Monte Carlo Simulation-based efficient exploration of the model of a Molten Salt Fast Reactor for the identification of abnormal operating conditions

YMSR Conference

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Introduction

Framework of the work

- The demonstration of the Gen-IV MSFR enhanced safety features with respect to other reactor concepts

Aim of the work

- Propose a Monte Carlo simulation-based method to map the system behaviour with respect to uncertainties and variations in physical and operational parameters and in components' states, by means of an efficient exploration of the MSFR state space;
- Exploit such maps to develop (prompt, on-line) incident detection methods for safer MSFR plant operation.

Characteristics of the Power Plant Simulator

- Developed using the object-oriented Modelica language, in Politecnico di Milano;
- 1D thermal hydraulics and heat transfer model;
- Ad-hoc neutronics for the MSFR.
- Suitable for the simulation of the plant response to control transients;

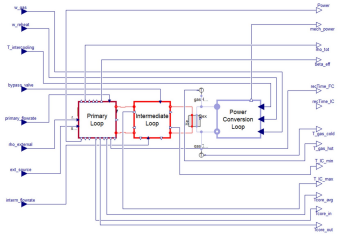

Figure: Power Plant Simulator

Choice of the input parameters I

Input		
Flow rate	Type	Variation
Fuel circuit	Linear	[-20;20]%
Intermediate circuit	Linear	0
Gas circuit	Linear	0

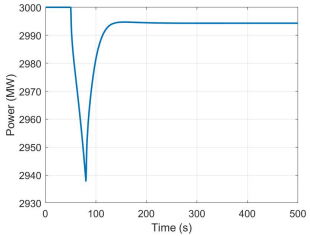

Figure: Power evolution $\Delta w_f = -20\%$

Similar inputs were provided for the simulations concerning the variations of the intermediate circuit and gas circuit flow rates.

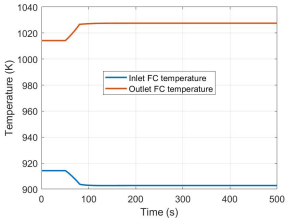

Figure: Temperature FC evolution $\Delta w_f = -20\%$

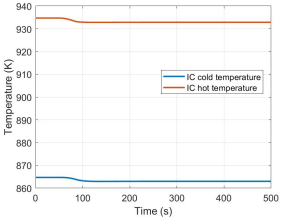

Figure: Temperature IC evolution $\Delta w_f = -20\%$

Choice of the input parameters II

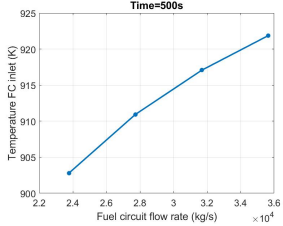

Figure: Inlet T_{FC} - sensitivity

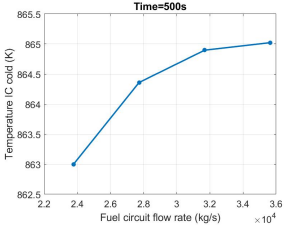

Figure: Cold T_{IC} - sensitivity

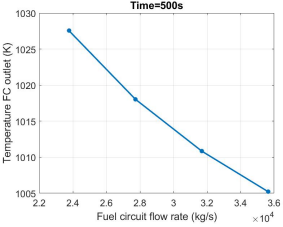

Figure: Outlet T_{FC} - sensitivity

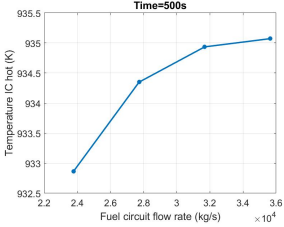

Figure: Hot T_{IC} - sensitivity

Example of an exponential variation I

Input		
Flow rate	Type	Variation
Fuel circuit	Exponential	0
Intermediate circuit	Exponential	0
Gas circuit	Exponential	-[90,80,70]%

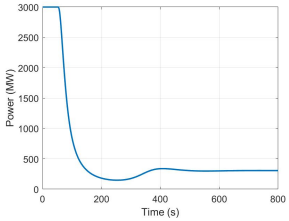

Figure: Power evolution $\Delta w_g = -90\%$

Similar inputs were provided for the simulations concerning the variations of the fuel circuit and intermediate circuit flow rates.

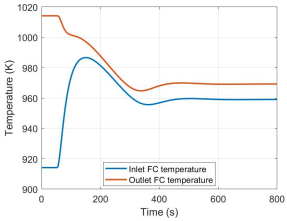

Figure: Temperature FC evolution $\Delta w_g = -90\%$

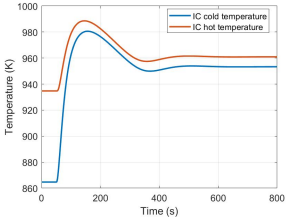

Figure: Temperature IC evolution $\Delta w_g = -90\%$

Example of an exponential variation II

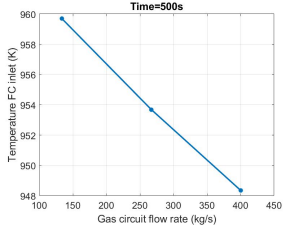

Figure: Inlet T_{FC} - sensitivity

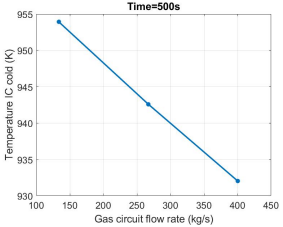

Figure: Cold T_{IC} - sensitivity

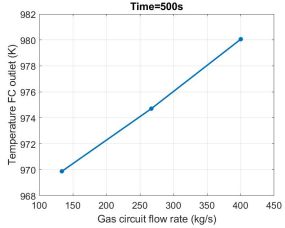

Figure: Outlet T_{FC} - sensitivity

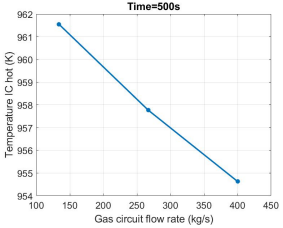

Figure: Hot T_{IC} - sensitivity

The need for an efficient adapting Monte Carlo sampling

Input			
Flow rate	Type	Variation	Start time
Fuel circuit	Exponential	-60%	50s
Intermediate circuit	Exponential	-60%	100s
Gas circuit	Exponential	-60%	150s

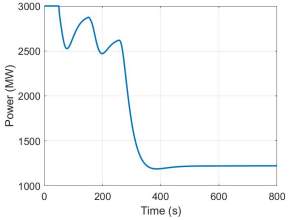

Figure: Power evolution

Curse of dimensionality! The number of possible inputs goes exponentially with the dimensionality of the problem.

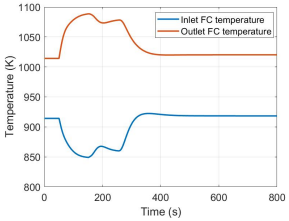

Figure: Temperature FC evolution

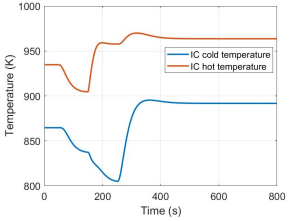

Figure: Temperature IC evolution

Definition of failure criteria

What kind of limits are present:

- Numerical limits: simulation failure;
- Physical limits: failure is defined by the analyst; ex: reaching $T_{max} = 1373K$ (structural damage) or $T_{min} = 858K$ (freezing) during a simulation.

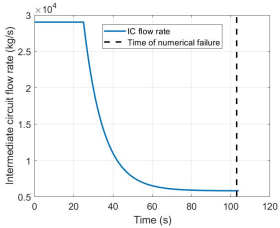

Figure: Numerical failure $\Delta w_i = -80\%$

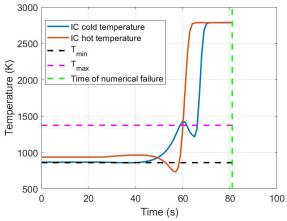

Figure: Various type of failure $\Delta w_i = -90\%$

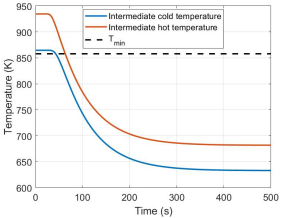

Figure: Physical failure $\Delta w_f = -90\%$

Boundary limits for the intensity of variation

Input		
Flow rate	Type	Variation
Fuel circuit	Exponential	[-90;0]%
Intermediate circuit	Exponential	0
Gas circuit	Exponential	0

Numerical failure occurs at: $\Delta w_f = -98\%$

Input		
Flow rate	Type	Variation
Fuel circuit	Exponential	0
Intermediate circuit	Exponential	[-90;0]%
Gas circuit	Exponential	0

Numerical failure occurs at: $\Delta w_i = -80\%$

Input		
Flow rate	Type	Variation
Fuel circuit	Exponential	0
Intermediate circuit	Exponential	0
Gas circuit	Exponential	[-90;0]%

Numerical failure occurs at: $\Delta w_g = -94\%$

Considerations:

- The most stringent limit is for the intermediate circuit flow rate: w_i;
- A reasonable interval for the exploration of the variations can be the range $[-90; 0]\%$

Physical and numerical limits I

Inputs (all the 1000 combinations)			
Flow rate	Type	Intensity	Start time
Fuel circuit	Exponential	[-90;0]%	25s
Intermediate circuit	Exponential	[-90;0]%	25s
Gas circuit	Exponential	[-90;0]%	25s

Inputs (all the 1000 combinations)			
Flow rate	Type	Intensity	Start time
Fuel circuit	Linear	[-90;0]%	25s
Intermediate circuit	Linear	[-90;0]%	25s
Gas circuit	Linear	[-90;0]%	25s

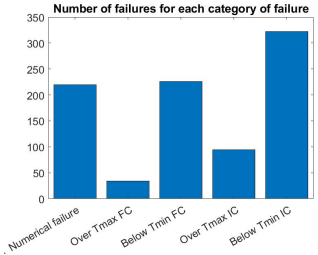

Figure: Number of failure per type - exp

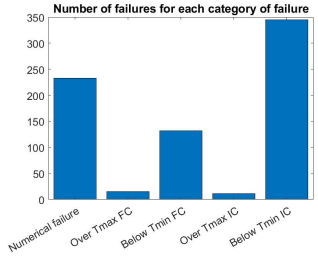

Figure: Number of failure per type - linear

Physical and numerical limits II

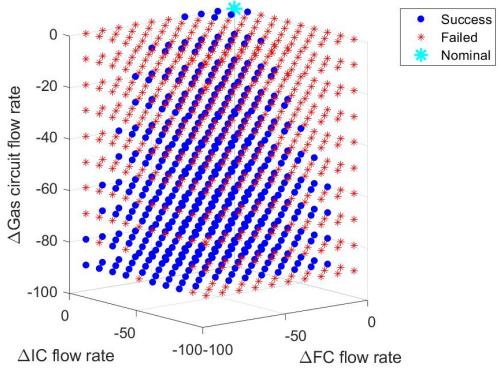

Figure: 3D map: Δw_f vs Δw_i vs Δw_g

Full 3D representation of the data.

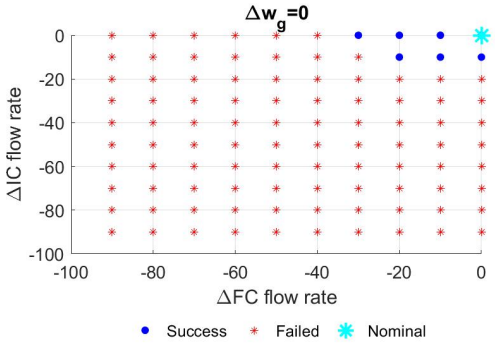

Figure: 2D map: Δw_f vs $\Delta w_i \mid \Delta w_g = 0$

If the gas circuit flow rate is at nominal level there is actually a small window for fail-free variations of fuel circuit and intermediate flow rates.

Physical and numerical limits III

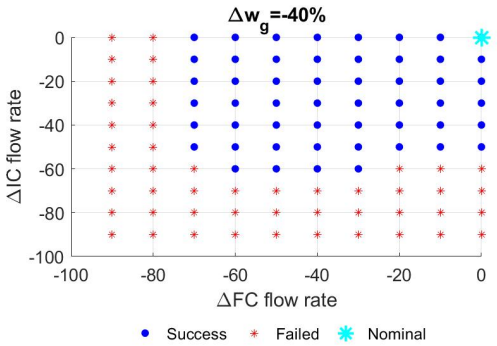

Figure: 2D map: Δw_f vs Δw_i | $\Delta w_g = -40\%$

Less failures appear to show when the gas circuit flow rate is reduced.

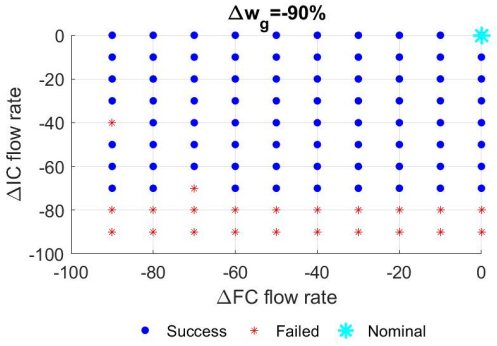

Figure: 2D map: Δw_f vs Δw_i | $\Delta w_g = -90\%$

The case with the largest gas circuit flow rate reduction is actually the one with less failures.

Conclusions and perspectives

Comments:

- The input parameters that affect the behaviour the MSFR power plant have been identified as: Fuel circuit, Intermediate circuit and Gas circuit flow rates;
- The most relevant input parameter for the reactor safety, at this stage of the work, appears to be the Intermediate circuit flow rate;
- Preliminary boundary limits of the state space exploration have been identified.

Further work:

- Application of an efficient exploration technique for the MSFR state space, based on the previous conclusions;
- The use of the mapped state space of the MSFR for the development of on-line incident detection method.

References I


https://samosafer.eu/project/


Claudio Tripodo, Andrea Di Ronco, Stefano Lorenzi, Antonio Cammi, Development of a control-oriented power plant simulator for the molten salt fast reactor, EPJ Nuclear Sci. Technol. 5, 13 (2019)


P. Turati, A. Cammi, S. Lorenzi, N. Pedroni, E. Zio, "Adaptive simulation for failure identification in the Advanced Lead Fast Reactor European Demonstrator", Progress in Nuclear Energy, vol. 103, 2018, pp. 176-190