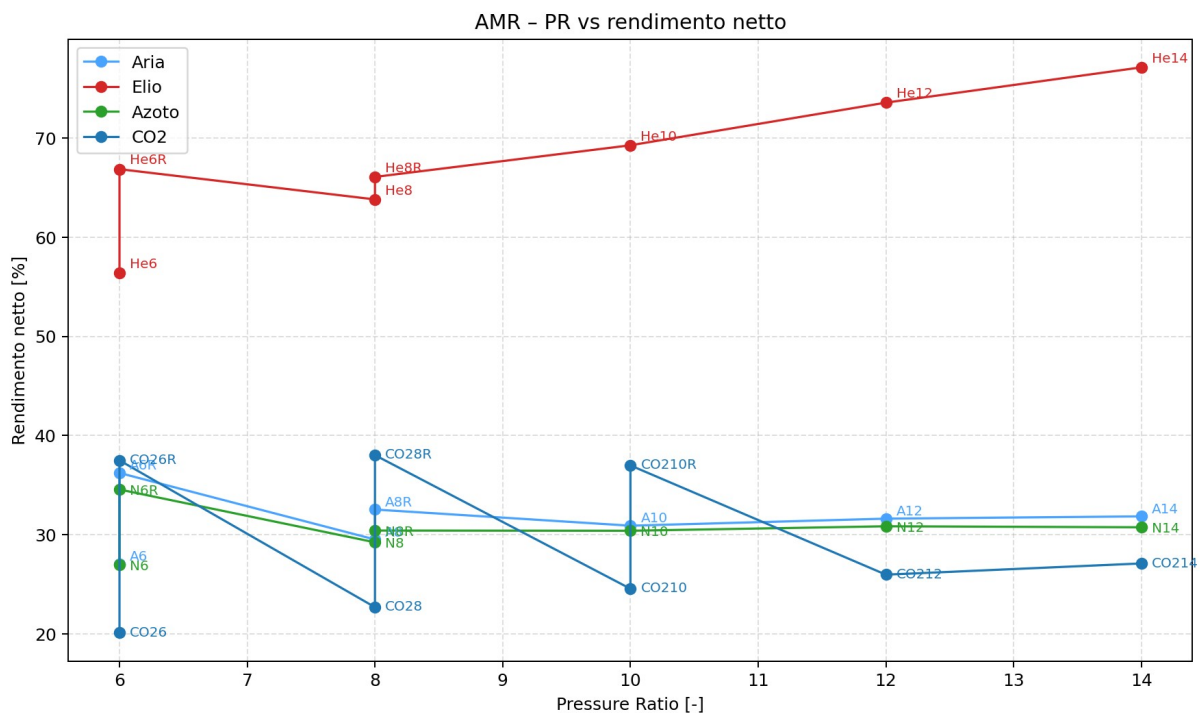


Figure 22 : AMR: PR vs Efficiency

Overall, the performance ranking emerging from the AMR case is clear: helium consistently occupies the top tier, air and nitrogen are situated at intermediate levels and are fairly close to one another, whilst CO_2 performs less well in a simple cycle but is potentially very interesting in the presence of heat recovery. From a methodological point of view, this is one of the most significant findings of the entire thesis, as it shows that, for a given heat source, the BoP working fluid can significantly alter the system's final performance.

4.2.2 Role of the recuperator in the AMR case

An analysis of the AMR results clearly highlights the role of the heat recovery unit. For all fluids considered, recovery efficiency is highest at low pressure ratios, i.e. when the temperature difference between the turbine outlet and the compressor outlet is most favourable. As the pressure ratio (PR) increases, the compressor outlet temperature rises and tends to reduce the benefit achievable through internal heat recovery.

In the case of air, the heat exchanger results in an increase of approximately 9 percentage points at PR = 6, which falls to around 3 points at PR = 8, before disappearing at higher PR values. A similar trend is observed for nitrogen, with an increase of approximately 7.6 points at PR = 6 and around 1.2 points at PR = 8. In the case of CO_2 , however, the recuperator produces the greatest absolute and relative benefits, with increases ranging from approximately 12 to 17 percentage points at the recovered points. Finally, helium shows a marked improvement at low PR, but still maintains high performance even in a simple configuration at higher compression ratios.

These results confirm that the recuperator should not be interpreted as a universally advantageous component, but rather as an element whose effectiveness depends directly on the thermal structure of the cycle and the fluid used. In the AMR case, it appears particularly useful when the cycle operates at a low pressure ratio or when the working fluid maintains a high capacity to utilise the residual heat leaving the turbine.

4.2.3 Summary of the AMR case

The AMR case demonstrates particularly effectively that the behaviour of the Balance of Plant is determined not only by the thermal level of the source, but also by the chosen working fluid and the cycle configuration. Since the concept is designed to supply the grid, isolated users and process heat, the flexibility demonstrated by the BoP side takes on significant design importance: there is no single optimal solution in an absolute sense, but a range of solutions whose desirability depends on the objective pursued, namely maximisation of efficiency, simplicity of plant design or optimisation of heat recovery.

In particular, the analysis suggests that, within the framework of the assumptions adopted, helium represents the best-performing solution in terms of net efficiency, whilst air and nitrogen provide more moderate but overall stable performance. CO_2 , although penalised in a simple cycle, exhibits behaviour of great interest in a recovery configuration. The AMR case thus confirms the validity of the approach adopted in the thesis: treating the reactor as a characterised heat source allows the sensitivity of the BoP to choices regarding the working fluid and the presence of the recuperator to be clearly highlighted.

4.3 Results of the eVinci case

The plant diagram to be considered in this discussion, shown in the Thermoflex workspace, is illustrated in Figures 23 and 24 in classic and regenerative configurations, with a PR of 8:

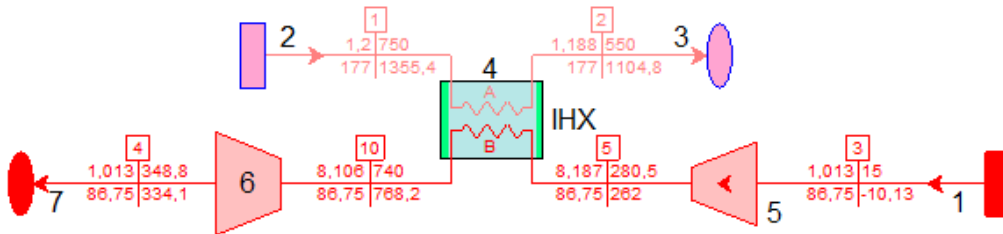


Figure23 : Thermoflex eVinci Brayton cycle scheme – PR 8

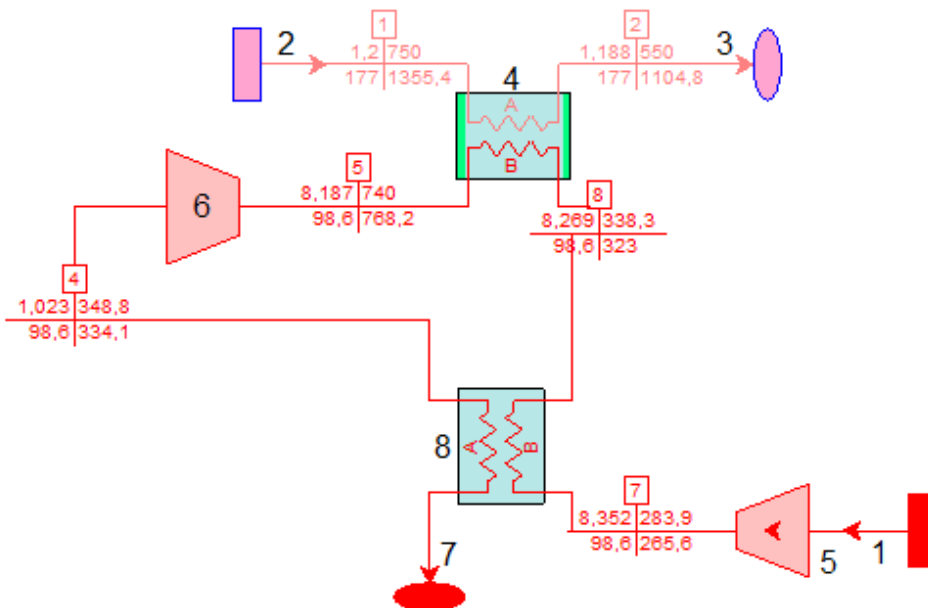


Figure24 : Thermoflex eVinci Brayton cycle scheme – PR 8 Regenerated

4.3.1 Net efficiency and pressure ratio trends

The eVinci case is studied as an open-air Brayton cycle, assuming an equivalent heat source consistent with the heat-pipe nature of the concept and with the presence, in the reference documentation, of an open-air Brayton cycle on the power conversion system side. This case is therefore particularly interesting not so much for direct comparison with AMR, but because it verifies the robustness of the procedure even in the presence of a source that does not derive from a classic convective primary.

Table 4.2 – Summary results of the eVinci case

PR	Recuperator	\dot{m}_{wf} [kg/s]	Compressor outlet temperature [°C]	T turbine outlet [°C]	$P_{el,net}$ [kW]	η_{net} [%]
6	No	79.15	233.8	393.7	12222	27.6
6	Yes	108.70	236.9	252.8	16,472	37.1
8	No	86.75	280.5	348.8	13,340	30.1
8	Yes	98.60	283.9	293.9	14,840	33.5
10	No	94.33	302.9	315.7	13,978	31.5
12	No	102.10	338.4	289.8	14320	32.3
14	No	110.20	370.0	268.7	14,448	32.6

In the simple cycle, net efficiency increases from approximately 27.6% at PR = 6 to approximately 32.6% at PR = 14. The trend is generally upward, but the rate of increase gradually diminishes at higher pressure ratios: the jump between PR = 6 and PR = 8 is significant, whilst beyond PR = 10 the increase in efficiency is more modest. This suggests that, in the model adopted, the benefit associated with an increase in the compression ratio tends to plateau in the upper part of the analysed range.

The recuperator proves to be very effective at low PRs. At PR = 6, net efficiency rises from approximately 27.6% to approximately 37.1%, whilst at PR = 8 it increases from approximately 30.1% to approximately 33.5%. However, as early as PR = 10, the useful thermal margin decreases significantly: in the simple configuration, $T_2 \approx 302.9$ °C and $T_4 \approx 315.7$ °C are observed, representing a positive but now limited difference. At subsequent values, the thermal hierarchy is reversed, with $T_4 < T_2$: at PR = 12, for example, $T_2 \approx 338.4$ °C and $T_4 \approx 289.8$ °C, whilst at PR = 14 we have $T_2 \approx 370.0$ °C and $T_4 \approx 268.7$ °C. Under these conditions, internal heat recovery is no longer thermodynamically favourable.

The results therefore confirm behaviour that is highly consistent with Brayton cycle theory: the recuperator is extremely useful when the compression ratio is relatively low, but progressively loses significance as PR increases, since the rise in compressor outlet temperature reduces or eliminates the possibility of utilising the residual heat of expansion.

4.3.2 Resulting mass flow rate and cycle structure

A particularly significant aspect of the eVinci case concerns the air mass flow rate, which increases monotonically as the pressure ratio rises in the simple configuration: from approximately 79.2 kg/s at PR = 6 up to approximately 110.2 kg/s at PR = 14. This trend is consistent with the iterative procedure: as the compression ratio varies, the cycle modifies its enthalpy equilibrium and requires a different flow rate to simultaneously satisfy the source constraints, the hot-end temperature level and the imposed operating conditions.

In recovery configurations, the mass flow rate is also high, but its interpretation must be considered alongside the improvement in efficiency. At $PR = 6$, the mass flow rate increases from approximately 79.2 kg/s in the simple cycle to approximately 108.7 kg/s in the recovered cycle; at $PR = 8$, from approximately 86.8 kg/s to approximately 98.6 kg/s. This highlights that the recuperator does not act as a mere marginal improvement to the cycle, but substantially alters its operating point.

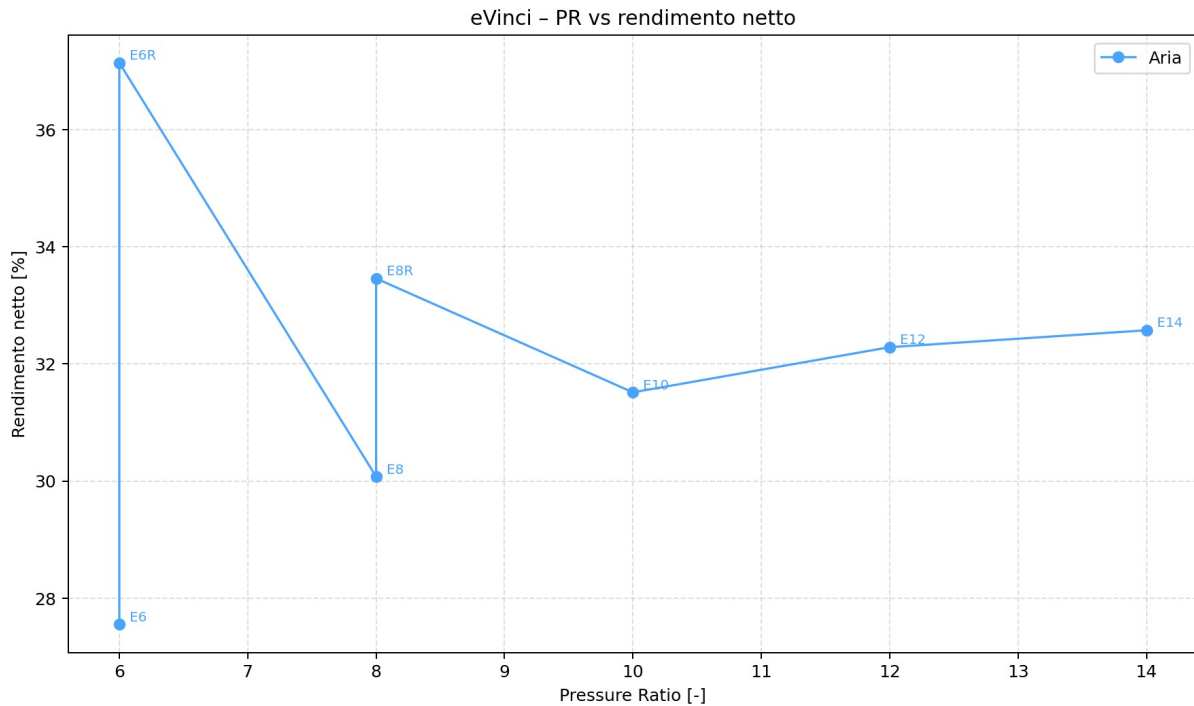


Figure25 : eVinci: PR vs Efficiency

Overall, the eVinci case shows that the air-cooled open Brayton cycle, coupled with an equivalent heat-pipe type heat source, exhibits regular and predictable behaviour: efficiency increases with PR, but recovery remains truly advantageous only in the lower compression ratio range. This result is important because it confirms that even in the case of a microreactor with an unconventional reactor-side architecture, it is possible to establish a coherent picture of the BoP performance.

4.3.3 Summary of the eVinci case

From an application perspective, eVinci is designed for remote communities, mining operations, critical infrastructure, data centres, industrial processes, district heating and hydrogen generation—that is, for a range of contexts where compactness, portability and flexibility of use are key factors. In this context, the results obtained show that the air-cooled BoP has a reasonable and clearly defined operating window: the simple cycle provides progressive and stable performance, whilst the recovered configuration appears particularly promising at lower pressure ratios.

The eVinci case also highlights a methodological point of relevance to the entire thesis: even when the reactor side does not correspond to a traditional primary circuit, representation via a

characterised heat source remains sufficient to systematically study the behaviour of the Balance of Plant.

4.4 Results of the OTRERA 300 case

The plant scheme to be considered in this discussion, shown in the Thermoflex workspace, is depicted in Figures 26 and 27 in classic and regenerative configurations, with a PR of 3:

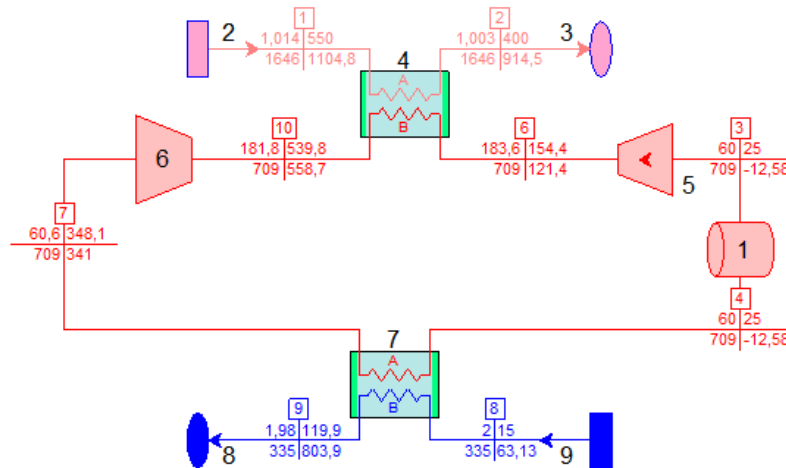


Figure26 : Thermoflex OTRERA Brayton cycle scheme - PR 3

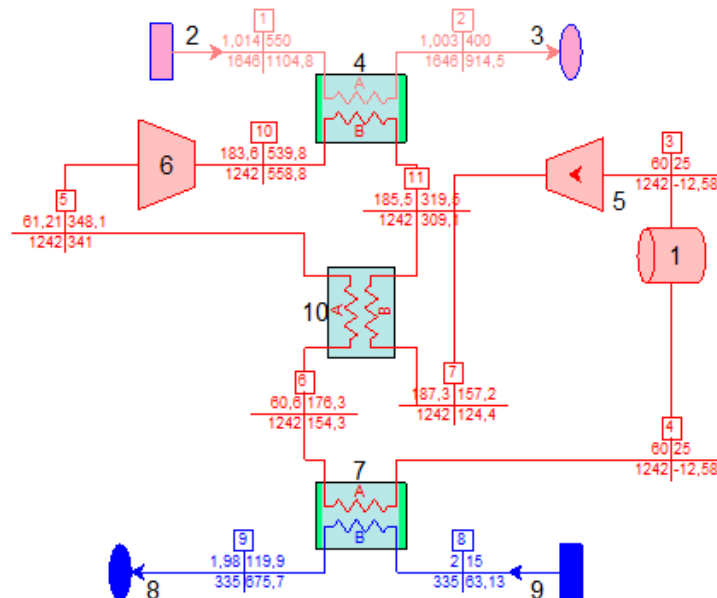


Figure27 : Thermoflex OTRERA Brayton cycle scheme – PR 3 Regenerated

4.4.1 Net efficiency trend in the closed nitrogen Brayton cycle

OTRERA 300 represents the largest-scale case and the one in which the link between the heat source and the conversion system is closest, as the reference documentation explicitly refers to a closed nitrogen Brayton cycle associated with the concept. The same source links the

system to the supply of decarbonised electricity and heat for industrial use, with installation near industrial sites and the utilisation of waste heat. For this reason, the OTRERA case serves as an important benchmark for verifying the behaviour of the BoP when the reactor and conversion data are already closely aligned prior to modelling.

Table 4.3 – Summary results of the OTRERA 300 case

PR	Recuperator	\dot{m}_{wf} [kg/s]	T compressor outlet [°C]	T turbine outlet [°C]	Net power [kW]	η_{net} [%]
2	No	632.0	102.0	414.3	38,840	12.9
2	Yes	1708.0	136.5	164.3	88,494	29.5
3	No	709.0	154.4	348.1	56,987	19.0
3	Yes	1242.0	157.2	176.3	96,704	32.2
4	No	785.3	196.0	304.5	66,916	22.3
4	Yes	1071.0	199.0	209.5	88009	29.3

In the simple cycle, net efficiency increases significantly, rising from approximately 12.4% at PR = 2 to approximately 21.4% at PR = 4. The increase in the compression ratio therefore produces, within this analysis window, a net improvement in performance. However, the recuperator brings about an even more pronounced change: at PR = 2, efficiency rises to approximately 28.3%, at PR = 3 it reaches approximately 30.9% and at PR = 4 it stands at around 28.1%. The maximum efficiency among the simulated points is therefore found in the recuperated configuration at PR = 3.

The graph shows that the recuperator is advantageous across the entire pressure ratio range studied, but that its benefit does not increase monotonically. The increase compared to the simple cycle is very high at PR = 2, remains significant at PR = 3 and decreases at PR = 4, whilst still remaining significant. This suggests that, for the range of conditions considered, there is an intermediate region where the balance between compression work, expansion work and internal heat recovery is particularly favourable.

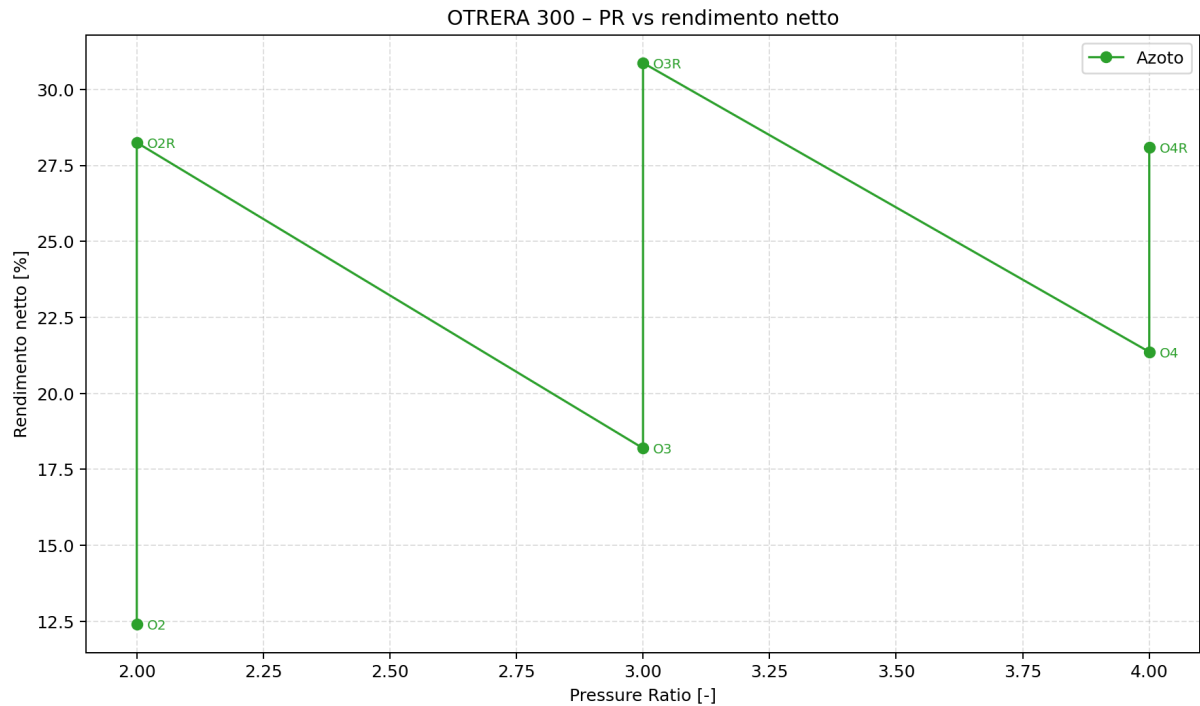


Figure28 : OTRERA - PR vs net efficiency

4.4.2 Characteristic temperatures and resulting mass flow rate

The characteristic temperatures of the cycle confirm the picture just described. In the simple configuration, T4 remains consistently well above T2: at PR = 2, T2 is approximately 102.0 °C and T4 is 414.3 °C; at PR = 3, T2 is 154.4 °C and T4 is 348.1 °C; at PR = 4, T2 = 196.0 °C and T4 = 304.5 °C. At all three points, the margin for recovery is therefore substantial, and this explains the high efficiency of the recuperator observed in the performance results.

The mass flow rate of the working fluid also shows an interesting trend. In the simple cycle, it increases with PR, rising from approximately 632 kg/s at PR = 2 to approximately 785.3 kg/s at PR = 4. In the recuperative configurations, the values are higher than those of the simple cycle for all simulated points, but decrease with the pressure ratio: approximately 1708 kg/s at PR = 2, 1242 kg/s at PR = 3 and 1071 kg/s at PR = 4. This behaviour is consistent with the fact that the recuperator profoundly alters the cycle's energy balance, shifting the operating point and enabling a more efficient utilisation of the available heat.

The results as a whole therefore suggest that, within the study range adopted for OTRERA 300, the nitrogen-fired closed Brayton cycle operates in a region where internal heat recovery is a decisive performance factor. Unlike what was observed in the eVinci case, here the recuperator is not confined to low pressure ratios, but remains advantageous across the entire range examined.

4.4.3 Summary of the OTRERA 300 case

The OTRERA 300 case highlights how a larger thermal source directly coupled to a nitrogen Brayton engine leads to a BoP response different from that of the two microreactors. The

recuperator plays a central rather than a marginal role, whilst the optimal PR value, within the analysed set, does not coincide with the upper limit of the range but with an intermediate condition. This result is particularly interesting, as it shows that an increase in the pressure ratio does not necessarily lead to a monotonic improvement in the recuperated configuration.

From an application perspective, this behaviour is consistent with the concept's intended use in industrial cogeneration contexts and for installation near significant thermal loads. The available documentation indeed emphasises the intention to supply not only electricity but also high-temperature heat to industrial users, with close integration between the reactor side and the conversion side. From this perspective, the BoP results obtained in this study appear highly significant, as they demonstrate that the utilisation of waste heat is an integral, rather than an ancillary, part of the system's performance logic.

4.5 Cross-cutting discussion of the results

The joint analysis of the three case studies allows us to draw some general conclusions regarding the behaviour of the Balance of Plant in the presence of different heat sources.

1. The first concerns the role of the pressure ratio. In all the cases examined, it directly influences the performance of the cycle, but not according to a single, universal law. In some cases, such as eVinci in a simple configuration, an increase in PR produces a progressive but increasingly less marked improvement; in others, such as OTRERA in a recovery configuration, a performance peak emerges at intermediate values; finally, in the AMR case, the effect of the pressure ratio also depends heavily on the working fluid.
2. The second observation concerns the non-independent nature of the mass flow rate. The results confirm that the working fluid flow rate cannot be considered a mere ancillary variable, nor, even less so, a quantity that can be arbitrarily set. Rather, it is a response of the cycle to the constraints imposed by the heat source and the configuration adopted. Consequently, the differences observed between the cases reflect not only the different power scales of the systems, but also the different ways in which each cycle must adapt to the source to balance the mass and energy balances.
3. The third observation concerns the recuperator. The entire simulation campaign shows that its effectiveness depends strictly on the thermal structure of the cycle. In the eVinci case, its advantage is concentrated at low pressure ratios; in the OTRERA case, it remains useful across the entire analysed range; in the AMR case, its benefit varies significantly from fluid to fluid. This leads to an important conclusion: the decision on whether or not to introduce a recuperator cannot be generalised a priori, but must be assessed on a case-by-case basis in relation to the heat source–working fluid pair and the operating window under consideration.

Finally, the results reinforce the central idea of the thesis: what most differentiates the three cases is not only the reactor technology itself, but the way in which the heat source imposes constraints on the power cycle. The engineering interest of the comparison therefore lies not in determining which reactor is better, but in showing how efficiency, mass flow rate, the role

of the heat recovery unit and the overall BoP structure change as the conditions imposed by the nuclear side vary.

4.6 Final application considerations

The results obtained can also be interpreted in the light of the possible applications of the three selected concepts. In the case of the AMR, the IAEA documentation explicitly refers to grid-connected applications, applications for isolated users and for process heat, as well as the possibility of use in single-module or multi-module configurations. In this context, the BoP's high sensitivity to the working fluid suggests that concepts of this type could benefit from a cycle design specifically tailored to the intended use, distinguishing, for example, between maximising electrical efficiency and optimising heat recovery.

For eVinci, the application areas outlined in the documentation include remote communities, mining operations, critical infrastructure, data centres, industrial processes, district heating and hydrogen generation. Here, the distinguishing feature is not so much the extreme maximisation of efficiency, but rather the compactness of the system, its portability and its ability to operate in decentralised or off-grid contexts. From this perspective, the results obtained for the open-air Brayton cycle demonstrate a configuration consistent with modular and flexible deployment, in which system simplicity can play an important role alongside net performance.

Finally, for OTRERA 300, the available documentation emphasises the cogeneration of electricity and heat in the vicinity of industrial sites and the availability of waste heat for industrial end-uses. The results of this study are in line with this application logic: the heat exchanger emerges as a key component, and the utilisation of waste heat appears to be a structural part of the cycle's behaviour. OTRERA 300 therefore represents the case where the link between the BoP's electrical performance and the potential for thermal integration with industrial uses is most evident.

Conclusions:

The work developed in this thesis made it possible to build a coherent research pathway which, starting from the analysis of the energy landscape and advanced nuclear technologies, leads to the modeling of the power conversion system for three case studies representative of different modes of integration between the thermal source and the Balance of Plant. The transition from the reactor benchmark to thermo-fluid dynamic simulation showed that, even in the presence of concepts that differ significantly in size, technology, and interface architecture, the problem can be reduced to a common methodological framework, in which the reactor is treated as a characterized thermal source and the BoP as the actual object of engineering analysis.

From a methodological point of view, one of the most significant results of the thesis lies in having shown that describing the source through nominal thermal power, hot-side thermal level, and heat-transfer fluid is sufficient to build simulation models that are coherent and physically interpretable for the conventional side. Within this framework, the pressure ratio is confirmed as the main parametric variable, whereas the mass flow rate of the working fluid does not represent an independent design choice, but rather a resulting quantity determined by the need to simultaneously satisfy the energy and thermal constraints imposed by the source. This aspect constitutes a central element in the interpretation of the results and represents one of the defining features of the adopted approach.

The analysis of the AMR case highlighted particularly clearly the sensitivity of the BoP to the working fluid. Under the same thermal source conditions, in fact, replacing air with helium, nitrogen, or CO₂ significantly affects both net efficiency and the role of the recuperator. Within the range of operating conditions investigated, helium yielded the highest performance, whereas air and nitrogen showed more moderate but relatively stable behavior. CO₂, although less favorable in the simple cycle, showed significant potential in the recuperated configuration. It follows that the choice of working fluid is not a secondary detail, but rather a design parameter capable of substantially influencing the response of the power conversion system.

For eVinci, treated as an open Brayton cycle with air, the results showed a regular behavior, with net efficiency increasing as the pressure ratio increased, and with the usefulness of the recuperator concentrated mainly at the lowest PR values. The interest of this case lies not only in the level of performance achieved, but above all in the verification of the robustness of the method even in the presence of a heat-pipe concept, and therefore one that cannot be reduced to a conventional convective primary circuit. In this sense, the eVinci simulation confirmed that representation through an equivalent thermal source can be effectively used to analyze the BoP even in non-conventional architectures.

Finally, the OTRERA 300 case showed a different behavior, consistent with the larger plant size and with the presence of a nitrogen closed Brayton cycle already mentioned in the reference sources. In this case, the recuperator does not represent a marginal refinement, but rather a decisive component for the overall performance of the cycle. The results indicate that internal heat recuperation remains advantageous over the entire pressure ratio range analyzed

and that the maximum net efficiency is achieved in a recuperated configuration at intermediate PR values. OTRERA 300 therefore made it possible to highlight particularly clearly the role of the thermal structure of the cycle and the integration between electricity production and the potential valorization of residual heat.

Overall, the most important result of the thesis may be summarized as follows: the behavior of the Balance of Plant does not depend solely on the nominal thermal power of the source, but on the way in which that source imposes constraints in terms of temperature, fluid, interface architecture, and opportunities for heat recuperation. Consequently, the comparison among the case studies should not be interpreted as a ranking of reactors, but rather as a comparison among different thermo-plant coupling conditions between the nuclear source and the power conversion system. This represents the main contribution of the work, since it shifts the focus from the mere classification of reactor concepts to the quality of their integration with the power cycle.

The analysis presented here had a preliminary character and was aimed at providing an initial assessment of the performance of power conversion systems associated with advanced nuclear reactors. To this end, several methodological simplifications were adopted, making it possible to focus on the main thermodynamic aspects of the BoP. The simulations were developed using THERMOFLEX, a software package widely employed for the analysis of energy cycles; the approach adopted was systemic in nature and made it possible to evaluate the overall behavior of the cycle, prioritizing the energy and plant-level consistency of the system as a whole over the detailed representation of individual components.

Within this framework, the nuclear reactor was represented as a characterized thermal source, defined through assigned operating parameters such as thermal power, hot fluid temperature, and heat-transfer fluid. This choice made it possible to focus the analysis on the power conversion system and to preserve comparability among heterogeneous case studies. At the same time, however, it entails a level of simplification that excludes an explicit modeling of the nuclear and thermo-hydraulic phenomena of the core, as well as of the design constraints more strictly related to the Nuclear Island, such as power density limits, the design of primary heat exchangers, the variability of reactor outlet temperature, and the transient behavior of the system. Similarly, further simplifications concerned the treatment of the working fluids and cycle components, through the use of thermophysical properties modeled within the software framework and the adoption of assigned performance parameters for turbines, compressors, and heat exchangers, without developing a detailed turbomachinery design or a complete engineering verification of their practical feasibility.

These limitations, however, do not reduce the value of the method with respect to the objectives of the thesis; rather, they define its scope clearly. The present work does not aim to provide a final system design, but rather to build a technical-methodological basis useful for understanding how different advanced nuclear thermal sources may affect the behavior of the power cycle and for identifying the variables most relevant to the overall performance of the BoP.

Looking ahead, the most natural future developments concern, first and foremost, the extension of the modeling approach toward a more detailed representation of individual

components and of the physical phenomena involved. In particular, preliminary sizing of the main cycle components appears to be of interest, as does the consolidation of turbomachinery feasibility in the analyzed configurations—through further investigations into compression architectures, turbine inlet temperature limits, and the distribution of work among the cycle components—as well as the analysis of integration issues between the nuclear system and the BoP. This may be complemented by the extension of the approach to additional cycle configurations, the evaluation of cogeneration scenarios, and the study of coupling with industrial thermal users, so as to compare the cases not only in terms of net efficiency, but also in terms of operational flexibility, plant compactness, and the quality of the heat available for non-electric applications. Further developments may also include sensitivity and uncertainty analyses on the main model parameters, possible multi-objective optimization approaches, and assessments of the economic implications associated with the different plant configurations.

From this perspective, the present work constitutes a basis for further studies aimed at a more comprehensive characterization of power conversion systems for advanced nuclear reactors, confirming that the value of BoP analysis lies not only in the estimation of performance, but above all in the ability to interpret, from a plant-engineering perspective, the problem of integration between the nuclear thermal source and the energy conversion system.

Appendix A – List of acronyms

List of acronyms and their definitions used in the text.

Acronym	Meaning
AMR	Advanced Micro Reactor
ARIS	Advanced Reactor Information System (IAEA)
BoP	Balance of Plant
BWR	Boiling Water Reactor
BWR-PWR	Boiling/Pressurised Water Reactor (LWR: boiling/pressurised water)
CHP	Combined Heat and Power (CHP)
FER	Renewable Energy Sources
Gen-IV	Generation IV
GFR	Gas-cooled Fast Reactor
GIF	Generation IV International Forum
GTHTR	Gas Turbine High Temperature Reactor (e.g. GTHTR-300)
HALEU	High-Assay Low-Enriched Uranium (high-enriched LEU, ~5–20% U-235)
HRSG	Heat Recovery Steam Generator
HTF	Heat Transfer Fluid
HTGR	High Temperature Gas-cooled Reactor
HTGR-VHTR	High/Very High Temperature Gas-cooled Reactor
HWR-SCWR	Heavy Water Reactor / Supercritical Water-cooled Reactor
IAEA	International Atomic Energy Agency (IAEA)
IEA	International Energy Agency (IEA)
IHTS	Intermediate Heat Transport System
IHX	Intermediate Heat Exchanger

LBE	Lead-Bismuth Eutectic (lead-bismuth eutectic alloy)
LEU	Low Enriched Uranium (uranium with a low enrichment level, <20% U-235)
LFR	Lead-cooled Fast Reactor
LMFR	Liquid-Metal Fast Reactor
LOCA	Loss-Of-Coolant Accident
LWR	Light Water Reactor
MMR	Micro Modular Reactor
MSR	Molten Salt Reactor
MSR-FHR	Molten Salt Reactor / Fluoride-salt-cooled High-temperature Reactor
MWe	Megawatt-electric
MWth	Thermal megawatt
N ₂	Nitrogen
NEA	Nuclear Energy Agency (OECD/NEA)
NSSS	Nuclear Steam Supply System (primary nuclear island)
PR	Pressure Ratio
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PWR	Pressurised Water Reactor
SCWR	Supercritical Water-cooled Reactor
SFR	Sodium-cooled Fast Reactor
SFR-LMR	Sodium-cooled Fast Reactor / Liquid-Metal Reactor
SMR	Small Modular Reactor
THERMOFLEX	THERMOFLEX (Thermoflow module for cycle simulation)
THERMOFLOW	Thermoflow (software suite for plant simulation and analysis)
TIT	Turbine Inlet Temperature

TRISO

TRi-structural ISOtropic (TRISO fuel particle)

UN

United Nations

VHTR

Very High Temperature Reactor

Appendix B – Dataset structure (Excel) and methodology

This chapter presents the distribution of the concepts surveyed (Table B.1), whilst the complete table listing the reactors and their characteristics is shown in Table B.2.

Methodological note (Table B.1): the distribution by technology family and thermal power threshold was obtained using a pivot table that counts unique designs after normalising the units and aligning the categories (controlled lists). The T_a thresholds (≤ 50 , ≤ 10 , ≤ 1 MWth) were applied to the nominal thermal power P_{th} ; for designs with a power range, the maximum declared power was adopted, as a conservative measure, whilst maintaining the traceability of the source (reference and page).

Selection of primary sources (catalogues/reports) and definition of the scope (SMRs, microreactors, relevant Gen-IV technologies).

Definition of the field dictionary and standard units; creation of an Excel template with mandatory/optional fields and traceability columns.

Population of the dataset with an initial ‘raw’ compilation and precise annotation of sources (reference, page, URL where applicable).

Standardisation (units and definitions) and automatic checks: net/gross consistency, plausible ranges, consistency between thermal and electrical power where both are available.

Cross-checking of key parameters (power, T_{out} , cycle) against at least one independent source where available; management of discrepancies using notes and precedence rules.

Freezing of a version (“snapshot”) used as a baseline for the selection of case studies and for setting up the THERMOFLEX models (Chapter 2).

This framework enables a transition from a qualitative description of the technological landscape to a set of justifiable assumptions and parameters, which will then be used: (i) as inputs for thermodynamic modelling of the Balance of Plant; (ii) as a basis for assessing the suitability of technologies in relation to end-users and districts (useful temperatures, operational continuity, size and modularity).[7–15]

Table B.1 – Distribution of surveyed reactors

CATEGORY	ALL	≤50MWth	≤10MWth	≤1 MWth
WATER-COOLED SMALL MODULAR REACTORS (LAND-BASED)	45	9	2	1
WATER-COOLED SMALL MODULAR REACTORS (MARINE-BASED)	10	2	0	0
GAS-COOLED SMALL MODULAR REACTORS	37	20	10	2
LIQUID METAL-COOLED MODULAR REACTORS	38	6	3	1
MOLTEN SALT SMALL MODULAR REACTORS	25	5	2	1
HEAT-PIPE MODULAR REACTORS	3	3	3	1
TOTAL	158	45	20	6

Table B.2 – List of surveyed reactors

Note: rows showing only the category serve as separators between technology families; missing values indicate data not available in the sources at the time of the snapshot.

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
WATER-COOLED SMALL MODULAR REACTORS (LAND-BASED)										
ACP100	CNNC (China)	PWR	Thermal	125	385	33.00%	319°C	Light water	Light water	UO2 <5%
AHWR-300-LEU	BARC (India)	LHR (HWR)	Thermal	304	920	33.00%		Light water	Heavy water	Th-U or Th-Pu, MOX <5%
AP300	Westinghouse (USA)	PWR	Thermal	330	990	33.00%	285°C	Light water	Light water	UO2 <5%
BWRX-300	GE-Hitachi (USA/Japan)	BWR	Thermal	300	870	34.50%	288°C	Soft water	Light water	O ₂ 3.4–4.95%
CAL-30	Calogena (France)	Pool-type	Thermal	0	30		110°C	Light water (demi)	Light water	UO2 <5%
CANDU SMR	Candu Energy (Canada)	PHWR	Thermal	300	960	31.25%		Light water	Light water	Natural UO2
CAP200	CGNPC (China)	PWR	Thermal	>200	600	>30.00%		Light water	Light water	UO2 4.2%, 24-month

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
										cycle
CAREM	CNEA (Argentina)	PWR	Thermal	30	100	30.00%	326°C	Light water	Light water	O ₂ 3.1%
CCR	Toshiba (Japan)	BWR	Thermal	423	1268	33.40%		Light water	Light water	
CNP-300	CNNC (China)	PWR	Thermal	300–340	1000	30.00–34.00%		Light water	Light water	UO ₂ <5%
DFBR-1	Deep Fission (USA)	PWR	Thermal	15	50	30.00%	315°C	Light water	Light water	UO ₂ <5%
DHR400	CNNC (China)	LWR	Thermal	0	400			Light water	Light water	UO ₂ <5%
DMS	Hitachi-GE (Japan)	BWR	Thermal	300	840	36.00%		Light water	Light water	UO ₂ <5%
ELENA	Kurchatov Institute (Russia)	PWR	Thermal	0.068	3.3	2.00%	328°C	Light water	Light water	UO ₂ (MOX) 15.2%
FBNR	UFRGS (Brazil)	PWR	Thermal	70	134	52.20%		Light water	Light water	TRISO
HAPPY200	SPIC (China)	PWR	Thermal	0	200		120°C	Soft water	Light water	UO ₂ <5%
i-SMR	KHNP/KAERI (South Korea)	PWR	Thermal	170	520	32.69%	321°C	Soft water	Light water	UO ₂ <5%
IMR	MHI (Japan)	PWR	Thermal	350	1000	35.00%		Light water	Light water	O ₂ 4.8%
IRIS	IRIS Consortium (USA/EU)	PWR	Thermal	335	1000	34.00%		Light water	Light water	UO ₂ /MOX 5%
KARAT-100	NIKIET (Russia)	BWR	Thermal	100	360	28.00%		Light water	Light water	UO ₂ 4%
KARAT-45	NIKIET (Russia)	BWR	Thermal	45–50	180	25.00–28.00%		Light water	Light water	UO ₂ 4.5%

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
LDR 50	Steady Energy (Finland)	PWR	Thermal	0	50	N/A	150°C	Soft water	Light water	UO2 LEU 4.99%
LEUNR	CSMC (Canada)	PWR	Thermal	0	0.1		130°C	Soft water	Light water	Cermet / UO2 <20%
mPower	BWXT (USA)	PWR	Thermal	195	575	34.00%		Light water	Light water	UO2 <5%
MRX	JAERI (Japan)	PWR	Thermal	33.3	100	33.30%		Light water	Light water	UO2 4.3%
NHR200-II	INET and CGN (China)	PWR	Thermal	0	200		280°C	Heavy water	Heavy water	UO2 <5%
Nuclearis N1	Nuclearis (USA)	PWR	Thermal	17	42	40.48%	319.8°C	Light water	Light water	UO2 HALEU <4.95%
NuScale Power Module	NuScale Power (USA)	PWR	Thermal	77	250	30.80%	321°C	Soft water	Light water	UO2 <5%
NUWARD SMR	EDF/CEA/Naval Group/TA (France)	PWR	Thermal	170	540 x2	31.50%	307°C	Light water	Light water	UO2 <5%
PHWR-220	NPCIL (India)	PHWR	Thermal	235	755	31.20%		Light water	Light water	UO2<5%
PWR-20	Last Energy (USA)	PWR	Thermal	20	80	25.00%	300°C	Light water	Light water	UO ₂ <5%
RITM-200N	OKBM Afrikantov (Russia)	PWR	Thermal	55	198 X2	27.78%	321°C	Light water	Light water	UO2 <20% CERMET
Rolls-Royce SMR	Rolls-Royce (UK)	PWR	Thermal	470	1358	34.60%	325°C	Soft water	Light water	UO2 <5%
RUTA-70	NIKIET (Russia)	PWR	Thermal	0	70			Light water	Light water	Cermet 3%
SMART100	KAERI (South Korea)	PWR	Thermal	107	365	29.31%	322°C	Light water (supercritical)	Light water (supercritical)	UO2 <5%

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
SMR-160	Holtec (USA)	PWR	Thermal	160	525	31.00%		Light water	Light water	UO2 5%
SMR-300	Holtec (USA)	PWR	Thermal	320	1050	30.50%	321°C	Light water	Heavy water	UO2 <5%
SNP350	SNERDI (China)	PWR	Thermal	350	1035	33.80%		Light water	Light water	UO2 <5%
SSR	AECL (Canada)	SCWR	Thermal	300	667	45.00%		Light water	Light water	Enriched U O Th
STAR	STAR Energy (Switzerland)	PTWR	Thermal	10	30	33.33%	300°C	Light water	Light water	UO2 LEU 19%
TEPLAT OR	UWB/CIIRC (Czech Republic)	HWR	Thermal	0	50–150		98°C	Heavy water	Heavy water	Spent VVER-440 UO2 fuel (<1.2%)
UK-SMR	Rolls-Royce (UK)	PWR	Thermal	443	1276	26.00%		Light water	Light water	UO2 <5%
UNITHERM	NIKIET (Russia)	PWR	Thermal	6.6	30	22.00%	330°C	High-purity light water	High-purity light water	UO2 19.75%
VK-300	NIKIET (Russia)	BWR	Thermal	250	750	33.00%		Light water	Light water	UO2 4%
W-SMR	Westinghouse (USA)	PWR	Thermal	>225	800	28.00%		Light water	Light water	UO2 <5%
WATER-COOLED SMALL MODULAR REACTORS (MARINE-BASED)										
ABV-6E	OKBM Afrikantov (Russia)	Floating PWR	Thermal	9	38	24.00%	325°C	Soft water	Light water	UO2, <20%
ACP100S	CNNC (China)	Floating PWR	Thermal	125	385	33.00%	~320	Light water	Light water	UO2, <5%
ACPR50S	CGNPC (China)	PWR	Thermal	50	200	25.00%	320°C	Soft water	Light water	UO2, <5%
TENDERS	KEPCO E&C (South Korea)	Floating PWR	Thermal	60	200	30.00%	322	Light water	Light water	UO2, LEU <5%
Flexblue	DCNS (France)	PWR	Thermal	160	600	26.70%		Light water	Light water	UO2, <5%

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
KLT-40S	OKBM Afrikantov (Russia)	Floating PWR	Thermal	35	150 x2	23.00%	316°C	Light water	Light water	UO ₂ , 18.6%
RITM-200M	OKBM Afrikantov (Russia)	Floating PWR	Thermal	50	190	26.32%	321°C	Soft water	Light water	UO ₂ , <20% CERMET
RITM-200S	OKBM Afrikantov (Russia)	Ship PWR	Thermal	55	198 X2	26.8%	318°C	Soft water	Light water	CERMET
SHELF-M	NIKIET (Russia)	Immersed NPP (iPWR)	Thermal	10	35	28.41%	308°C	Light water	Light water	O ₂ (19.7%)
VBER-300	OKBM Afrikantov (Russia)	Floating NPP	Thermal	325	917	35.00%		Light water	Light water	UO ₂ 4.95%
GAS-COOLED SMALL MODULAR REACTORS										
A-HTR-100	Eskom Holdings SOC (South Africa)	HTGR	Thermal	50	100	50.00%	1200°C	Helium	Graphite	CPF
Allegro	CEA (France)	GFR	Fast	0	50–100		530–850 °C (driver/ceramic core)	Elio		MOX
AMR	Power Cell Micro Reactor (Afrika S.)	HTGR	Thermal	3	10	33.33%	750°C	Helium	Graphite	TRISO/LBE eutectic/SiC
ANTARES	Framatom e/AREVA (France)	HTGR	Thermal	N.A.	600			Helium	Graphite	
BANR	BWX Technologies (USA)	HTGR	Thermal	N/A	50–75		800°C	Helium	Graphite	TRISO (UN)
Blossom Energy SMR	Blossom Energy (Japan)	HTGR	Thermal	60	180	33.33%	320°C	Helium	Graphite	TRISO HALEU (UO ₂)
EM2	General Atomics (USA)	GFR	Fast	265	500	53.00%	850°C	Helium		UC 14.5% LEU
FMR	General Atomics (USA)	GFR	Fast	50	100	50.00%	800°C	Helium		TRISO (UO ₂)
GT-MHR	OKBM Afrikantov (Russia)	HTGR	Thermal	288	600	48.00%		Helium	Graphite	CPF LEU or Wpu

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
GTHTR300	JAEA (Japan)	HTGR	Thermal	300	600	50.00%	950°C	Helium	Graphite	UO ₂ 14% TRISO
HECTAR	KAERI (Republic of Korea)	HTGR	Thermal	N/A	90		750°C	Helium	Graphite	TRISO (UC)
Holos Mono	HolosGen (USA)	HTGR	Thermal	10	22	45.45%	855°C	Helium	Graphite	TRISO UCO (19.95%)
Holos Quad	HolosGen (USA)	HTGR	Thermal	10	22	45.45%	856°C	Helium	Graphite	TRISO UCO (19.95%)
HTGR-POLA	NCBJ (Poland)	HTGR	Thermal	11.5	30	38.33%	750°C	Helium	Graphite	TRISO UO ₂ (10–12%)
HTMR-100	Stratek Global / STL (South Africa)	HTGR	Thermal	35	100	35.00%	750°C	Helium	Graphite	LEU<10%, Th/LEU, Th/HEU, Th/P
HTR-10	INET, Tsinghua University (China)	HTGR	Thermal	2.5	10	25.00%	700°C	Helium	Graphite	Spherical helium, TRISO particles fuel 17%
HTR-PM	INET, Tsinghua University (China)	HTGR	Thermal	155	250 x2	42.00%	750°C	Helium	Graphite	Pebble CPF 8.5%
HTR50S	JAEA (Japan)	HTGR	Thermal	17.2	50	34.40%	750°C 900°C (2nd Phase)	Helium	Graphite	TRISO UO ₂ (5.9–9.4%)
HTTR	JAEA (Japan)	HTGR	Thermal	N/A	30	N/A	850°C (MAX 900°C)	Helium	Graphite	TRISO UO ₂ ceramic-coated (3–10%)
Jimmy HTR	Jimmy (France)	HTGR	Thermal	N.A.	10–20	N/A	550°C (MAX 700°C)	Helium	Graphite	TRISO UCO (<19.75%)
Kaleidos	Radiant Industries (USA)	HTGR	Thermal	1	3.5	28.57%	700°C	Helium	Graphite and ZrH	TRISO HALEU UO ₂
KRONOS MMR	NANO Nuclear Energy (USA)	HTGR	Thermal	3–5–15	10–45		660°C	Helium	Graphite	TRISO (UO ₂)
LOKI MMR (formerly Pylon D1)	NANO Nuclear Energy (USA)	HTGR	Thermal	N.A.	5	N/A	727°C	Helium	Graphite	TRISO (UO ₂ /UCO)

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
MHR-100	OKBM Afrikantov (Russia)	HTGR	Thermal	87	215	41.00%		Helium	Graphite	CPF LEU <20%
MHR-T	OKBM Afrikantov (Russia)	HTGR	Thermal	205.5	600 x4	34.00%		Helium	Graphite	CPF 20%
MMR	NANO Nuclear Energy (USA)	HTGR	Thermal	15	45	33.30%	660°C	Helium	Graphite	TRISO-FCM
MN-1	MobileNuclear Energy (USA)	HTGR	Thermal	0.35	1	N/A	650°C	Helium	Graphite	UC/UN
PBMR-100	PBMR SOC Ltd (South Africa)	HTGR	Thermal	100	250	40.00%		Helium	Graphite	TRISO-coated UP2
PBMR-400	PBMR SOC Ltd (South Africa)	HTGR	Thermal	165	400	41.30%		Helium	Graphite	CPF 9.6% LEU
PeLUit-40	BATAN (Indonesia)	HTGR	Thermal	10	30	33.33%	750°C	Helium	Graphite	TRISO UO2 (<17%)
Prismatic HTR	General Atomics (USA)	HTGR	Thermal	150	350	42.80%		Helium	Graphite	TRISO (Coated UCO 15.5%)
Project Pele	BWX Technologies (USA)	HTGR	Thermal	1–5				Helium	Graphite	TRISO (UO)
RDE / Micro-PeLUit	BATAN (Indonesia)	HTGR	Thermal	3	10	30.00%	750°C	Helium	Graphite	Spherical CPF <17%
SC-HTGR	Framatome Inc. (USA/France)	HTGR	Thermal	272	625	43.50%		Helium	Graphite	TRISO (UCO<20%)
Starcore SMR	Starcore (Canada)	HTGR	Thermal	20	36	55.60%	750°C	Helium	Graphite	TRISO
U-Battery	URENCO (UK)	HTGR	Thermal	4	10	40.00%	750°C	Helium	Graphite	TRISO (17–20%)
Xe-100	X-energy LLC (USA)	HTGR	Thermal	80	200	40.00%	750°C	Helium	Graphite	TRISO (UCO <15.5%)
LIQUID METAL-COOLED MODULAR REACTORS										
4S	Toshiba (Japan)	LMFR	Fast	10	30	33.33%	510°C	Sodium		MF (U-Zr <20%)
AFR-100	ANL/DOE (USA)	LMFR	Fast	100	250	40.00%	550°C	Sodium		U-Zr 13.5%

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
ALFRED	ENEA/ Ansaldo Nucleare (Italy)	LFR	Fast	125	300	41.70%	550°C	Lead		MOX
ARC-100	Advanced Reactor Concepts (USA)	SFR	Fast	100	286	34.97%	510°C	Liquid sodium		U-Zr LEU
ASTRID	CEA (France)	SFR	Fast	600	1500	40.00%	550°C	Sodium		MOX
Aurora Powerhouse	Oklo Inc. (USA)	LMFR	Fast	15–50	50–150	33.33%	500°C	Sodium		U-Zr HALEU <20%
Blue Capsule	BC Tech. (France)	SFR	Thermal	50	150	33.33%	750°C	Sodium		UO2 TRISO
BREST- OD-300	NIKIET/ RDIPE (Russia)	LFR	Fast	300	700	43.00%	535°C	Lead- Bismuth		U-Pu-N Mixed
CFR-600	CIAE (China)	SFR	Fast	600	1500	40.00%	550°C	Sodium		UO2/ MOX
DF300	Dual Fluid Energy (USA)	LMFR	Fast	N/A	600		1000°C	Sodium		U-Cr alloy liquid
ELFR	Ansaldo/ ENEA (Italy/EU)	LFR	Fast	630	1500	42.00%		Sodium		MOX
ENHS	UC Berkeley (USA)	LFR	Fast	50	125	40.00%	800°C	Lead- Bismuth		Pu-U/U- Zr
G4M (Hyperion)	Gen4 Energy (USA)	LMFR	Fast	25	70	35.70%	500°C	Lead- Bismuth		UN 19.75%
HEXANA	HEXANA (France)	SFR	Fast	150	800	18.75%	530°C	Sodium		Y

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
KALIMER-600	KAERI (South Korea)	LMFR	Fast	600	1523.4	39.40%	545°C	Sodium		U-TRU-Zr
Leadir-PS100	Northern Nuclear Ind. (Sweden/USA)	LMR	Fast	36	100	36.00%	500°C	Lead		TRISO
LFR-AS-200	Newcleo (Luxembourg)	LFR	Fast	200	480	42.00%	530°C	Lead		MOX 14.6%, 20.4%, 23.2% in Pu CERCER
LFR-AS-30	Newcleo (Luxembourg)	LFR	Fast	N/A	90		530°C	Lead		MOX 14.6%, 20.4%, 23.2% in Pu CERCER
LFR-TL-X	Hydromin e Nuclear Energy (Luxembourg)	LFR	Fast	5	15 X2	33.33%	420°C	Lead		LEU 19.8%
LSPR	Tokyo Tech. (Japan)	SFR	Fast	53	150	35.30%	510°C	Sodium		U-Pu-N/ Upu-Zr 10%– 12.5%
Marvel	INL/DOE (USA)	LMR	Thermal	0.015– 0.027	0.075–0.1	20.00– 27.00%	520°C	Sodium-potassium eutectic	Hydrogen	U-ZrH HALEU (19.75%)
MicroURANUS	UNIST (South Korea)	LMFR	Fast	20	60	33.33%	650°C	Sodium		UO ₂ 8, 10, 12%
Sodium	TerraPower/GE-Hitachi (USA)	SFR	Fast	345	840	41.10%	500°C	Sodium		U-Zr HALEU Metal Alloy
Otrera 300	Otrera Energy (USA)	SFR	Fast	110	300 x2	36.67%	550°C	Sodium		MOX ceramic
PBWFR-150	Tokyo Tech. (Japan)	LMFR	Fast	150	450	33.30%	600°C	Lead-Bismuth		U-Pu nitride

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
PEACER	SNU (South Korea)	LMFR	Fast	300	850	35.00%	750°C	Lead-Bismuth		U-TRU-Zr
PGSFR	KAERI (South Korea)	SFR	Fast	150	400	37.50%	545°C	Sodium		U-TRU-Zr
Prism	GE-Hitachi (USA)	LMFR	Fast	311	500	62.00%	510°C	Sodium		U-Pu-Zr Metallic
RAPID-L	CRIEPI (Japan)	LMFR	Fast	0.2	5	4.00%	1100°C	Lithium		40–50%
SALUS-100	KAERI (South Korea)	LMFR	Fast	100	267	37.45%	510°C	Sodium		U-Zr
SEALER Micro	LeadCold (Sweden)	LFR	Fast	3	8	38.00%	432°C	Lead		UO ₂ 19.75%
SEALER-55	LeadCold (Sweden)	LFR	Fast	55	150		450°C	Lead		UN
SEALER-One	Blykalla (Sweden)	LFR	Fast	N/A	70		450°C	Lead		UN
START	Transmute x (Switzerland)	LMFR	Fast	N/A	600		450°C	Sodium		U-Pu Nitride
SUPERSTAR	Argonne National Laboratory (USA)	LMFR	Fast	120	300	40.00%	550°C	Sodium		U-Pu-Zr Particulate <12%
SVBR-100	AKME/OKBM Afrikantov (Russia)	LBFR	Fast	100	280	37.00%	490°C	Lead-Bismuth		UO ₂ <19.3%
TWR-P	TerraPower (USA)	SFR	Fast	600	1475	41.00%	500°C	Sodium		U-Zr
WLFR	Westinghouse (USA)	LFR	Fast	>450	950	47.00%	510°C	Molten lead		UN LEU≤19.75%
MOLTEN SALT SMALL MODULAR REACTORS										
CA Waste Burner	Copenhagen Atomics (Denmark)	MSR	Thermal	20	50	40.00%	675°C	Molten salt (LiF-ThF ₄)	Heavy water	LiF-ThF ₄ fuel salt
CA Waste Burner 0.2.5	Copenhagen Atomics	MSR	Thermal	N.A.	100		675°C	Molten salt (LiF-ThF ₄)	Heavy water	LiF-ThF ₄ fuel salt

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
	(Denmark)									
CMSR (MSTW)	Seaborg Tech. (Denmark)	MSR	Thermal	110	250	44.00%	650°C	Na-actinide fluoride salt	Graphite	Na-actinide fluoride (Th/U/Pu)
Energy Well	CVR (Czech Republic)	FHR	Thermal	8	20	40.00%	700°C	Molten salt FLiBe	Graphite	UO ₂ TRISO <20%
Flex Reactor	Moltex Energy (United Kingdom)	MSR	Thermal	24	60	40.00%	700°C	Molten salt fuel and coolant AlF ₃ /NaF	Graphite	UF ₃ , UF ₄ and NaF (LEU 5%) fluorides
FUJI	ITMSF (Japan)	MSR	Thermal	200	450	44.00%	704°C	Molten fluoride salt LiF–BeF ₂ –ThF ₄ –UF ₄	Graphite	MSF fuel (Th ²³³ U), 2% Pu or LEU
Hermes	Kairos Power (United States)	FHR	Thermal	0	35	N/A	650°C	LiF–BeF ₂ molten fluoride salt	Graphite	TRISO (HALEU 19.75%)
IMSR 400	Terrestrial Energy (Canada/USA)	MSR	Thermal	195	442 x2	44.12%	700°C	Molten fluoride salt	Graphite	MSF<5%
KP-FHR	Kairos Power (United States)	FHR	Thermal	140	311	45.00%	650°C	Molten fluoride salt (LiBeF ₄)	Graphite	TRISO pebble bed (19.75% LEU)
LFTR	Flibe Energy (USA)	MSR	Thermal	250	600	42.00%	650°C	Molten salt (LiF–BeF ₂ –UF ₄)	Graphite	LiF–BeF ₂ –UF ₄
MCFR	TerraPower (USA)	MSR	Fast	310	720	43.00%	500°C	Molten chloride salt		Molten chloride salt and molten HALEU

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
MCSFR	Elysium Industries (USA/Canada)	MSR	Fast	50	100	50.00%	650°C	Molten salt chloride		MSF HALEU
Mk1 PB-FHR	University of California, Berkeley (USA)	FHR	Thermal	100	236	42.00–42.50%	700°C	Li ₂ BeF ₄ molten fluoride salt	Graphite	TRISO particles (19.9% LEU)
MSR-1	Natura Resources / ACU (United States)	MSR	Thermal	N.A.	1	N/A	650°C	Molten fluorides FLiBe (LiF-BeF ₂ -UF ₄)	Graphite	LiF-BeF ₂ -UF ₄ fuel salt and HALEU
MSR-100	Natura Resources (United States)	MSR	Thermal	100	250	40.00%	650°C	Molten fluorides (LiF-BeF ₂ -UF ₄)	Graphite	LiF-BeF ₂ -UF ₄ fuel salt, molten fluoride
ODIN	NANO Nuclear Energy Inc. (USA)	MSR	Thermal	1–1.5	5	20.00–30.00%	400°C	Molten salt NaNO ₃ –KNO ₃	Zirconium hydride ZrH	U-ZrH _x HALEU
SmAHTR	Oak Ridge National Laboratory (USA)	FHR	Thermal	50	125	40.00%	700°C	FLiBe molten fluoride salt (LiF–BeF ₂)	Graphite	TRISO particles (19.75% LEU)
smTMSR-400	SINAP, CAS (China)	MSR	Thermal	168	400	42.00%	650°C	Molten salt (LiF-BeF ₂ -UF ₄ -ThF ₄)	Graphite	LiF-BeF ₂ -UF ₄ -ThF ₄ fuel salt
Stable Salt Reactor - Wasteburner	Moltex Energy (UK/Canada)	MSR	Fast	300	750	40.00%	590°C	Molten chloride salt (MgCl ₂ –NaCl)		MSF fuel (reactor-grade Pu)
Stable Salt Reactor – Th. Spectrum	Moltex Energy (UK/Canada)	MSR	Thermal	300	750	40.00%	700°C	NaF–ThF ₄	Graphite	MSF fuel (LEU 5%), breeding U-233 (Th)
Stellarium	Stellaria Energy (France)	MSR	Fast	110	250 (x2)	44.00%	750°C	Molten chloride salt		Molten chloride salt fuel

Reactor Name	Designers	Type	Spectrum	Capacity MWel	Thermal Power MWth	Thermal efficiency	T outlet	Refrigerant	Moderator	Fuel
ThorCon 500	ThorCon Int. (Indonesia /USA)	MSR	Thermal	250	557 x2	44.90%	704°C	NaBe/UF ₄ -based molten salt	Graphite	Molten fluorides HALEU 19.7%
Thorizon	Thorizon BV (Netherlands/France)	MSR	Fast/Thermal (more than one design)	100	250	40.00%	550°C	Molten chloride salt		Molten salt fuel (Th/U)
TMSR-LF	SINAP (China)	MSR	Fast/Thermal (more than one design)	168	373	45.00%	650°C	Molten salt (LiF-BeF ₂ -UF ₄ -ThF ₄ , Pu-bearing salt)	N/A (if fast design)	LiF-BeF ₂ -UF ₄ -ThF ₄ fuel salt
XAMR	NAAREX (France)	MSR	Fast	40	80	50.00%	625°C	Molten salt chloride		Molten chloride, actinides, Pu
HEAT-PIPE MODULAR REACTORS										
Antares R1	Antares Nuclear Inc. (USA)	Heat-pipe	Thermal	0.1–0.3	1	10.00–30.00%	800°C	Liquid sodium in heat pipes	Graphite	TRISO HALEU (UCO)
eVinci	Westinghouse Electric Co. (USA)	Heat pipe	Thermal	1–15 (5)	3–40 (15)	33.33–37.50%	750°C	Liquid sodium in heat pipes	Graphite	UO ₂ or UN 19.75% TRISO
Movelux	Toshiba Corporation (Japan)	Heat pipe	Thermal	3-4	10	30.00–40.00%	685°C	Liquid sodium in heat pipes	Calcium hydride CaH ₂	US LEU 4.8–5%

References:

- [1] International Energy Agency (IEA), The Path to a New Era for Nuclear Energy. Paris: IEA, 2025.
- [2] International Energy Agency (IEA), Electricity 2025: Analysis and Forecast to 2027. Paris: IEA, 2025.
- [3] OECD Nuclear Energy Agency (NEA), The NEA Small Modular Reactor Dashboard: Third Edition, NEA No. 7737, revised version 5 September 2025. Paris: OECD Publishing, 2025.
- [4] International Atomic Energy Agency (IAEA), Nuclear Power Reactors in the World, Reference Data Series No. 2, IAEA-RDS-2/45, 2025 Edition. Vienna: IAEA, 2025.
- [5] International Atomic Energy Agency (IAEA), Small Modular Reactors: Advances in SMR Developments 2024, IAEA/PAT/008. Vienna: IAEA, 2024.
- [6] International Atomic Energy Agency (IAEA) – Advanced Reactors Information System (ARIS), Small Modular Reactor Technology Catalogue, 2024 Edition, 3rd ed. Vienna: IAEA, 2025.
- [7] I. L. Pioro (Ed.), Handbook of Generation IV Nuclear Reactors: A Guidebook, 2nd ed. Cambridge, UK: Woodhead Publishing, 2023.
- [8] I. L. Pioro, R. B. Duffey, P. L. Kirillov, G. V. Tikhomirov, N. Dort-Goltz, and A. D. Smirnov, “Current status of SMRs and S&MRs development in the world,” in Handbook of Generation IV Nuclear Reactors: A Guidebook, 2nd ed., I. L. Pioro, Ed. Cambridge, UK: Woodhead Publishing, 2023.
- [9] N. E. Todreas and M. S. Kazimi, Nuclear Systems I: Thermal Hydraulic Fundamentals. New York: Hemisphere Publishing Corporation, 1990.
- [10] M. J. Moran, H. N. Shapiro, D. D. Boettner, and M. B. Bailey, Fundamentals of Engineering Thermodynamics, 8th ed. Hoboken, NJ: Wiley, 2014.
- [11] H. I. H. Saravanamuttoo, G. F. C. Rogers, and H. Cohen, Gas Turbine Theory, 5th ed. Harlow, UK: Pearson Education, 2001.
- [12] X. L. Yan, HTGR Brayton Cycle: Technology and Operations. MIT Workshop on New Cross-cutting Technologies for Nuclear Power Plants, Cambridge, USA, 30–31 January 2017.
- [13] Thermoflow, Inc., THERMOFLEX / THERMOFLOW – Tutorials and Documentation. Southborough, MA: Thermoflow.