
MSR Summer School - SAMOFAR Project

Lecco, 3rd July, 2017

# Control Strategies of MSR

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Nuclear Reactors Group

# Outline

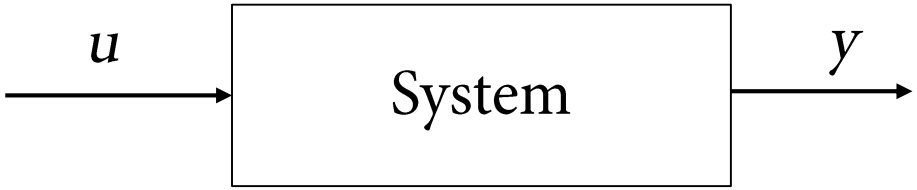
**Control**
General introduction on control problem
Feedback control
Some examples from the past
Stability and controller

**Control + Nuclear**
What controlling Nuclear Power Plants means?
Control loop
Operational modes: startup
Control design approach
Control-oriented modelling

**Control + Nuclear + Molten Salt Reactor**
MSR control issues
Control schemes

## What control means?

A control problem deals with all the action needed to obtain a **desired behavior** from a system.



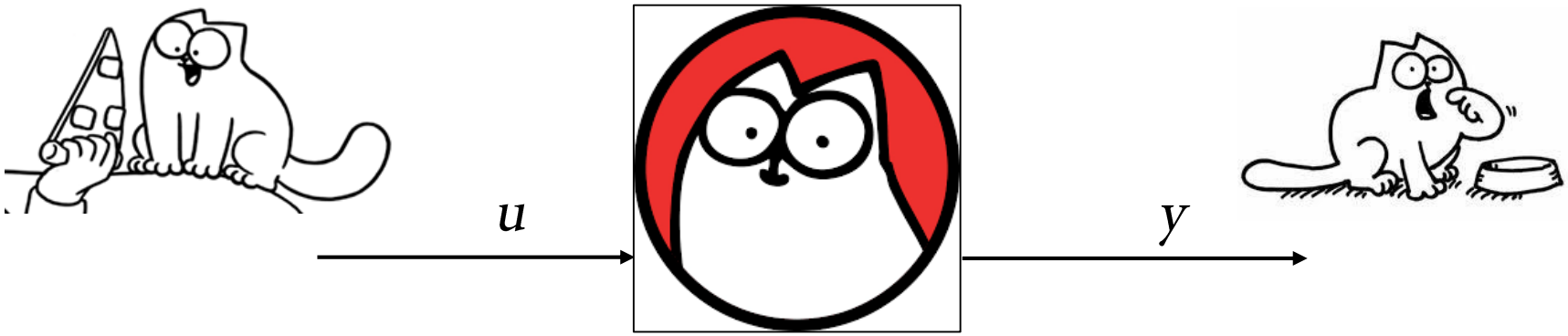

. System to be controlled. It is possible to act on some variables of input (u, *control variables*) in order to change the behavior of the system. We are interested in the evolution of some outputs (y, *controlled variables*)

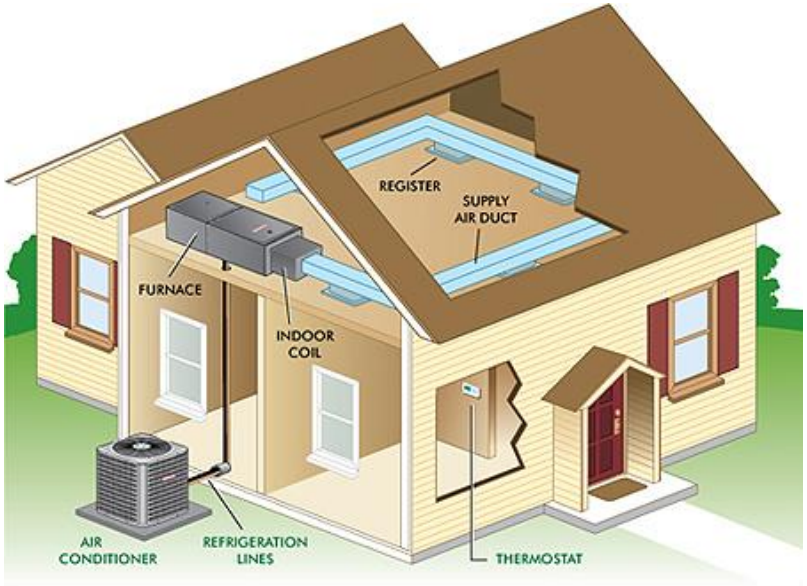
. Desired behavior. Which is the evolution or the value that we want for the controlled variables ($y_0$, setpoint)

**Aim:** determine the action to be performed on the input in order to limit the error ($e = y - y_0$) as small as possible – **controller** and **control law**

# Control

In every moment of the day, we have control problems!




**Control problem:** Control the temperature of the house

**Controlled variable y:** temperature in the house

**Setpoint $y_0$:** reference temperature

**Control variable u:** heat produced by the furnace/boiler

# Control

**Why control is important?**

. Make the system work in a safe way, meeting the performance specifications and the operational constraints

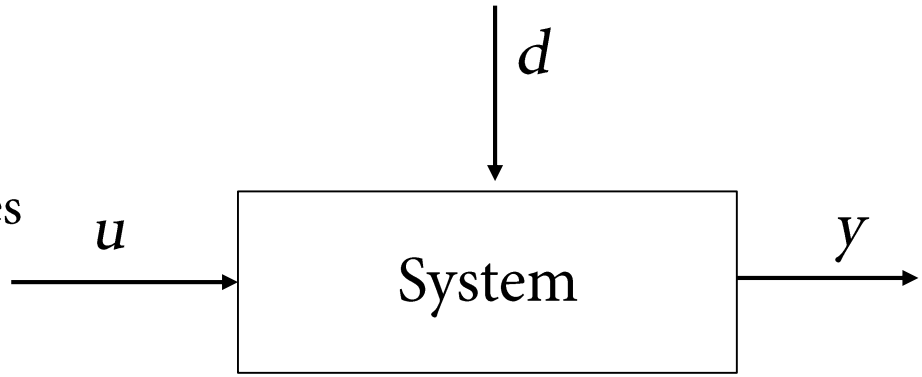
. Ensure the correct value for the controlled variables

**Additional purposes:**

. Limit the influence of external disturbances

. Ensure the stability of the system

. Optimize the performance of the system



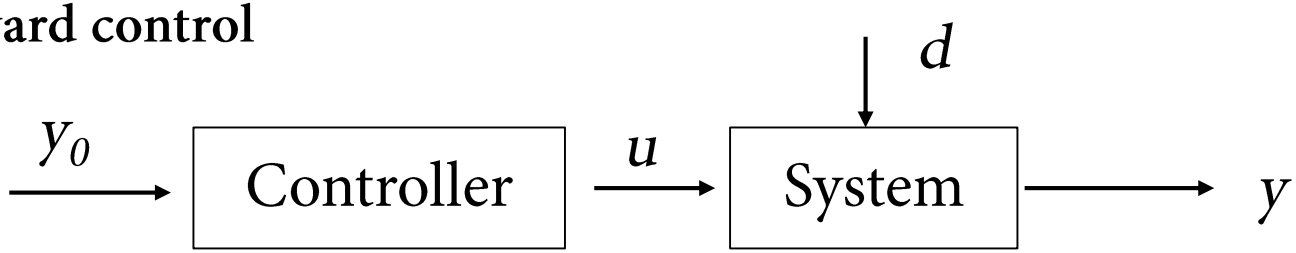

**Basic type of control:**

. Manual

. Automatic

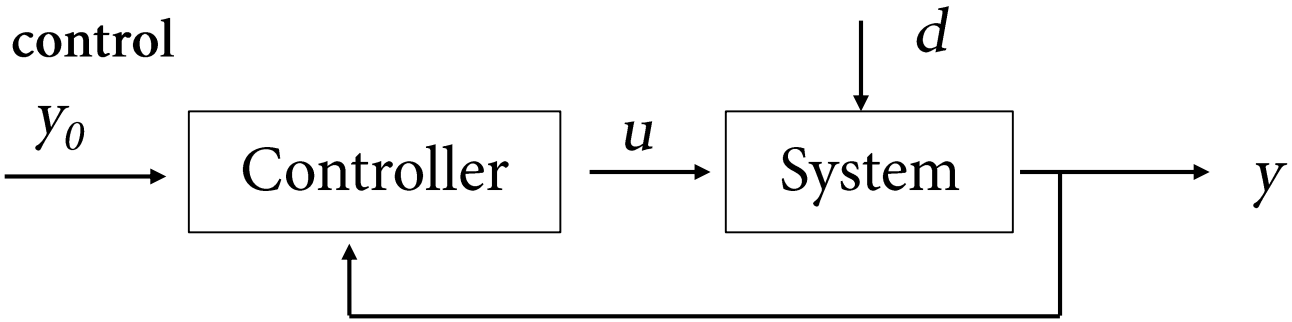
# Control

**Feedforward control**




. The control law based on a system model and does not depend on the output

**Feedback control**

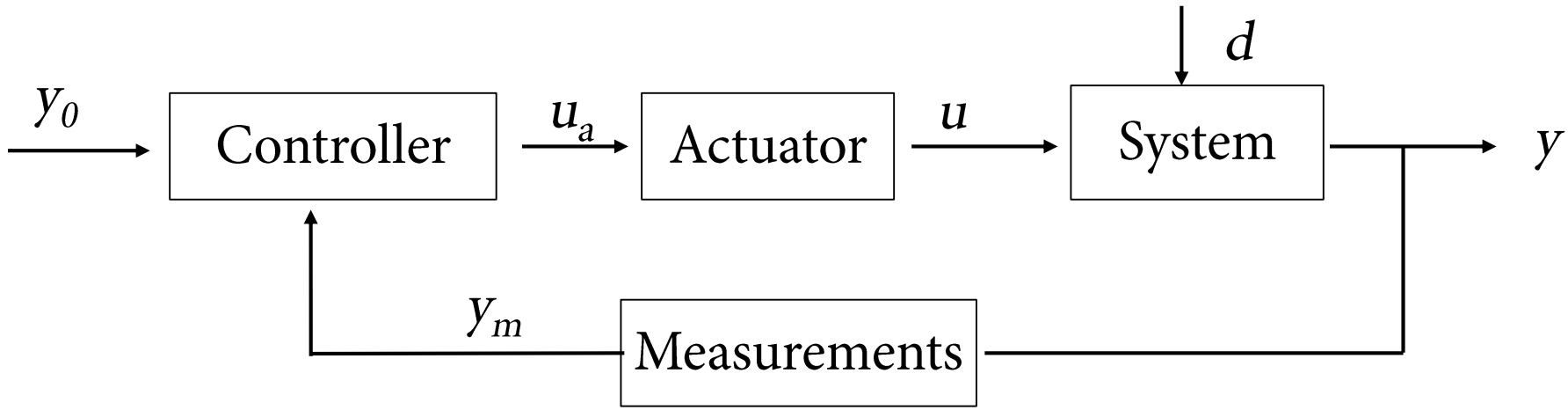



. The control law is based on the outputs (or better, on their measurements)

| | Feedforward | Feedback |
|---|---|---|
| Measurement of y | No | Yes |
| Accurate modelling | Yes | No |
| Impact of disturbances | High | Low |

# Control

How to communicate with the controller? **Measurements and actuators**




**Measurements**: provide the controller with the value of the output

**Actuator**: transform the control action into an effective action on the system

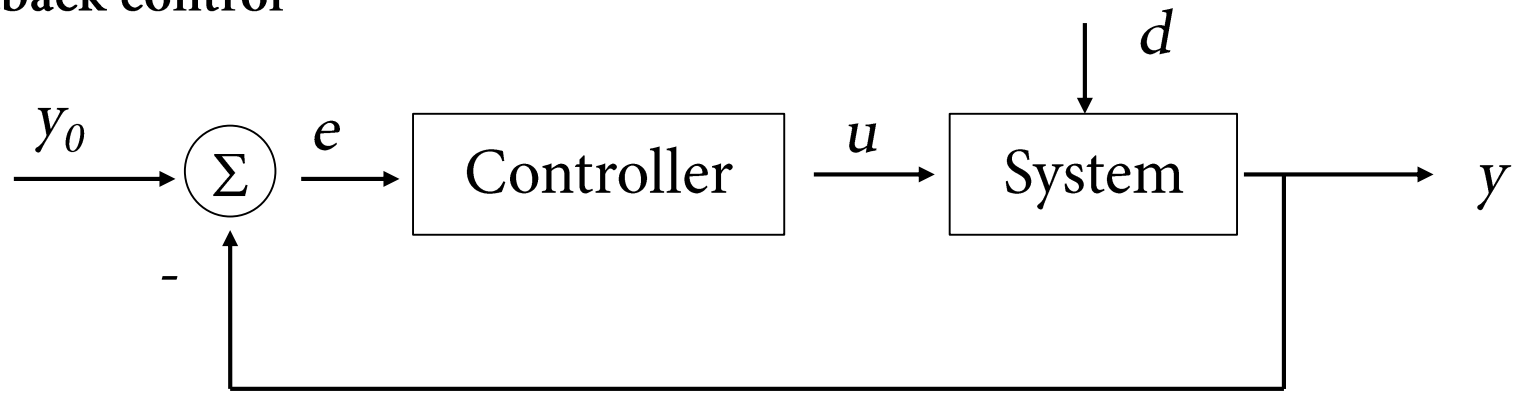
Measurements and control actions are affected by:

. Uncertainty (white noise)

. Malfunctions

# Control

**Feedback control**




. The controller receive the distance between the actual value and the desired value

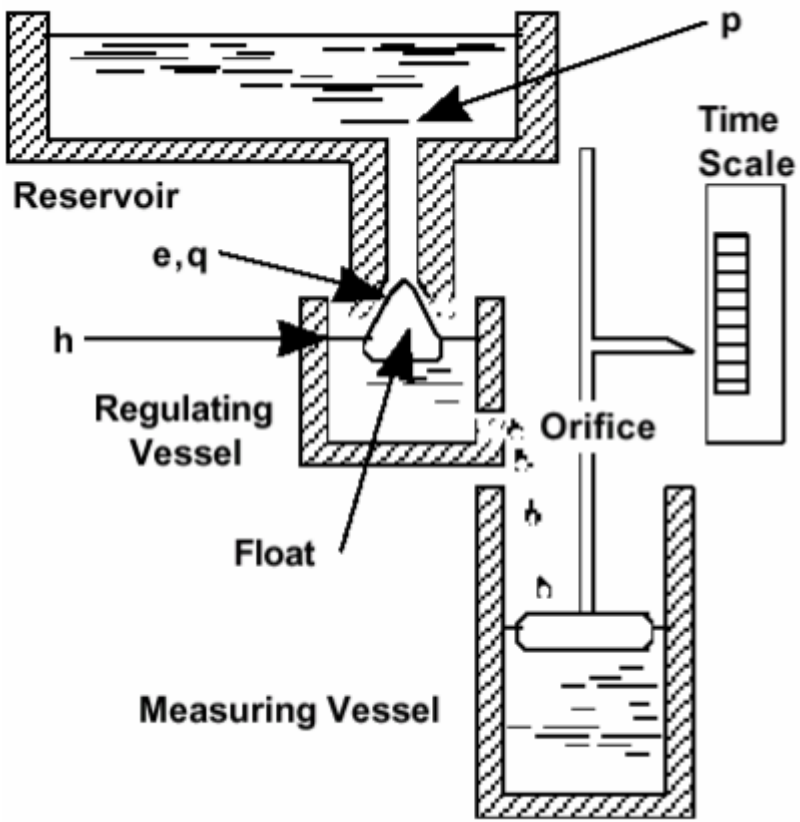
. The actuating error should be zero – at least we have to limit within acceptable limits

## Question time..

In what year was the first application of the feedback control?

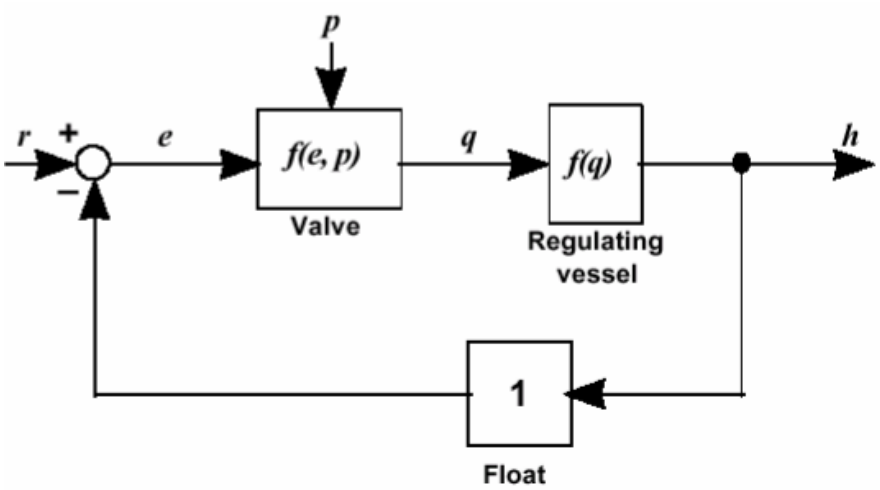
# Control

270 BC :the water clock of Ktesibios used a float regulator




**Control problem**: ensure a constant water level

**Controller**: float




Stefano Penzier (http://www.dia.uniroma3.it/autom/FdAcomm/Lucidi)

# Control

The first automatic feedback controller used in an industrial process:
the James Watt's flyball **governor** (1769) for steam engines

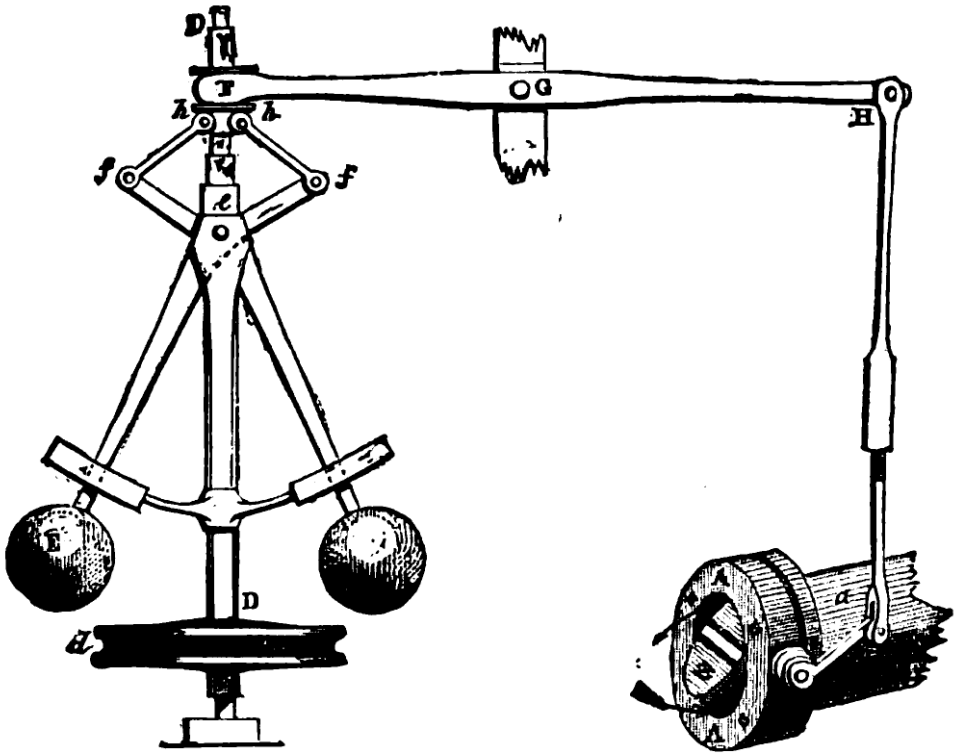


FIG. 4.—*Governor and Throttle-Valve.*

By R. Routledge - Image from "Discoveries & Inventions of the Nineteenth Century" by R. Routledge, 13th edition, published 1900., Public Domain, https://commons.wikimedia.org/w/index.php?curid=231047

. Used in textile mill, wheels and looms connected
. When a loom is added, the engine speed decreases

. Ball governor:

Engine speed increase
The balls swing out
Throttle valve reduced the steam flow
Engine speed decrease

# Control

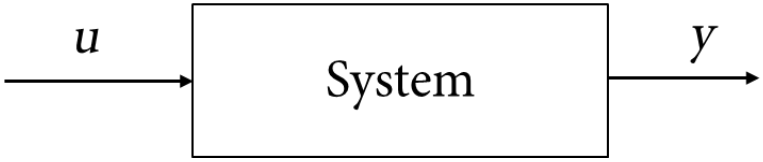
. The main drawback of the feedback control… it may create **instability**

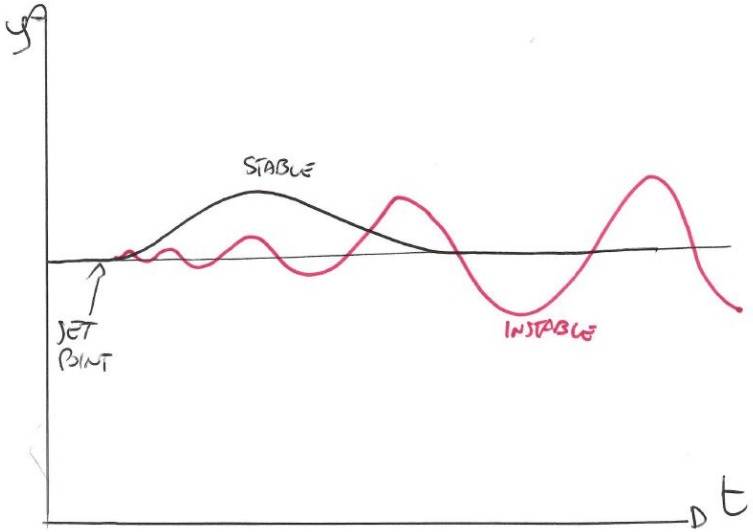
. Instability is a dynamic phenomenon - insight into dynamics when dealing with control

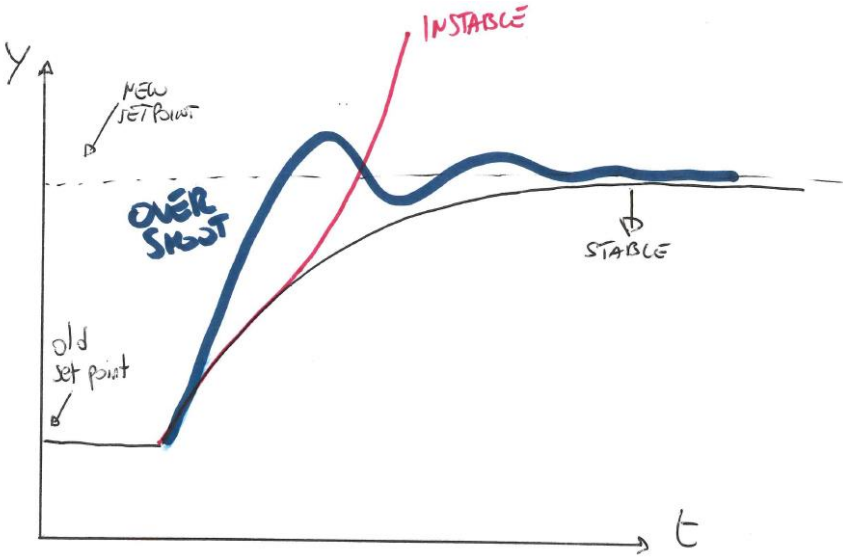
**Stability**

. of the equilibrium

. of the system

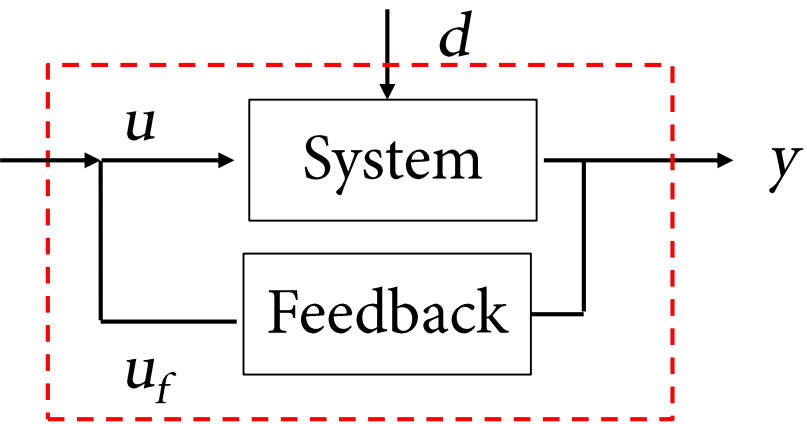



The stability can be studied if we model our system! **Dynamic system modelling**

Stability of a **feedback** system




. Negative feedback

y ↑ generates $u_f$ so as to y ↓ - stable

. Positive feedback

y ↑ generates $u_f$ so as to y ↑ - instable

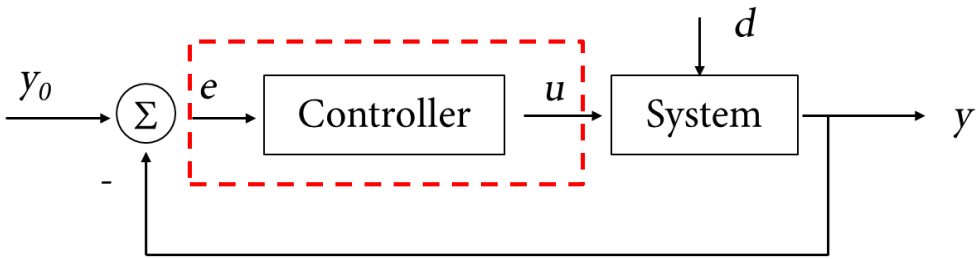
Stability of a **feedback controlled** system

The stability of the feedback system is not granted even if the system is stable!

Feedback control can add instability!

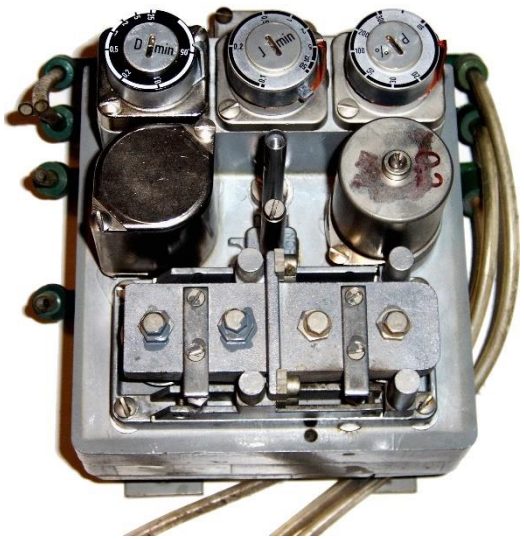
# Control

## Controller and control laws




$$u = f(e)$$

## PID controllers: Proportional – Integral – Derivative



Snip3r at Dutch Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1942158

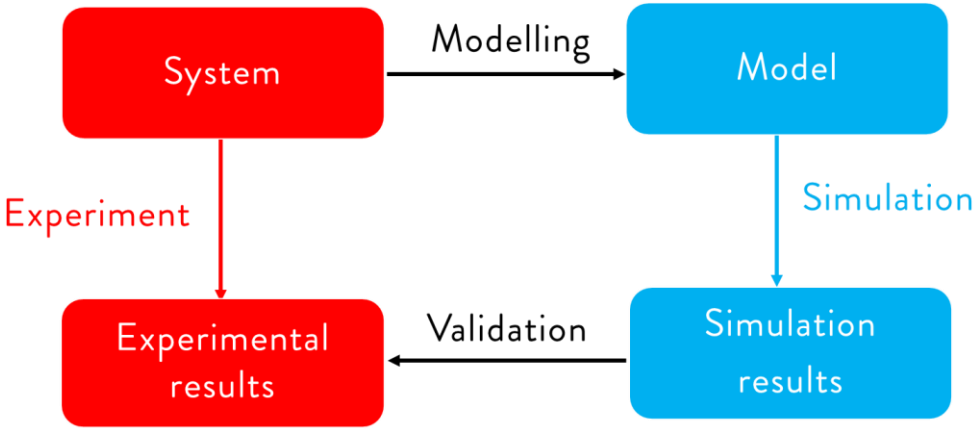
$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

# Control

## Control design

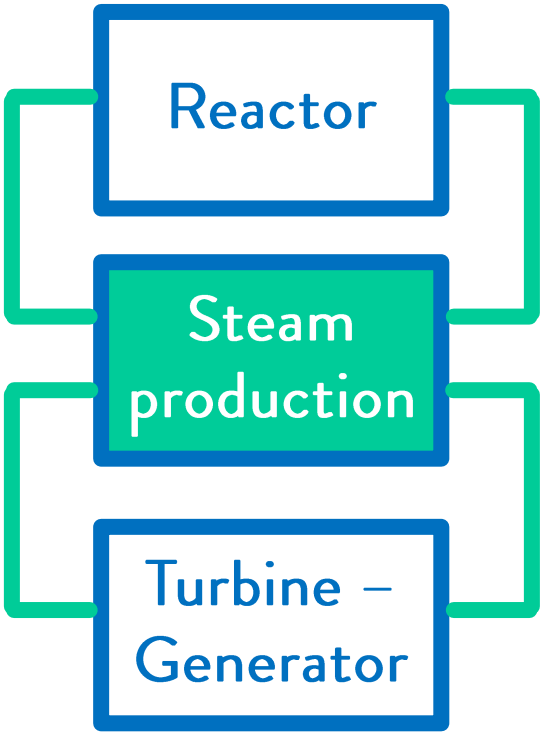
- Control goals
- Identification of the variables to control
- System configuration
- Modelling of system
- Modelling of controller
- Optimization

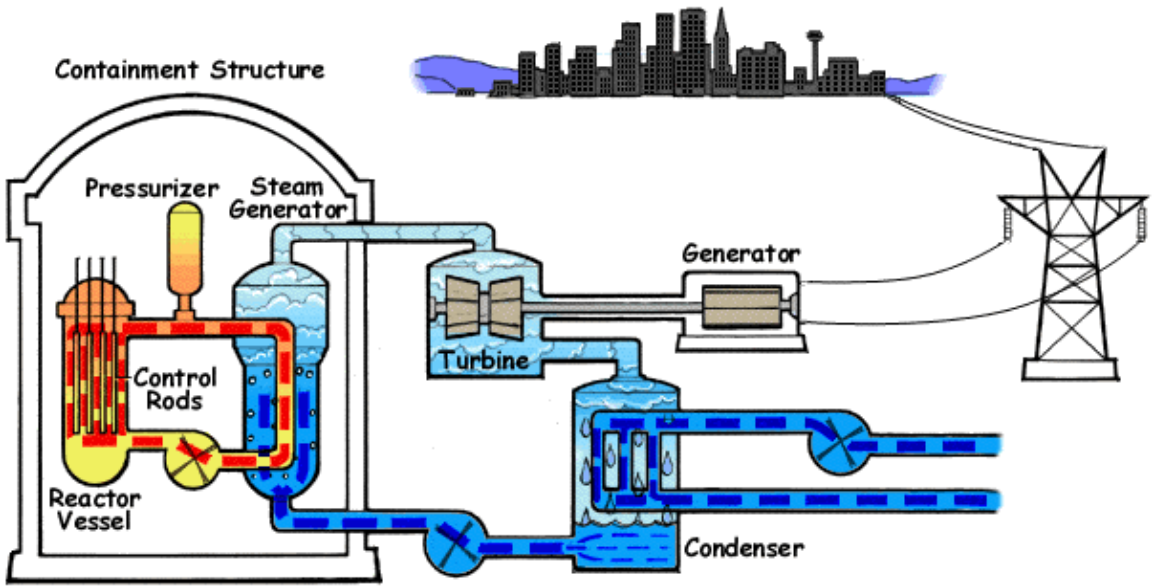
Even with feedback control, modelling of the system is relevant for design, evaluate and test the controller



## What controlling Nuclear Power Plants means?

Allowing to regulate the reactor power in accordance with the system demands in a *consistent and constrained* way – maintain the energy balance!



# Control & Nuclear

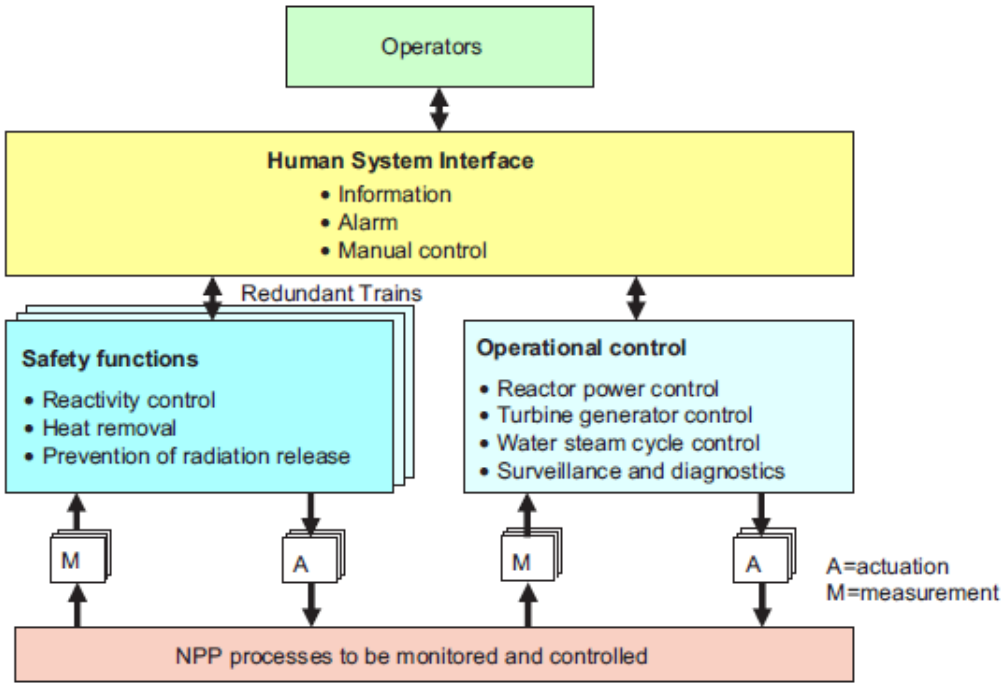
Control system ensure optimum working conditions for the controlled variables avoiding the need for the protection system to shut down the plant

**Controlled variables**

. Fission
. Heat transfer
. Flow
. Pressure
. Temperature

**"Control variables"**

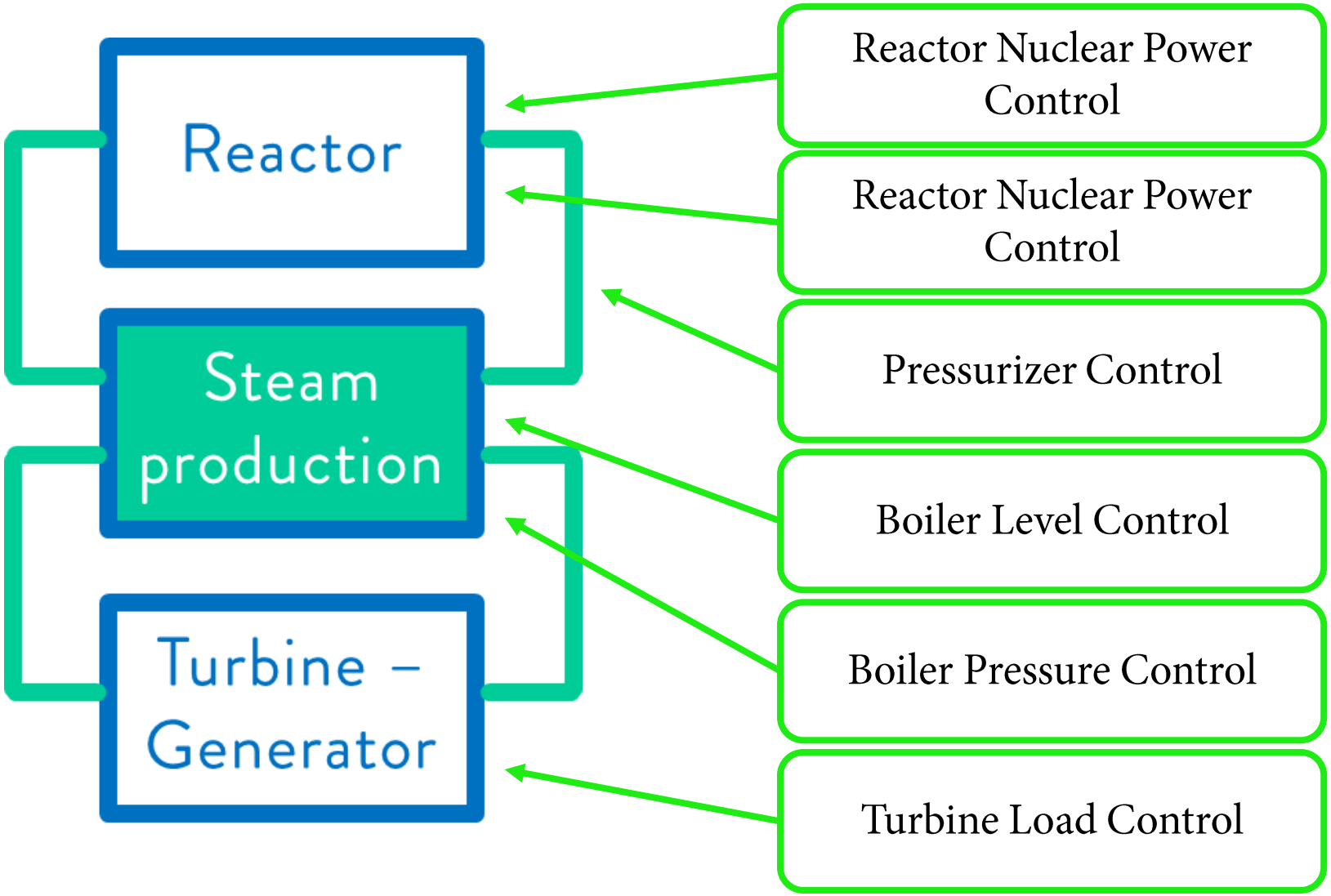
. Control rods
. Valve
. Pump




IAEA, Core Knowledge on Instrumentation and Control Systems in Nuclear Power Plants, IAEA Nuclear Energy Series, No. NP-T-3.12 Guides

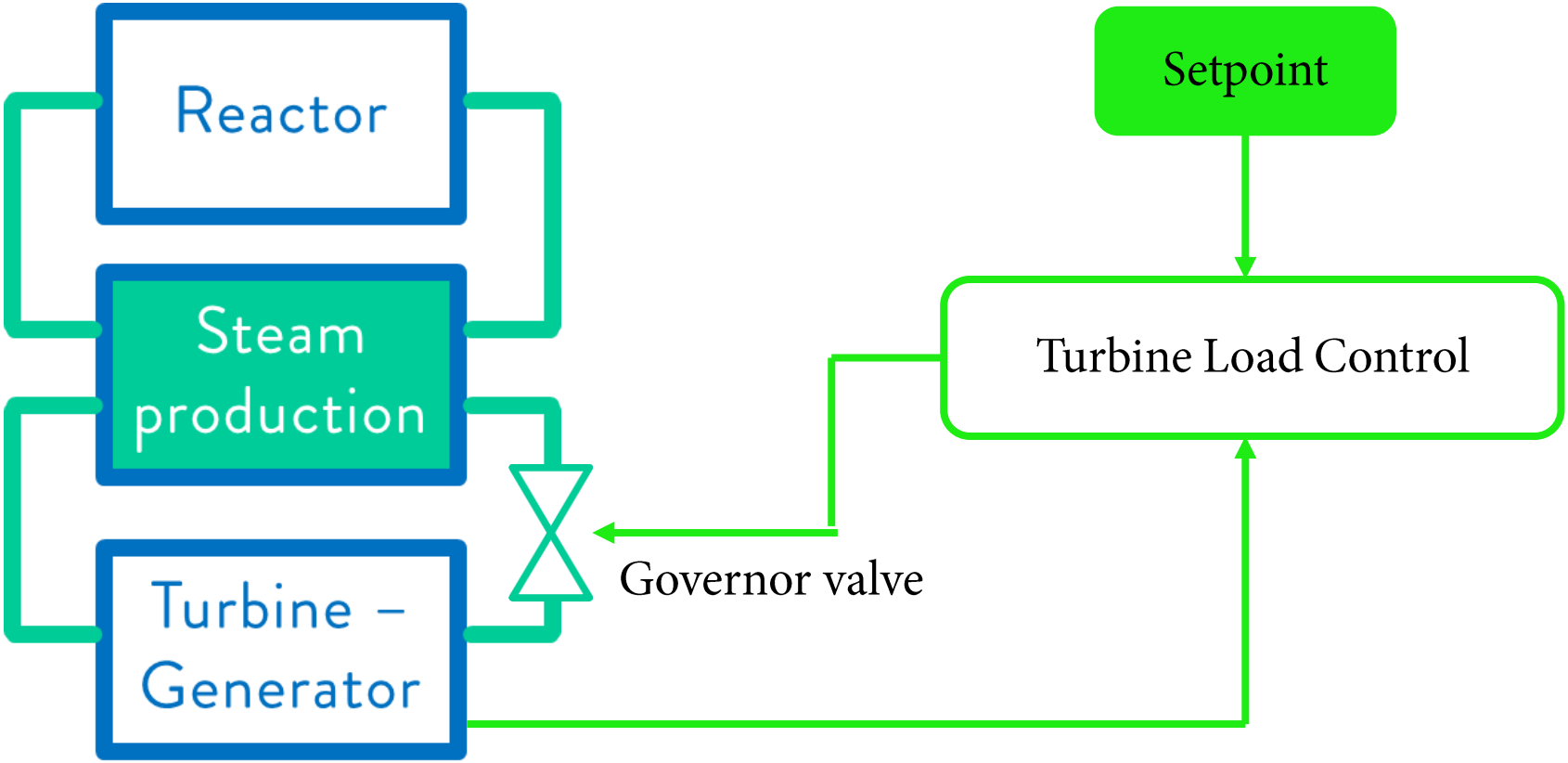
**Control loop**: in a decentralized control scheme framework "what controls what"
Pairing selection between control and controlled variables

# Control & Nuclear



How to control the power of NPP?

**Turbine-leading-Reactor mode** (or reactor-follows) - PWR



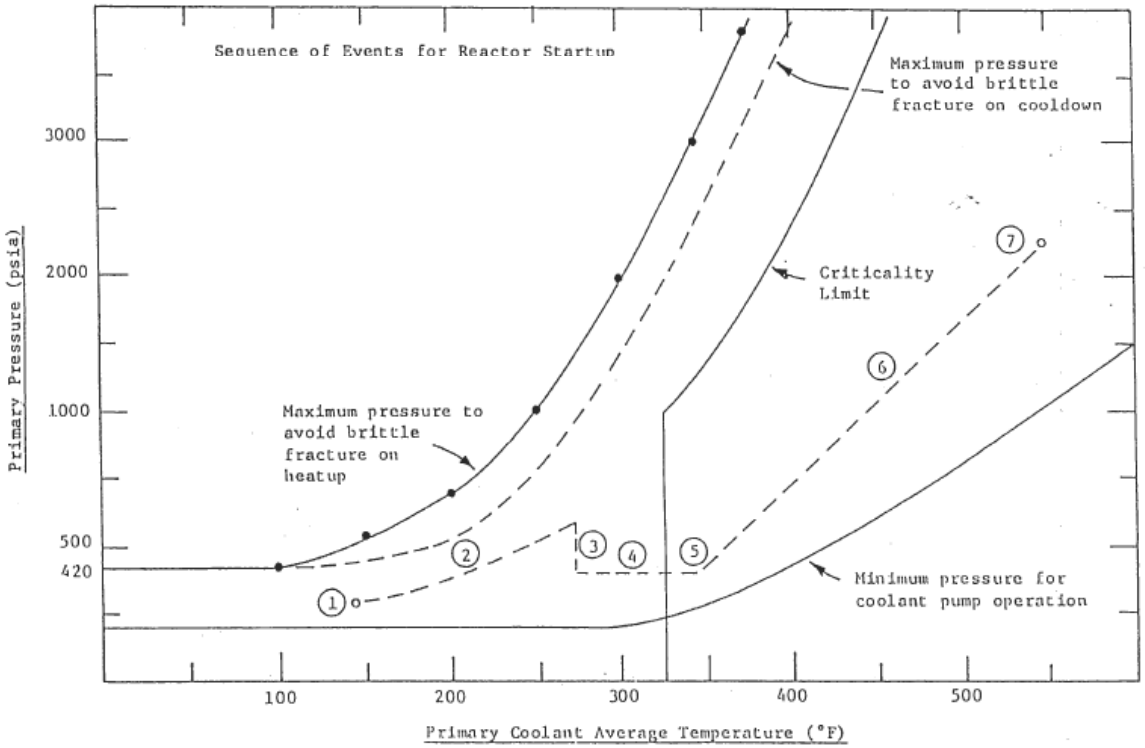

The other control loops keep the controlled variables close to the setpoint

# Control & Nuclear

A Nuclear Reactor does not bear at full power…

Control strategies for startup, shutdown and other operational modes are needed

**Startup:** process whereby all operating systems are taken from a cold shutdown to a hot operating status.



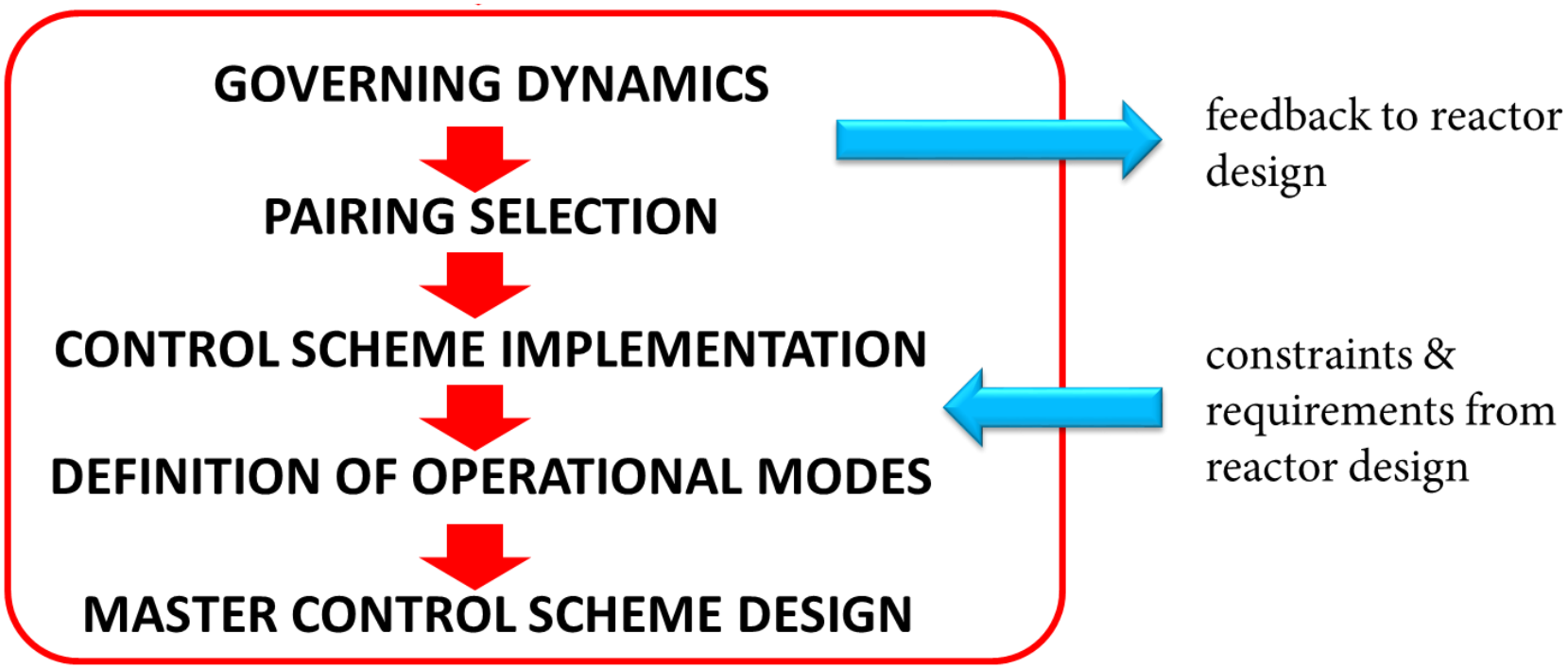

J.A. Bernard, Light-Water Reactor Startup/Shutdown, MIT

**Coordination of control action:**

- Precritical checklist
- SG chemistry
- Pressure/T coordination with pressurizer
- Heat up with pumps
- Adjust chemistry
- Criticality attainment
- SG in operation
- Steam admitted to the turbine

# Control & Nuclear

**Control of nuclear reactor:** simulation tools for realization, testing and validation allows improving the **control system design**



## Control-oriented simulation

. Evaluating the robustness and stability of the dynamic system itself on its entire power range

. Simulating reactor response to typical transient initiators, obtaining more detailed information about its overall dynamic behavior

. Guidelines for the conception of control system

. Understand interactions among input and output variables

$$\begin{cases} \dfrac{dn}{dt} = \dfrac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{8} \lambda_i c_i + q \\ \dfrac{dc_i}{dt} = \dfrac{\beta_i}{\Lambda} n - \lambda_i c_i \qquad i = 1, \dots, 8 \end{cases}$$

$$\rho = \sum_i \alpha_i (T_i - T_{i,o})$$

$$M_f C_f \frac{dT_f(t)}{dt} = q(t) - k_{fc}(T_f(t) - T_c(t))$$

$$M_c C_c \frac{dT_c(t)}{dt} = k_{fc}(T_f(t) - T_c(t)) - h_{cl}(T_c(t) - T_l(t))$$

$$M_l C_l \frac{dT_l(t)}{dt} = h_{cl}(T_c(t) - T_l(t)) - \Gamma C_l (2T_l(t) - 2T_{in}(t))$$

## Stability

Stability analysis can be performed starting from simplified modelling of the system representing the governing dynamics

$$\begin{cases} \dfrac{dn}{dt} = \dfrac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{8} \lambda_i c_i + q \\ \dfrac{dc_i}{dt} = \dfrac{\beta_i}{\Lambda} n - \lambda_i c_i \qquad i = 1, \dots, 8 \end{cases}$$

$$\rho = \sum_i \alpha_i (T_i - T_{i,o})$$

$$M_f C_f \frac{dT_f(t)}{dt} = q(t) - k_{fc}(T_f(t) - T_c(t))$$

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$$M_l C_l \frac{dT_l(t)}{dt} = h_{cl}(T_c(t) - T_l(t)) - \Gamma C_l (2T_l(t) - 2T_{in}(t))$$

$$\boxed{\begin{aligned} \dot{\hat{x}}(t) &= \hat{A}\hat{x}(t) + \hat{B}\hat{u}(t) \\ \hat{y}(t) &= \hat{C}\hat{x}(t) + \hat{D}\hat{u}(t) \end{aligned}}$$

$$\hat{x}(t) = e^{\hat{A}t}\hat{x}_0 = \sum_{k=0}^{+\infty} \frac{(\hat{A}t)^k}{k!}\hat{x}_0 = diag\{e^{s_1 t}, e^{s_2 t}, \dots, e^{s_n t}\}\hat{x}_0$$

Eigenvalues trajectories across the Gauss plane defines system behaviour

Condition for asymptotically stability: $Re\{s_i\} < 0, \quad i = 1, 2, \dots, n$

# Control issues of MSR

The MSR concept (thermal and fast) is **very promising** but…

. Very little experience compared to present nuclear reactor systems (Gen II & III)
. Fuel motion is not common in nuclear reactors
. "Standard" nuclear codes for simulation are not suitable (they are tailored on the modelling needs of present generation of nuclear reactors)

| Peculiarities | Issues |
|---|---|
| Drift of delayed neutron precursors | impact on $\beta_{eff}$ and on **dynamics** & **control** feature |
| Strong coupling between neutronics and thermal-hydraulics | require **dedicated** tools for simulation analysis |

Control strategies retrieved from LWRs and SFRs **not suitable**

different reactor (drift of delayed neutron precursors, fast dynamics due to the coupling between neutronics and thermal-hydraulics), different control strategies

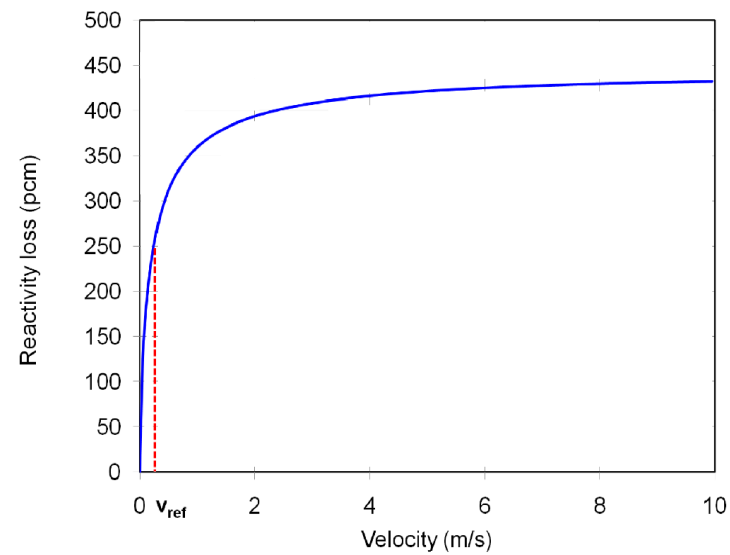
# Control issues of MSR

$$\begin{cases} \dfrac{dn(t)}{dt} = \dfrac{\rho - \beta}{\Lambda} n(t) + \sum \lambda_i c_i(t) \\ \dfrac{dc_i(t)}{dt} = -\lambda_i c_i(t) + \dfrac{\beta_i}{\Lambda} n(t) - \dfrac{1}{\tau_c} c_i(t) + \dfrac{1}{\tau_c} c_i(t - \tau_{ec}) e^{-\lambda_i \tau_{ec}} \end{cases}$$

**Precursors leaving the core**

**Precursors that re-enter in the core – did not decay in the external circuit**

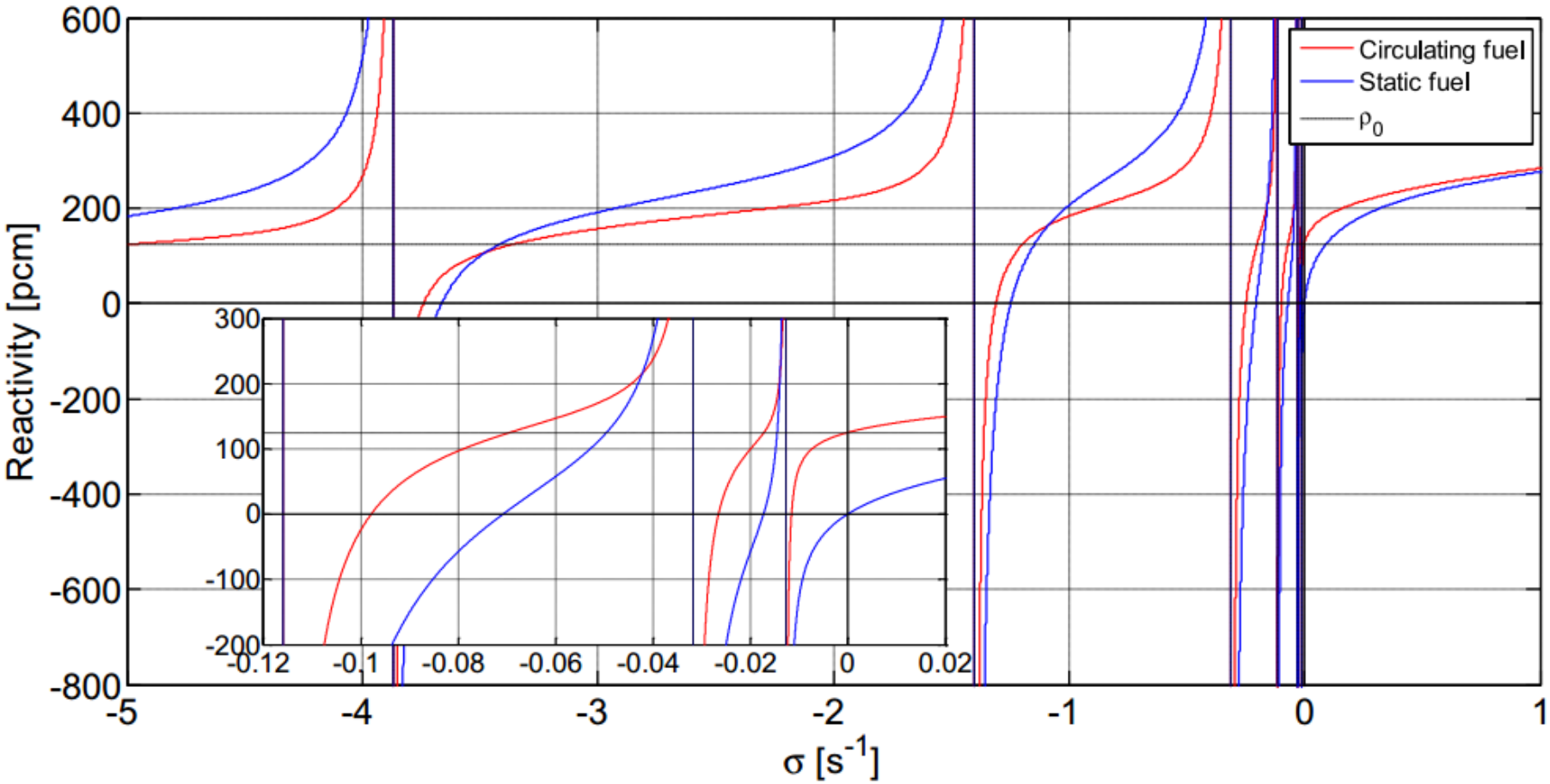
$$\rho_0 = \beta - \sum \frac{\beta_i \lambda_i}{\lambda_i + \dfrac{1 - e^{-\lambda_i \tau_{ec}}}{\tau_c}}$$




. $\beta$ is relevant for control
. Limited $\beta$ in circulating fuel reactor
. Relevant for the startup and shutdown of MSR.

Cammi, A., Di Marcello, V., Guerrieri, C., Luzzi, L., 2011a. Transfer Function Modeling of Zero-Power Dynamics of Circulating Fuel Reactors. Journal of Engineering for Gas Turbines and Power 133 (5), 052916_1–8.

# Control issues of MSR



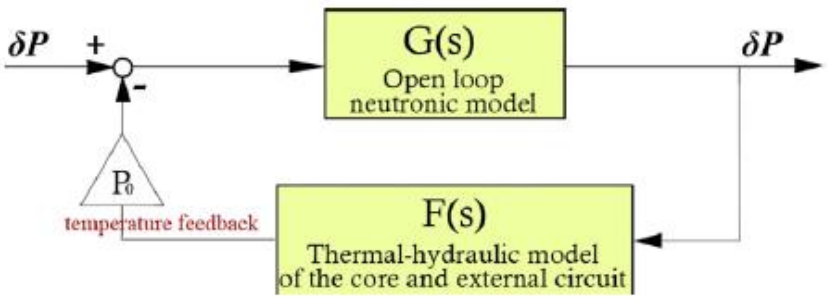

. "New" in-hour equation – depends on fuel velocity

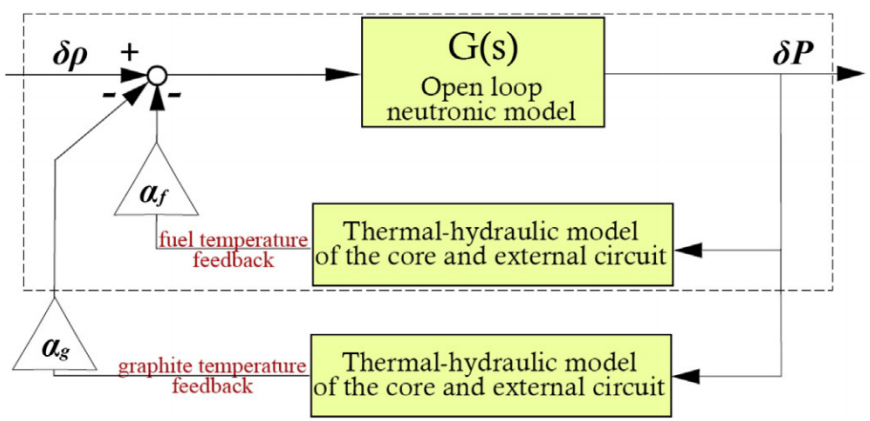
. Zero-power kinetics is different

Guerrieri, C., Cammi, A., Luzzi, L., 2013. An approach to the MSR dynamics and stability analysis. Progress in Nuclear Energy 67, 56–73.

# Control issues of MSR

**What happens if we add temperature feedbacks?**




MSFR

Doppler effect: negative -2 pcm/K

Density effect: strong negative -5 pcm/K

$$\Sigma_F(T_F) = \left[\frac{\boldsymbol{d_F}}{\boldsymbol{d_{F,0}}}\right]\left[\Sigma_{F,0} + A \cdot ln\left(\frac{T_F}{T_{F,0}}\right)\right]$$

MSBR

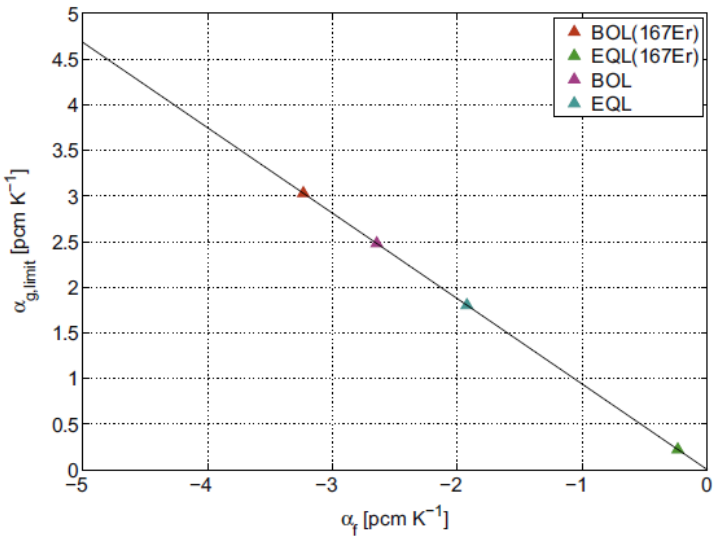
Salt temperature effect: -3 pcm/K

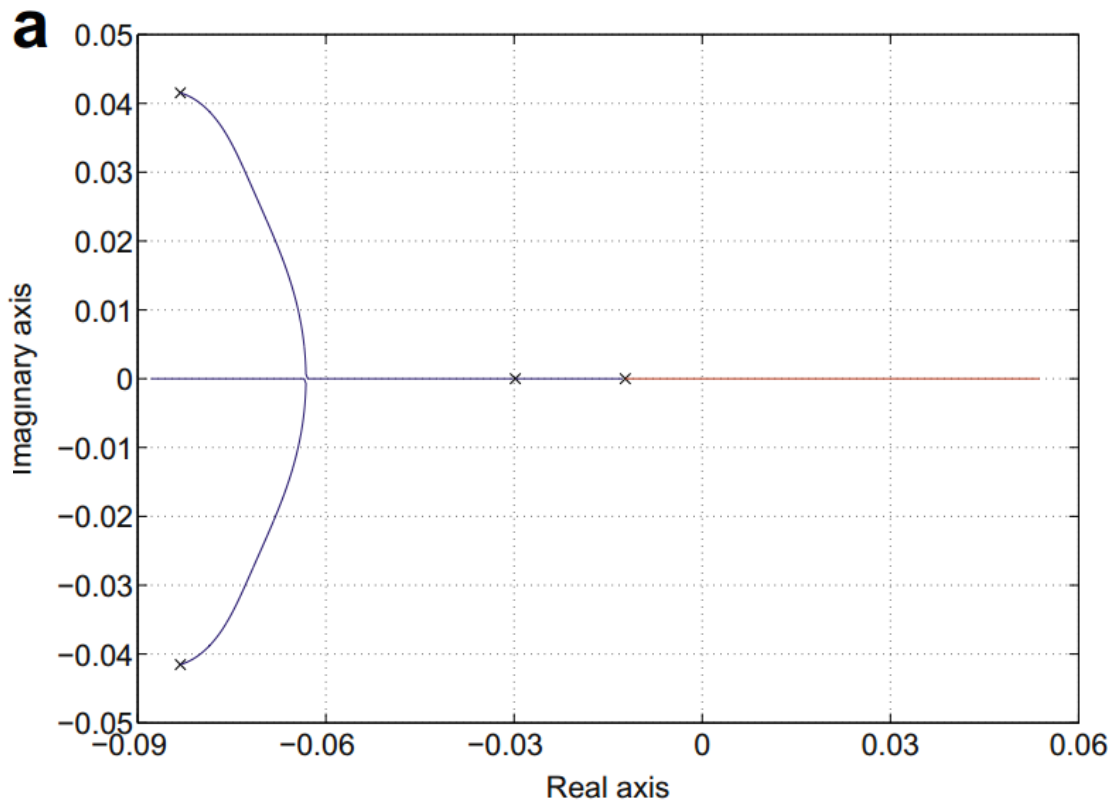
Graphite effect: 2.3 pcm/K 0.6 pcm/K

Guerrieri, C., Cammi, A., Luzzi, L., 2013. An approach to the MSR dynamics and stability analysis. Progress in Nuclear Energy 67, 56–73.

# Control issues of MSR

$$\dot{\hat{x}}(t) = \hat{A}\hat{x}(t) + \hat{B}\hat{u}(t)$$
$$\hat{y}(t) = \hat{C}\hat{x}(t) + \hat{D}\hat{u}(t)$$



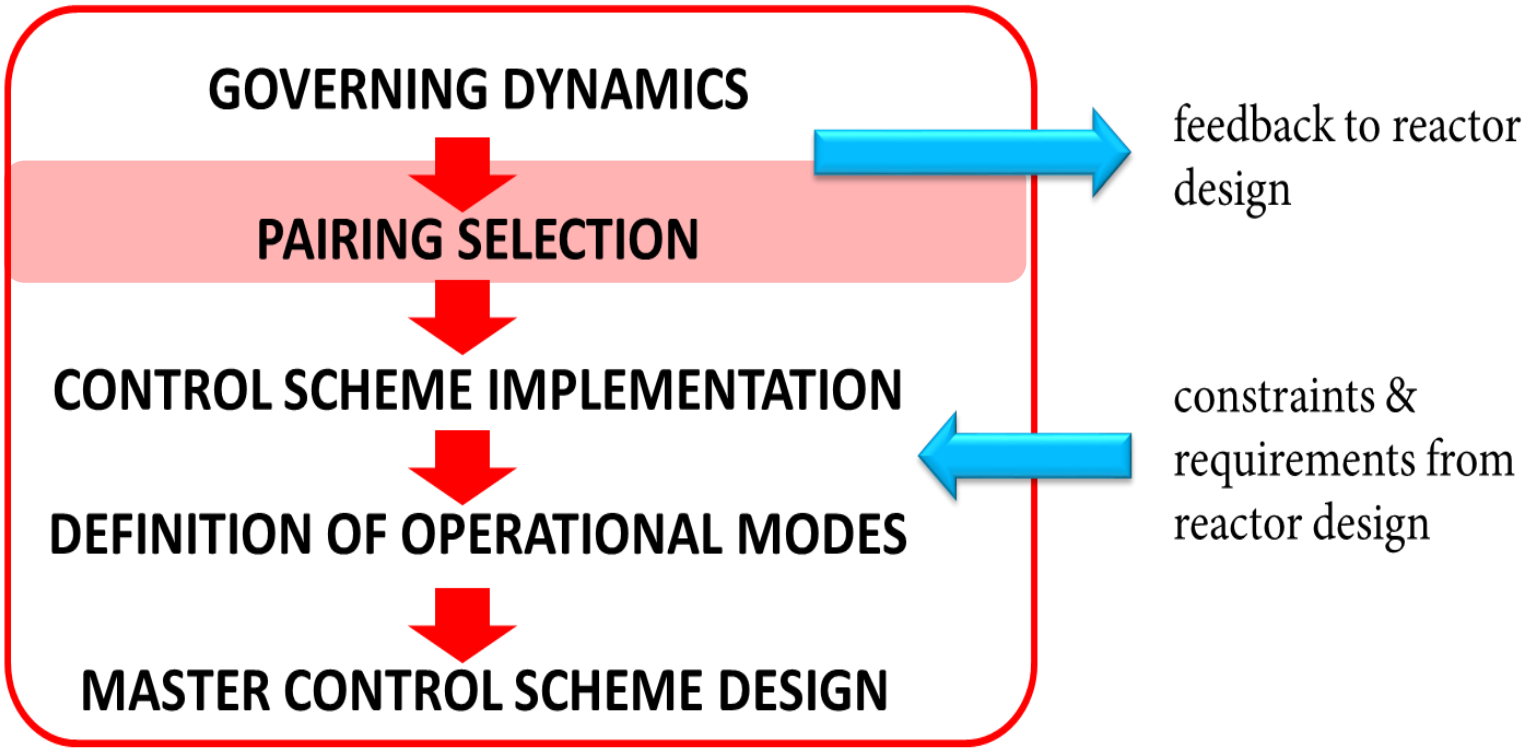




Guerrieri, C., Cammi, A., Luzzi, L., 2013. An approach to the MSR dynamics and stability analysis. Progress in Nuclear Energy 67, 56–73.

# Control issues of MSR

**What controls what?**

Matching between control and controlled variables

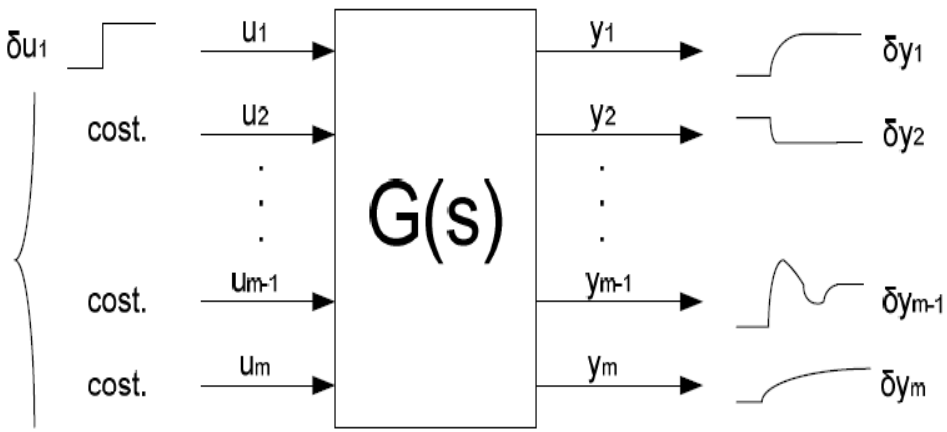


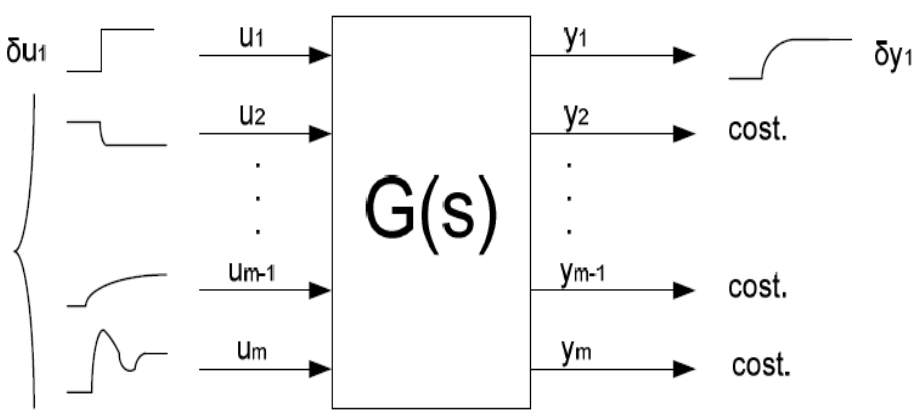

Usually the coupling comes from dynamics analysis and experience

Guerrieri, C., Cammi, A., Luzzi, L., 2014. A preliminary approach to the MSFR control issues. Annals of Nuclear Energy 64, 472–484.

# Control issues of MSR

*Multiple Inputs, Multiple Outputs* (MIMO) → Decentralized Control Scheme →
→ Several uncoupled SISO systems → Coupled control loops Problem →RGA




Open Loop

$$g_{ji} = G_{ji}(0) = \frac{\delta y_{jOL}}{\delta u_i}$$

Closed Loop

$$h_{ji} = \frac{\delta y_{jCL}}{\delta u_i}$$

Coefficient Relative Gain Array

$$\lambda_{ji} = \frac{g_{ji}}{h_{ji}}$$

Pairing Selection Criterion

$\lambda_{ji} \sim 1$ ✓

$\lambda_{ji} \sim 0$ X

$\lambda_{ji} < 0$ XX

# Control issues of MSR

| Control variables | Controlled |
|---|---|
| Power | Control Rods (not in the MSFR!) |
| Inlet core temperature | Primary salt flow rate |
| Outlet core temperature | Intermediate salt flow rate |
| Outlet temperature of intermediate salt | Inlet temperature of the energy conversion fluid |

Case i

| | $\rho_{cr}$ | $\Gamma_1$ | $\Gamma_2$ | $T_{cool}^{h\ in}$ |
|---|---|---|---|---|
| P | 0.01 | **0.38** | 1.02 | −0.41 |
| $T_f^{c\ out}$ | **0.63** | 0.31 | 0.20 | −0.14 |
| $T_f^{c\ in}$ | 0.36 | 0.30 | **1.16** | −0.82 |
| $T_{cool}^{h\ out}$ | 0.00 | 0.00 | −1.37 | **2.37** |

Guerrieri, C., Cammi, A., Luzzi, L., 2014. A preliminary approach to the MSFR control issues. Annals of Nuclear Energy 64, 472–484.

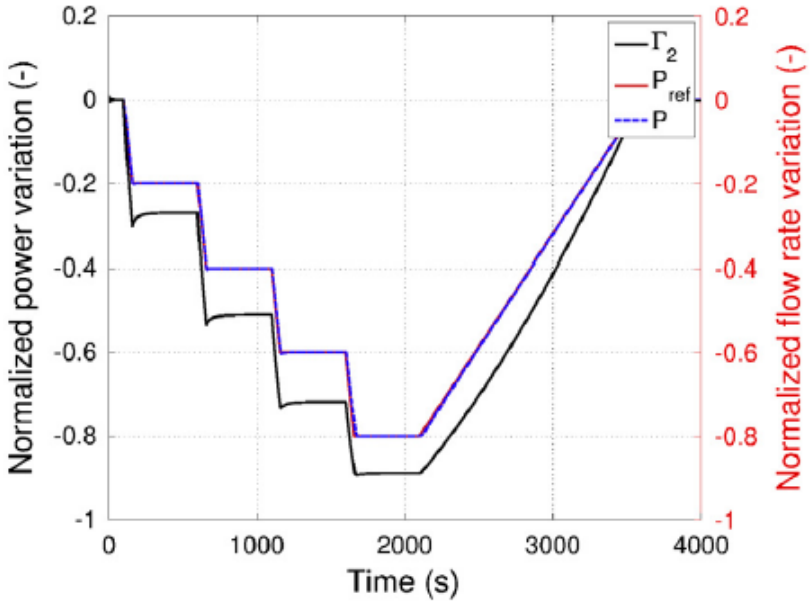
# Control issues of MSR

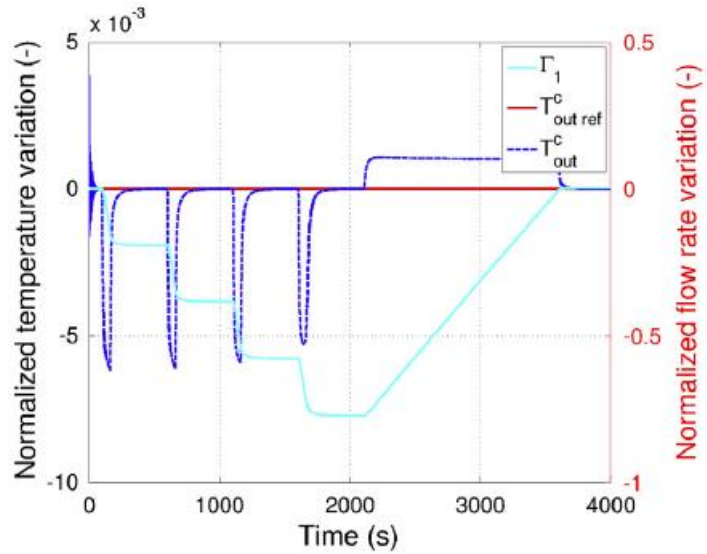
| Control variables | Controlled |
|---|---|
| Power | ~~Control Rods (not in the MSFR!)~~ |
| Inlet core temperature | Primary salt flow rate |
| Outlet core temperature | Intermediate salt flow rate |
| ~~Outlet temperature of intermediate salt~~ | ~~Inlet temperature of the energy conversion fluid~~ |

| Case 3-A | | | Case 3-B | | |
|---|---|---|---|---|---|
| | $\Gamma_1$ | $\Gamma_2$ | | $\Gamma_1$ | $\Gamma_2$ |
| $P$ | 0.36 | **0.64** | $P$ | 0.40 | **0.60** |
| $T_f^{c\ out}$ | **0.64** | 0.36 | $T_f^{c\ in}$ | **0.60** | 0.40 |

Guerrieri, C., Cammi, A., Luzzi, L., 2014. A preliminary approach to the MSFR control issues. Annals of Nuclear Energy 64, 472–484.

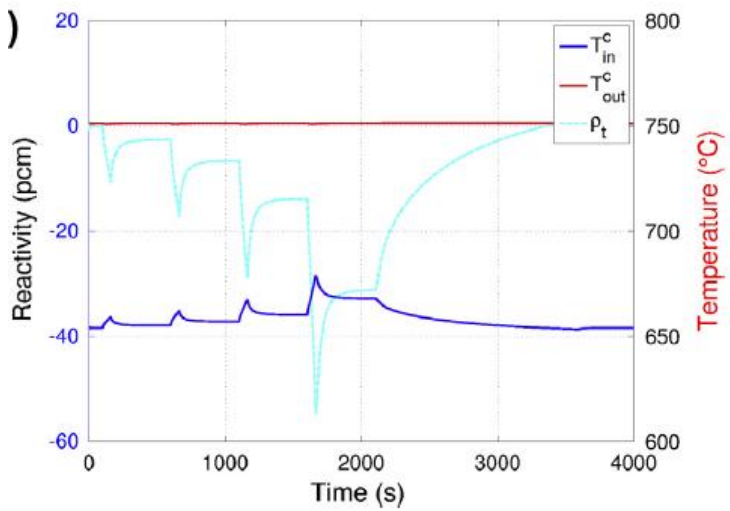
# Control issues of MSR




Case 3-A

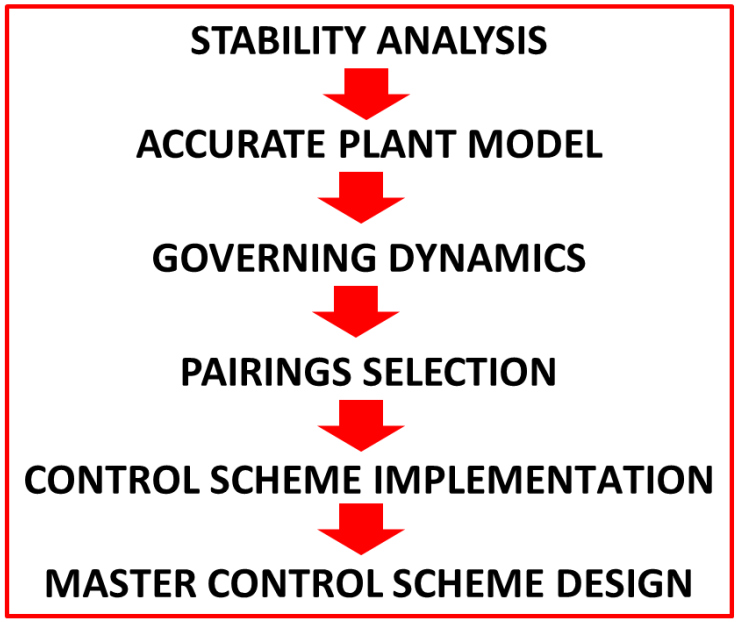
| | $\Gamma_1$ | $\Gamma_2$ |
|---|---|---|
| $P$ | 0.36 | **0.64** |
| $T_f^{c\ out}$ | **0.64** | 0.36 |




Guerrieri, C., Cammi, A., Luzzi, L., 2014. A preliminary approach to the MSFR control issues. Annals of Nuclear Energy 64, 472–484.

# Conclusions

. Control means impose the desired behavior to the reactor
. MSRs have features that makes this task more multi-discinplinary than the conventional one

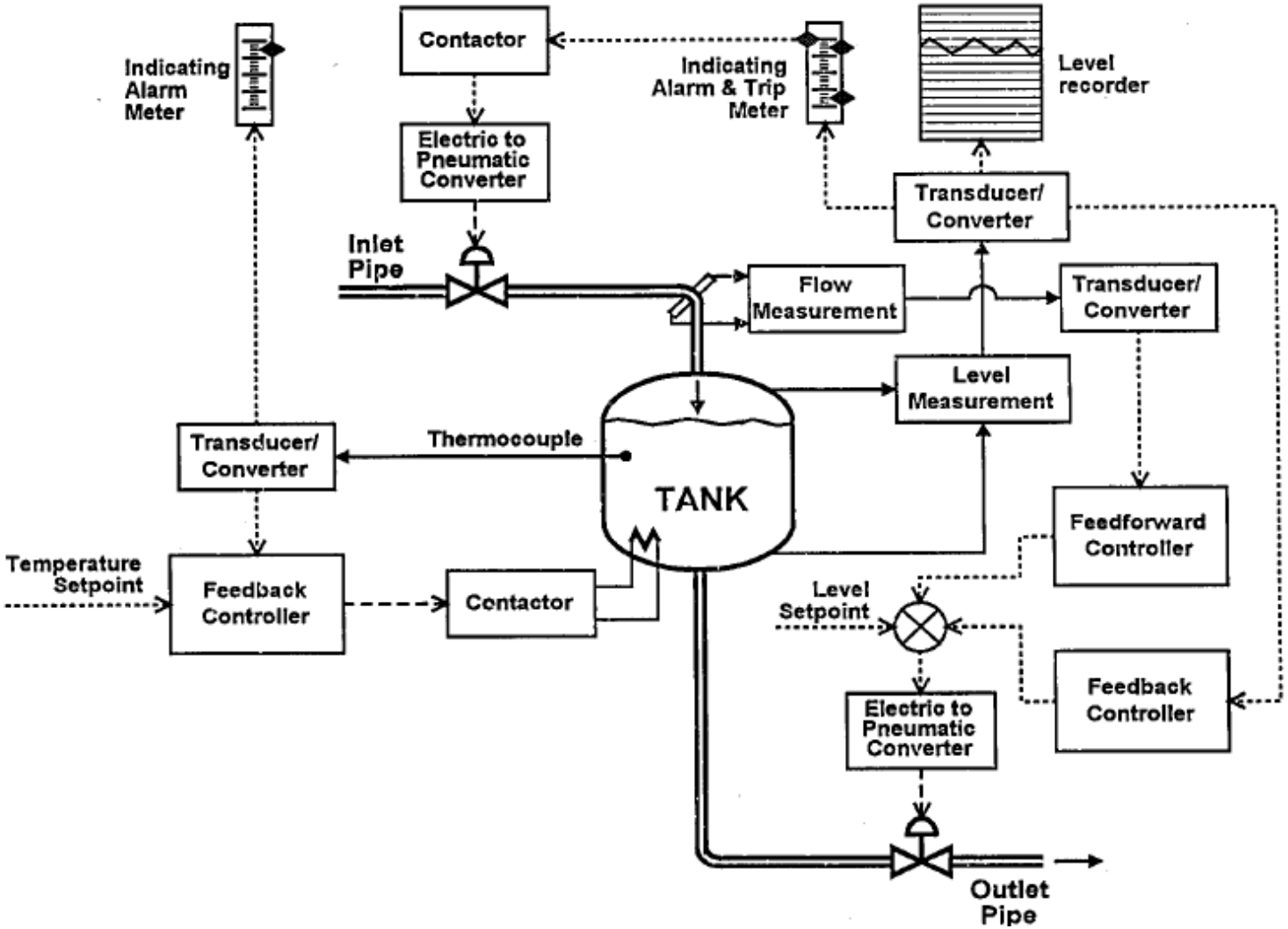



Multistep and multidisciplinary task: we need simulations to prove our control schemes works!

. Control without CR? Why not.. Take advantage from the strong coupling between thermal-hydraulics and neutronics


# *Thank you for your attention*

# Control

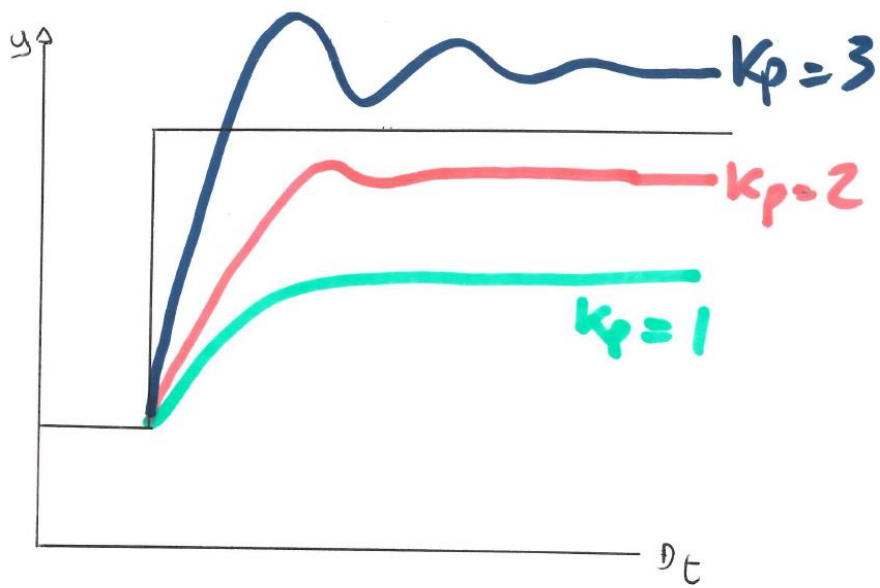



G. Bereznai, Introduction to control systems, https://canteach.candu.org/Content%20Library/20044401.pdf

# Control

PID controllers: **Proportional** – Integral – Derivative

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$




. The control action is proportional to the error

. For every % of the e(t), a $K_p$ % of u(t) is generated

. It operates usually with a permanent residual error

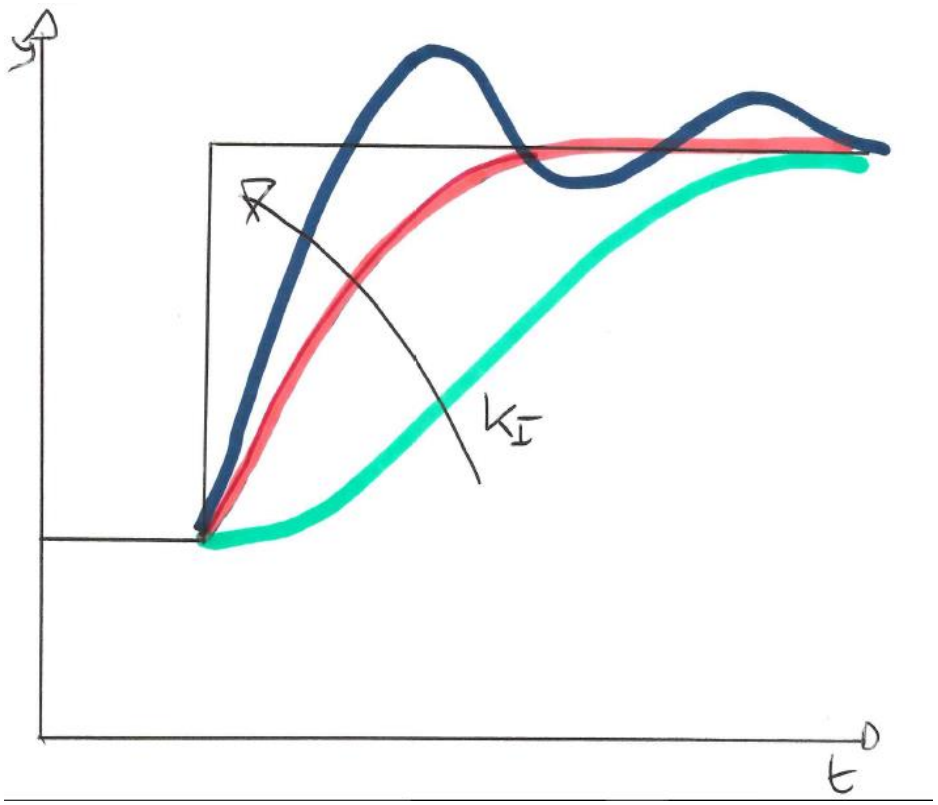
. Usually, the error does not tend to zero

. High values of $K_p$ make the system instable

# Control

PID controllers: Proportional – **Integral** – Derivative

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$




. The control action is proportional to the integral error

. Avoid oscillation in the control action

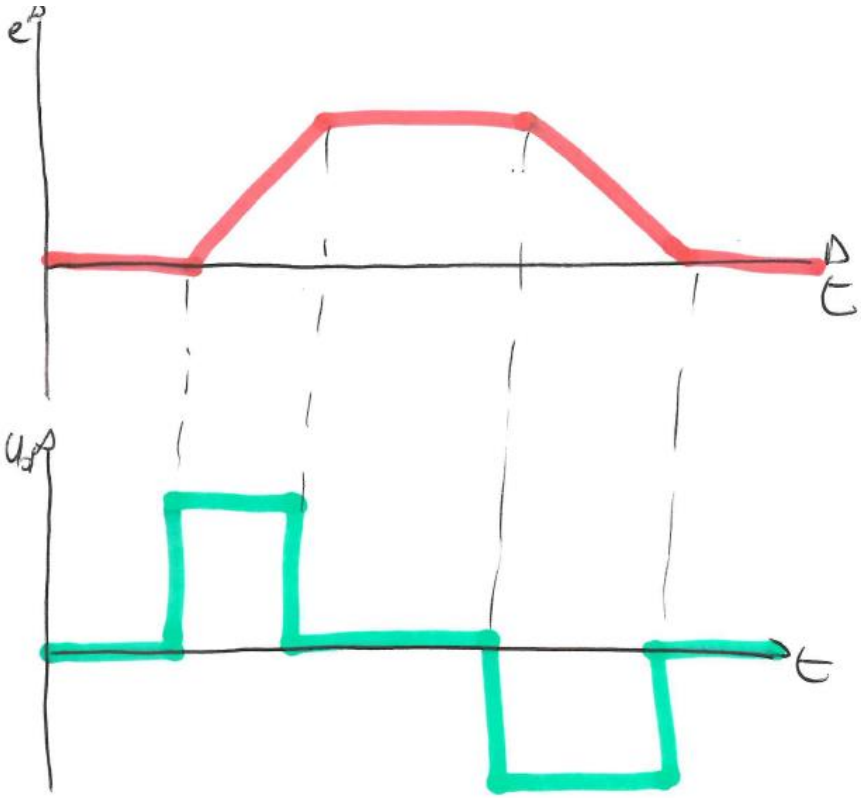
. The error tends to zero

. Overshoots and undershoots with high values of $K_i$

# Control

PID controllers: Proportional – **Integral** – Derivative

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$




. The control action is proportional to the error derivative

. The control action try to "anticipate" the error

. It cannot be used by itself

. In industrial fields, it is not used since in case of step variation, it contribute to the control action with an impulse