Safety of the coupling between SMRs and electric and non-electric applications
Extension of the conventional safety approach and study of hybridization transients

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- Background from previous work (W. Ambrosini)
- Further developments and safety cases considered in TANDEM (P. Olita)
- Conclusions

Introduction

- In line with the interest for non-electric applications of SMRs, the attention is here focused to **nuclear SMR systems hybridized “with other energy sources, storage systems and energy conversion applications to provide electricity, heat and hydrogen.”**
- The purpose of this hybridization is suggested in the fact that **SMR technology thus has the potential to strongly contribute to the energy decarbonisation in order to achieve climate-neutrality in Europe by 2050.**
- In this aim, **the safety issues of SMRs related to their integration into hybrid energy systems were specifically addressed** , involving specific interactions between SMRs and the rest of the hybrid systems; new initiating events will have to be considered in the safety approach.

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Introduction (cont'd)

- The purpose to analyse the safety aspects of SMRs when included into cogeneration networks has been a specific subject in our analyses

- The issues addressed concern the **potential safety impacts of intensive and flexible SMR operation in a power system with significant intermittent renewable energy sources (RES) penetration** and the analysis of the **safety aspects of SMRs when included into cogeneration networks**

- In this frame, **the specific constraints and risks induced by the combination of a nuclear system with a cogenerating network need to be discussed and evaluated**, considering the specific features of **light water SMRs** under development in Europe

Introduction (cont'd)

- This presentation focuses on **two specific aspects of the work** performed on this subject:

    - **a summary of precious background information collected in the initial phase**, related to previous studies about the safety aspects of nuclear reactors when included in cogeneration networks
    - **the description of some safety-relevant transients** addressed within TANDEM and of the results obtained in their analyses

- **General conclusions** are then drawn from the work performed on this aspect

Background from previous work
General Aspects

- A first phase of the study was devoted to the collection **of existing information about the safety aspects emerging in case of coupling of nuclear reactors with a hybrid network**

- Though the available studies were not particularly abundant, **reports by IAEA** provided summary information mainly on large reactors in cogeneration applications, also considering existing applications of nuclear reactors in support to non-electric applications, highlighting interesting safety concerns

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Background from previous work
General aspects (cont'd)

- A great help was also found in **the work done in past decades in the European Nuclear Cogeneration Industrial Initiative (NC2I)**, as a pillar of the Sustainable Nuclear Energy Technology Platform (SNETP)
- In this frame, **projects specifically concerning High Temperature Reactors** or **Very High Temperature Reactors** dealt with safety issues related to the combination of those nuclear reactors with various cogeneration scenarios, providing also suggestions useful for our case (LW-SMRs)
- **General publications by various international organisations** were also considered, sometimes finding useful suggestions
- Summary information on the status of the **work performed in past years on subjects related to the purpose of this report in this specific field by the Technical Supporting Organisations (**TSOs as IRSN, GRS and ENERGORISK) was also discussed

Background from previous work
General aspects (cont'd)

- **An attentive collection** of the addressed documents highlighted the **main messages** that could be useful for the next steps

- **Two relevant phases of the work** were:
  - **the Summary of relevant issues emerging from the survey**
  - **the considerations by TSOs on flexibility and cogeneration**

- **These parts are discussed hereafter**

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Background from previous work
Summary of relevant issues emerging from the survey

Definition of the cogeneration application and of the energy mix scenario

If **load-following or flexibility** to cope with a cogenerating process are asked to an SMR, its safety analysis will change substantially at the level of assumed initial conditions for the deterministic evaluation of accidents

In fact, it will be necessary to include **a full range of starting conditions with partial load operation**, thus making more varied and complex the analysis

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Background from previous work

Summary of relevant issues emerging from the survey (cont'd)

Degree of decoupling of the NPP from the grid and the cogeneration process

Cogeneration will necessarily imply coupling with the industrial process. The following aspects need to be considered:

- **differences in regulations:** applicable to the industrial process and to the nuclear plant: not to be mixed from a regulatory point of view (?!)
- **differences in standards**: e.g., this applies to cybersecurity issues, but also to hardware requirements (e.g., codes of regulations applied to component design)
- **physical separation:** a sufficient distance of the NPP from the production process seems to be necessary though this distance could be reduced with respect to the case of large reactors → need of a proper discussion of separation for SMRs

Background from previous work
Summary of relevant issues emerging from the survey (cont'd)

Degree of decoupling of the NPP from the grid and the cogeneration process (cont'd)

- **ownership separation:** it can be assumed that the ownership of the NPP and the one of a district heating grid or a hydrogen production plant may be different
- **human resource separation:** it seems necessary to evaluate if the workers of the NPP and the ones of the industrial application have to be subjected to the same regimes in terms of radiation protection and protection from other hazards
- **bidirectional barriers:** it seems necessary to avoid mutual negative influence on the safety of either installation
- **level of nuclear safety and of the interfaced industrial application**

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Background from previous work

Summary of relevant issues emerging from the survey (cont'd)

Degree of decoupling of the NPP from the grid and the cogeneration process (cont'd)

- A principle repeated several times is that **the level of safety of the nuclear power plant should not be adversely affected by the presence of the interfaced industrial application**
- This issue is definitely linked to that of the **separation** and of the **interposed barriers**
- Indeed, the safety assessment methodology seems to have necessarily **to consider the combination of the two systems and to assess the safety of each one of them and of their combination in a cogenerating environment**
- Important aspects, e.g., as the definition of **the extent at which maintenance of the nuclear power plant can be conditioned to the needs of the cogenerating application**, must be considered

Background from previous work
Summary of relevant issues emerging from the survey (cont'd)

Methodology of safety analysis

- It must be clarified **at what extent the usual methodologies of probabilistic and deterministic safety analysis can be considered sufficient for the cogenerating system**, once integrated with an appropriate evaluation of the "external" risks induced by the interfaced industrial application
- It must be considered if the usual concepts of **Defence in Depth (DiD), Multiple Barriers** and other similar ones can be safely applied to the present case, once the appropriate ingredients in terms of external risks have been included
- Questions as the one of the applicability of the principle of designing against the **single-failure** to the combined nuclear and cogenerating plants need to be assessed

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Background from previous work

Summary of relevant issues emerging from the survey (cont'd)

Flexibility in NPP operation

- Issues as the **degree of load-following** and the flexibility of the NPP in view of the needs of the cogenerating application must be considered
- At a higher level, it must be decided **if the nuclear plant should be operated in load-following to accomplish with the needs** of the industrial application and of the electrical grid **or if an attempt should be made to keep the NPP operating at a constant regime**, with a dynamic partitioning of the power between electricity production and district heating or hydrogen production or heat storage
- Indeed, **this choice will condition the type and the frequency of anticipated operational occurrences** to be considered in the safety analysis of the plant.
- **Economics and safety are strongly affected by this choice**: given the need to show competitiveness of SMRs would suggest opting mostly for a full power operation

Background from previous work
Summary of relevant issues emerging from the survey (cont'd)

Safety of the electrical energy supply to the NPP

- The introduction of a nuclear power plant in **an electrical grid dominated by Renewable Energy Sources will pose the problem of the availability of a sufficient quality of the off-site electrical power** to be provided to the plant in case of need
- This has again to do with **the frequency of the AOOs to be assumed in the safety analysis** of the nuclear power plant
- In this regard, **energy storage and an architecture that can make the nuclear reactor sufficiently autonomous from the electrical grid may strongly improve the safety level** achieved in the cogenerating hybrid system

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Background from previous work
Summary of relevant issues emerging from the survey (cont'd)

Impact of the NPP on the industrial process

- It is necessary to single out the importance that aspects of the **possible radioactive contamination of the heat carrier** may have of the linked industrial process
- Likewise, the **requirements of stability of the production of the exchanged heat** must be assessed

General safety issues of SMRs in view of licensing

- Safety concerns are related to the **modularity and multi-unit characteristics** (e.g., due to the interaction between modules in terms of common mode failures, characterisation of the source term from multiple units on a site, etc.).
- An issue to be clarified is the one of the **"graded" approach**, in relation of the claims of **higher safety of SMRs** with respect to large nuclear reactors and to the **nature of "advanced"** (i.e., not yet "proven" or even FOAK) of their concepts.

Background from previous work
Considerations by TSOs on flexibility and cogeneration

In this part of the study, **both GRS and IRSN proposed considerations based on their experience in the field**

In particular, GRS proposed detailed discussions of the following issues

- **The effects of load following on structures, systems and components (SSCs)** in terms of additional loads that must be attentively considered
- **Safety aspects for the coupling of SMRs with chemical processes** (for GCR and MSR)
- **Interface of safety, security and safeguards** of the presence of cogenerating facilities

Background from previous work

Considerations by TSOs on flexibility and cogeneration (cont'd)

Likewise, IRSN expanded on flexibility and load following

- **Quick variations**, **daily variations** and **weekly/monthly variations** are considered for their specific impacts
- The **impact of frequent load variations** on the plant has been then discussed addressing issues related to the **core, Pellet Cladding Interaction (PCI), thermal load and fatigue, wear and tear and waste management** (due to boron concentration variation)
- **Impact of the power changes on safety assessment**

It is clear that **all these aspects highlighted by GRS and IRSN on the basis of the experience in assuring "flexibility" of large NNPs have an impact on the expected behaviour of SMRs in a cogeneration and RES dominated energy environment**

Background from previous work
Moving forward…

Definition of meaningful study cases

Considering the applications to be analysed, suitable case studies had to be identified, in order to exercise the safety assessment methodology on the basis of meaningful conditions.

INDEED, THIS BRINGS US TO THE SECOND PART OF THIS PRESENTATION

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Further developments and safety cases considered in TANDEM
Identification of the safety cases

The IAEA proposes grouping possible power plant states into four categories:

1. Normal operation
2. Anticipated Operational Occurrences (AOOs)
3. Design Basis Accidents (DBAs)
4. Design Extended Condition (DECs)

Categories 1 and 2 will be impacted by the cogenerating setup of the power plant and/or by the interaction between the plant and the hybrid energy system.

Category 3 (DBAs) could also be impacted.

Category 4 (DECs) are not expected to be impacted. This category is out of the scope of the TANDEM project.

Further developments and safety cases considered in TANDEM
Identification of the safety cases (cont'd)

Among the AOOs and DBAs categories, one has been investigated the most since it includes safety scenarios that are possibly impacted by the cogeneration setup:

- Increase or decrease in heat transfer from primary to secondary circuit
- Partial loss of core coolant flow
- Inadvertent control rod insertion / withdrawal
- Increase or decrease of reactor coolant inventory
- Radioactive release from a subsystem or component

AOO scenarios included in this category:

- Feed water flow increase due to feed water system malfunction
- Turbine trip
- Short term loss of offsite power (<2hrs)
- …

DBAs scenarios included in this category:

- Main steam line break
- Small steam piping failure
- Long term loss of offsite power (>2hrs)
- …

Affected by cogeneration

Further developments and safety cases considered in TANDEM

Identification of the safety cases (cont'd)

Among the AOOs and DBAs categories, one has been investigated the most since it includes safety scenarios that are possibly impacted by the cogeneration setup:

- Increase or decrease in heat transfer from primary to secondary circuit

Event	Possible impact of cogeneration	
	On prevention	On severity
Loss of the external electrical load leading to a short term (<2 hrs) loss of offsite power (DBC-2)	**Favorable**	None
Loss of the external electrical load leading to a long term (>2 hrs) loss of offsite power (DBC-3)	**Favorable**	None
Small steam piping failure (including break of connecting lines) (DBC-3)	**Unfavorable**	None
All the other DBC-2, 3 and 4	None	None

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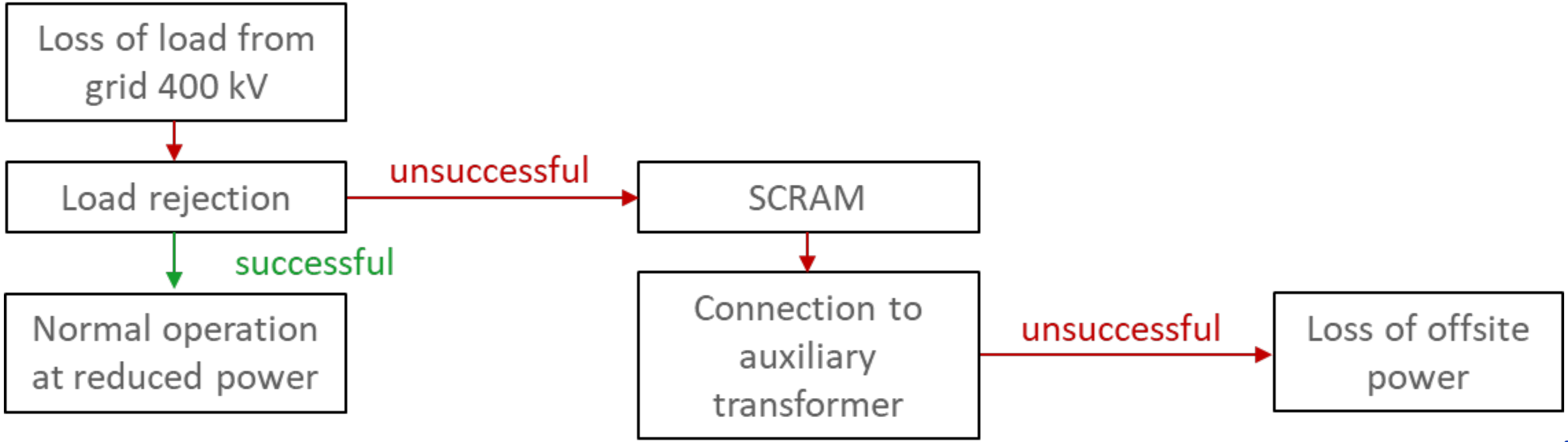
Further developments and safety cases considered in TANDEM
Identification of the safety cases (cont'd)

A long-term Loss of Offsite Power (LOOP) typically results from a malfunctioning of the power grid. It is considered one of the most likely transients to occur in a hybrid energy system.



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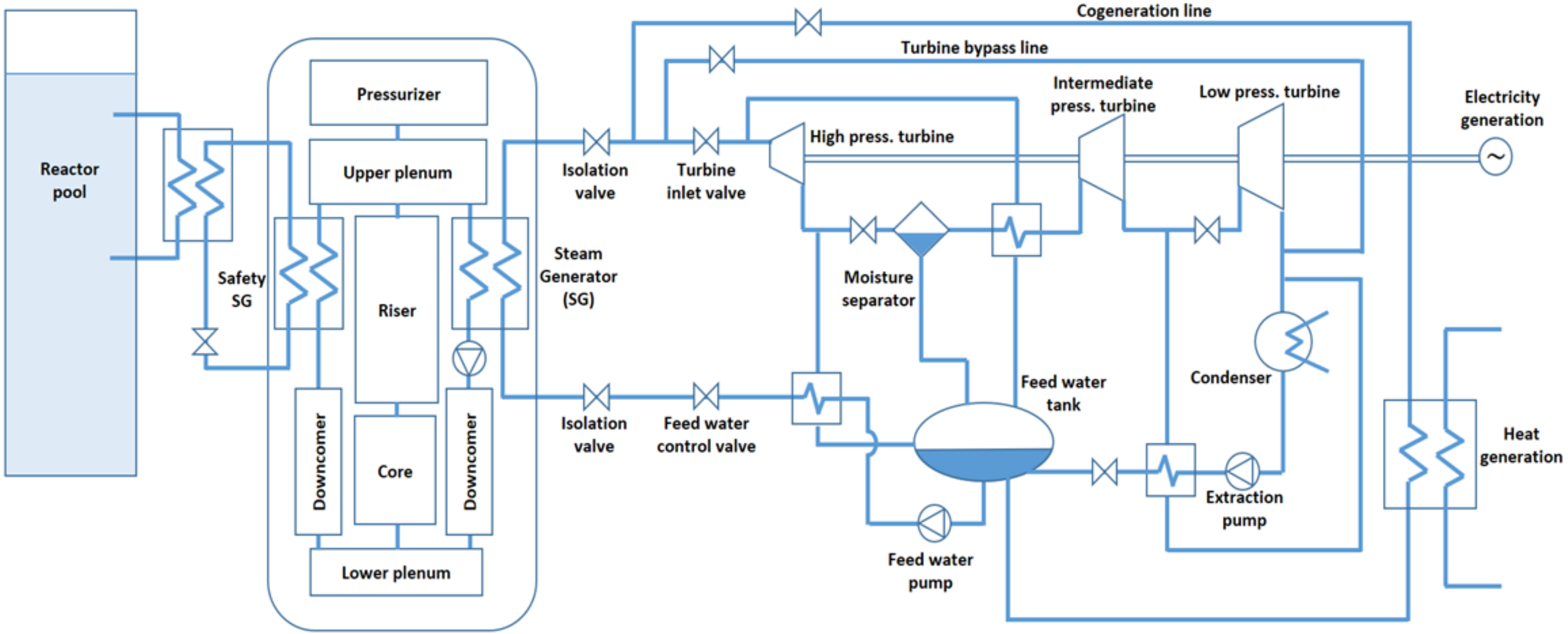
Further developments and safety cases considered in TANDEM

E-SMR model layout

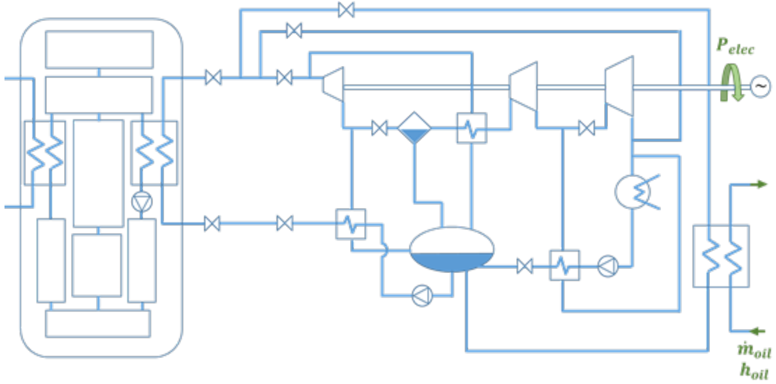


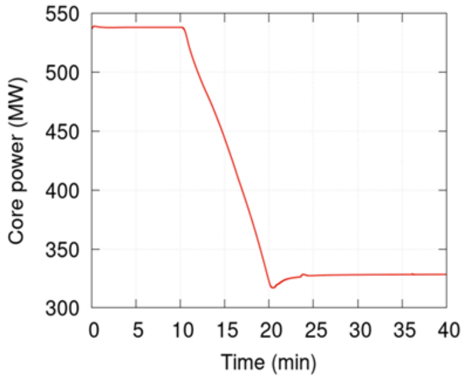
Nuclear Steam Supply System (NSSS)

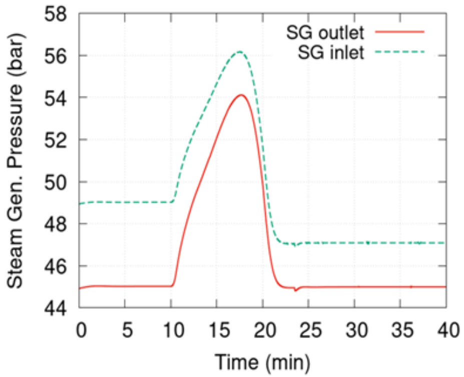
Balance of Plant (BoP)

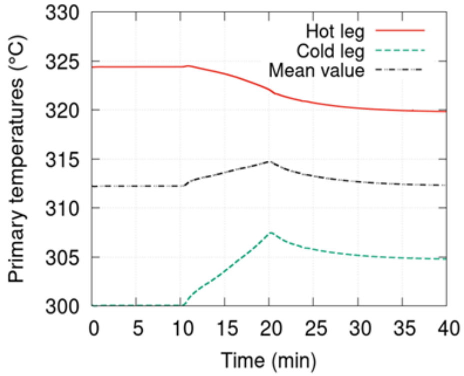
Further developments and safety cases considered in TANDEM
Preliminary tests of the E-SMR model

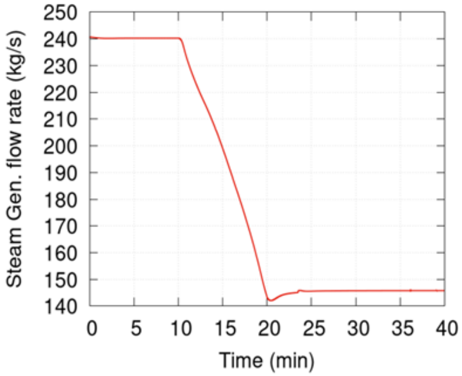
Power ramp from 100% to 50% of nominal electrical power



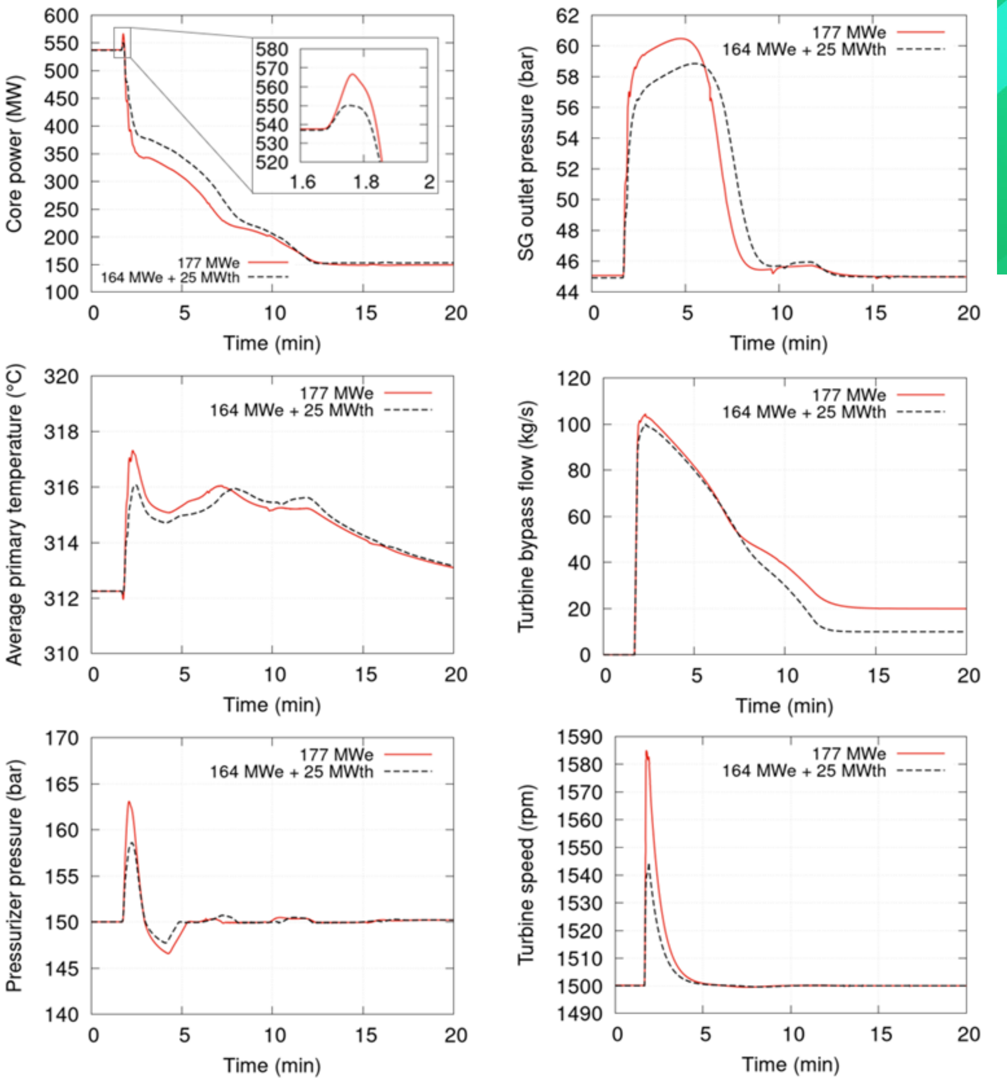








Safety cases considered: Successful load rejection.

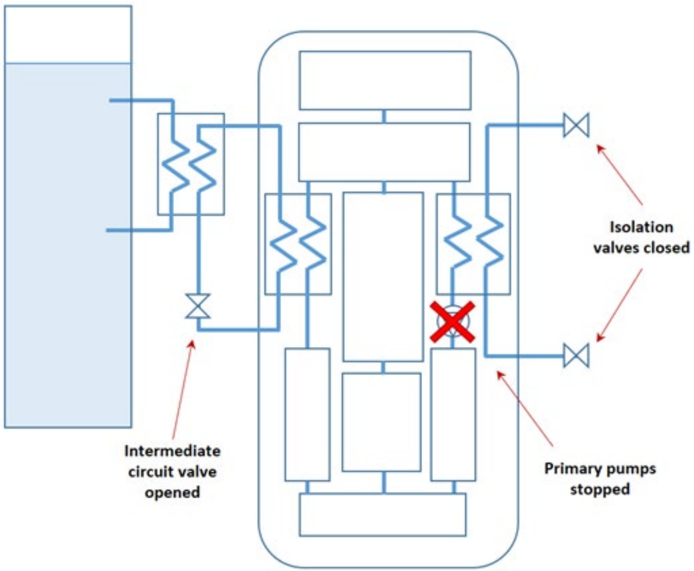


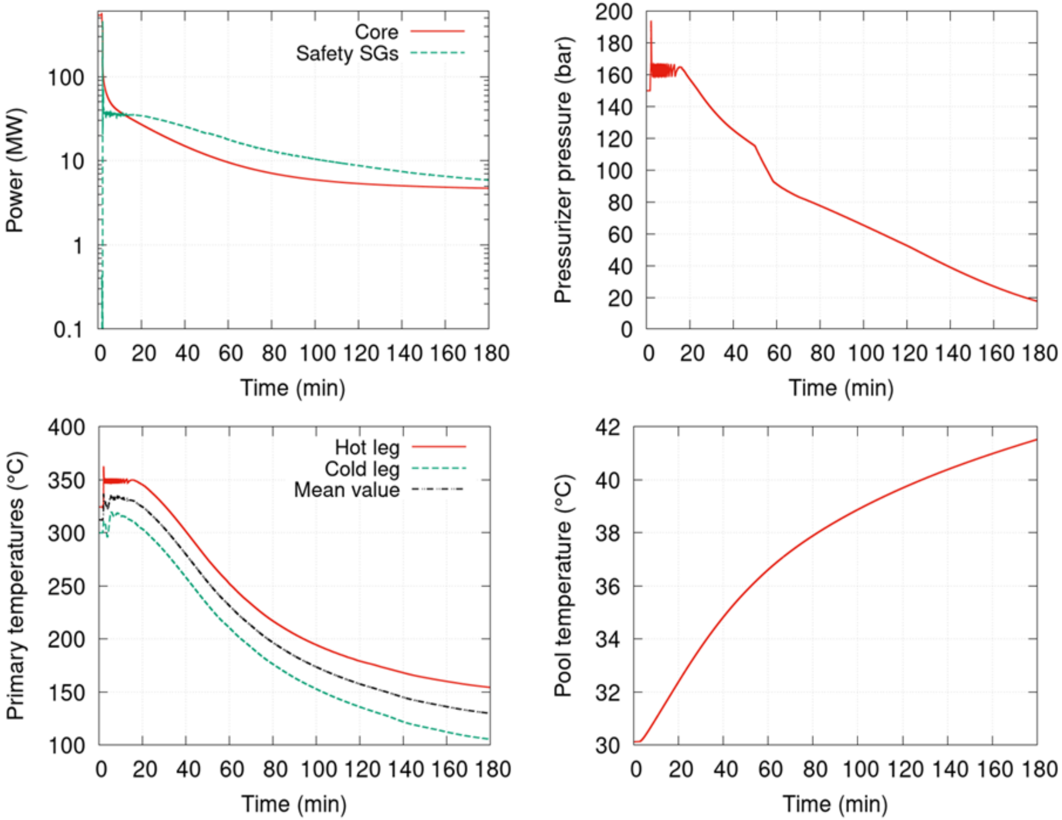
Fully electric case	vs	Hybrid case
177 MWe		164 MWe
0 MWth		25 MWth

Load rejection might fail due to too high core power variation, primary or secondary overpressure, etc.

Load rejection transient is smoother in the hybrid case → less likely to fail, better for safety

Safety cases considered: Loss of offsite power





Same results between fully electric and hybrid case
→ no impact of cogeneration on the accident

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Conclusions

From the cases considered in this work, it appears that **cogeneration is not expected to adversely affect the severity of any DBA**; however, **it may play a role in their prevention**. In particular:

- **Cogeneration can reduce the risk of failing a load rejection** procedure and incurring in a loss of offsite power scenario (a design basis transient that can also evolve into a DBA if it lasts for several hours)
- **Cogeneration is expected to (slightly) increase the risk of a small steam piping failure**, which is a DBA.

Load rejection and loss of offsite power have been here simulated with a coupling between:

- **a Nuclear Steam Supply System (NSSS) model,** developed with the safety code CATHARE3
- **a Balance of Plant (BoP) model,** developed using the ThermoPower library in the Modelica language.

The results of the load rejection simulations confirm that **the transient is less severe when the plant is cogenerating compared to when it is generating only electricity**.

The results of the loss of offsite power simulations are practically identical between the cogeneration and electricity only cases, confirming that **cogeneration is not expected to have any significant impact on the accident severity**

Conclusions (cont'd)

While **assessing the safety of SMRs when included in cogenerating systems will require a detailed Probabilistic Safety Assessment (PSA),** to be performed when the characteristics of the reference SMR plant will be available, **the TANDEM project identified issues and methodologies of assessment providing answers to previously posed questions**

The different energy hub scenarios elaborated in the project clarify the boundary conditions in which the SMR will possibly work in a decarbonized energy system dominated by RES, storage systems and industrial heat users

The **coupling between thermal-hydraulic system codes (CATHARE and ATHLET) with a variety of BOP systems** conceived to represent the needs for cogeneration has provided **tools for the systematic assessment of the safety characteristics of the SMR plant** in such a context

The addressed calculation cases provided useful indications about the behaviour of the SMR in such conditions

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Get in touch for more information:

Thanks for your attention !

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