INDUSTRIAL APPLICATIONS OF PREDICTIVE FUNCTIONAL CONTROL

Lyngby 2011

J.Richalet

TECHNOLOGY - METHODOLOGY

1955+

Operational amplifier
µA709 !

Electric circuits.
Frequency domain

PID

1970

Digital computer

Modelling Simulation
Identification

MBPC …PFC

End of the Sixties:

- ORIGIN OF MODEL BASED PREDICTIVE CONTROL

- PETROLEUM INDUSTRY / DEFENCE INDUSTRY

.Refineries :

How to handle constraints on MV's and CV's ?

How to control a multivariable process ?

.Defence :

How to control a process with a non stationary set point with no lag error (follow-up servo) ?

….the past…

1968 : Basic principles of Predictive Control

1973 : 1st version of PFC/ IDCOM

1974 : 1st industrial applications of PFC/IDCOM

Steam Generator/ Reactor/ Distillation

1978 : 1st contribution MPC “Automatica “ (problems..!)

1980-85 : HIECON with Set Point (Houston)

1989 : Extension from PFC to PPC:

Parametric Predictive Control (control by reactor flow..)

1998 :1st implementation of an MPC in the native library of a PLC : Modicon. Schneider-Electric.Momentum.Concept

TARGET

« Easy to Understand, to Implement, to Tune »

- **Solve what PID cannot solve,**
  but in continuity with PID…..
- **Control parameters with a clear physical meaning.**

- **No explicit integrator in the loop**
- **No matricial calculus**
- **No iterative minimisation on line**
- **Open technology….**
- **Fits with industrial specific control needs !**

ELEMENTARY TUTORIAL EXAMPLE

$$P = \frac{G\, e^{-\theta s}}{1 + Ts} = M = \frac{y}{u}$$

θ = Tsamp . r

$y(n) = \alpha\, y(n-1) + (1-\alpha) \,.\, u(n-1-r) \,.\, G$ $\quad \alpha = e^{\frac{-Tsamp}{T}}$

Trajectory expo. : λ

1 coincidence point: H

1 Base function: step

Processus with delay $y_{Pr}(n) := y_P(n) + y_M(n) - y_M(n-r)$

Target : $\Delta_P(n+H) = (C - y_{Pr})\,(1 - \lambda^H)$

Model : Model increment :

Free mode $y_M(n)\, \alpha^H$

Forced mode $u(n) \,.\, GM\left(1 - \alpha^H\right)$

:

Increment = Free(n+h) + Forced(n+h)- ymodel(n)

The only mathematical problem for trainees …!

Control equation : $\Delta P(n+H) = \Delta M(n+H)$

$$(C - y_{Pr}(n))\ (1 - \lambda^H) = y_M(n)\ \alpha^H + u(n)\, GM(1 - \alpha^H) - y_M(n)$$

$$u(n) = \frac{(C - y_{Pr}(n))\ (1 - \lambda^H)}{GM(1 - \alpha^H)} + \frac{y_M(n)}{GM}$$

4 BASIC PRINCIPLES OF PFC : J. PIAGET

– Operating Image	- Internal independant Model
– Target – Sub Target	– Reference Trajectory
– Action	– Solver. Functional basis Structured future MV
– Comparison : – Predicted / Actual	– Error compensator

- *Natural Control : "You would not drive your car using a PID scheme"*

FIRST INDUSTRIAL APPLICATIONS OF P.F.C.

DEFENCE

- Mine hunter
- Ariane 5 attitude control
- Missile autopilot
- Laser guided missile (t=62 microsecond…)
- Gun turrets
- Radar antennas
- Infra Red camera
- High speed Infra Red
- Missile launch
- Camera mount
- Radar antennas
- Laser mirror
- Tank turret (T. 55)
- Mine sweeper auto-pilot

Aircraft carrier auto-pilot

AUTOMOTIVE

- Gear box test bench
- Dynamic test bench engine
- Fuel injection
- Idle fuel injection
- Clutch antistroke
- Gear box (tank)
- Hybrid car (electric-fuel)

Air conditioning

METALLURGICAL INDUSTRIES

- Coating lines aluminium
- Thickness control - Roll eccentricity
- Mono-multi-stands Rolling mills
- Continuous casting (slab)
- Push-ovens
- Coke furnace
- Hot/cold/Thin rolling mills
- Steam generators

MISCELLANEOUS (Chem reactors and distillation excluded)

- Bioreactor Melissa ESA
- Plastic extrusion robot (high speed)
- Temperature control of gas furnace
- Temperature control of TGV train carriage
- River dam level control (T=1 hour)
- Powder milk dryer
- Electric furnace brazing etc….

…the oldest MBPC… 1968

A "few" thousands applications in many fields

EXOTIC APPLICATIONS…

North : Molde (Norway)

South : Plaza Huincul (Patagonia-Argentina)

East : Hokaido (Japan)

West : Mobile (USA.DEGUSSA)

High : Eiffel Tower elevator !

Space : European Space Agency : Mars project bioreactors (2029 !)

Depth : Mine hunter boat

Speed : Temperature cabin (TGV : 574.8 km/h W.record)

Fast : Laser guided bomb (Tsampling : 65 µs)

Slow : River dam level (Tsampling : 1 hour / FP model on line)

Ecology: Diester from colza

Animal : Dog food pellet dryer

Plants : Greenhouses

etc…

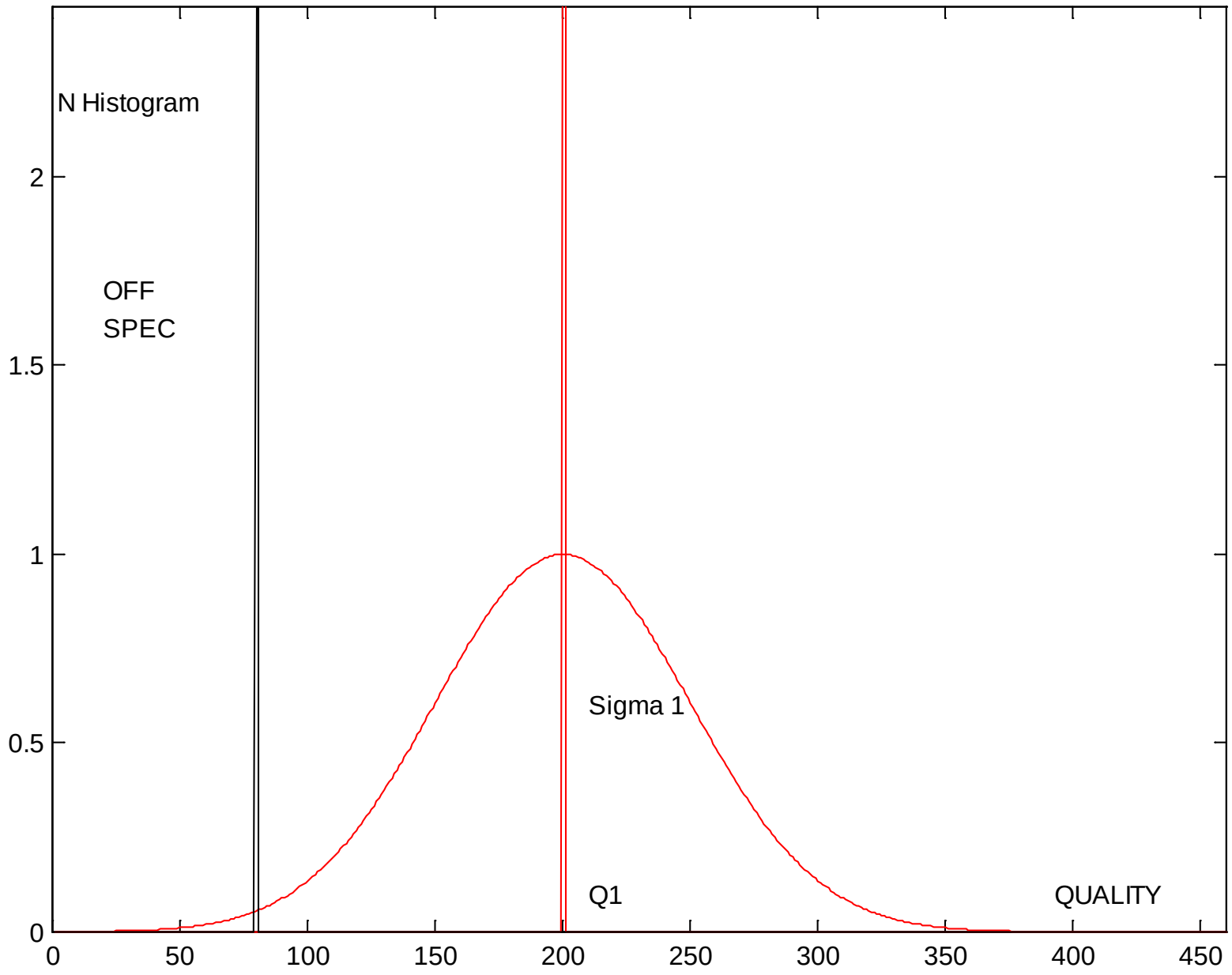
AT WHAT LEVEL DO WE OPERATE ?

Back to Basics:

- **Level 0 : Ancillary processes e.g: FIC/ Pid (the valve is the nightmare of control !)**
- **Level 1 : Dynamic control with constraints**
- **Level 2 : Optimization of working conditions**
- **Level 3 : Production planning**

.Level N is operative if level N-1 works well…!

. »There are no technical problems, but only technical aspects of economic problems … »


N Histogram
OFF
SPEC
Sigma 1
Q1
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1.5
2
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100
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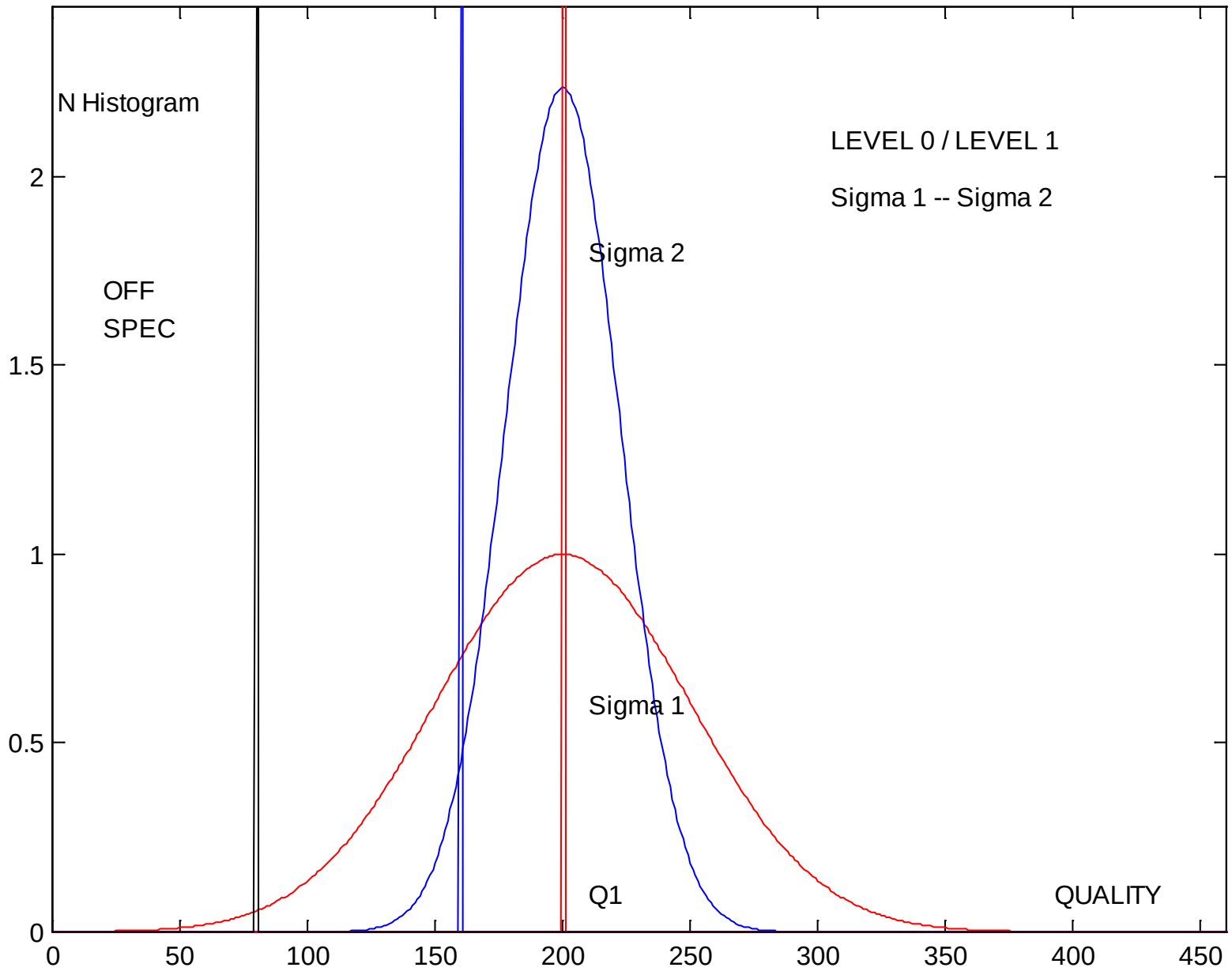
250
300
350
400
450


N Histogram
LEVEL 0 / LEVEL 1
Sigma 1 -- Sigma 2
Sigma 2
OFF
SPEC
Sigma 1
Q1
QUALITY
0
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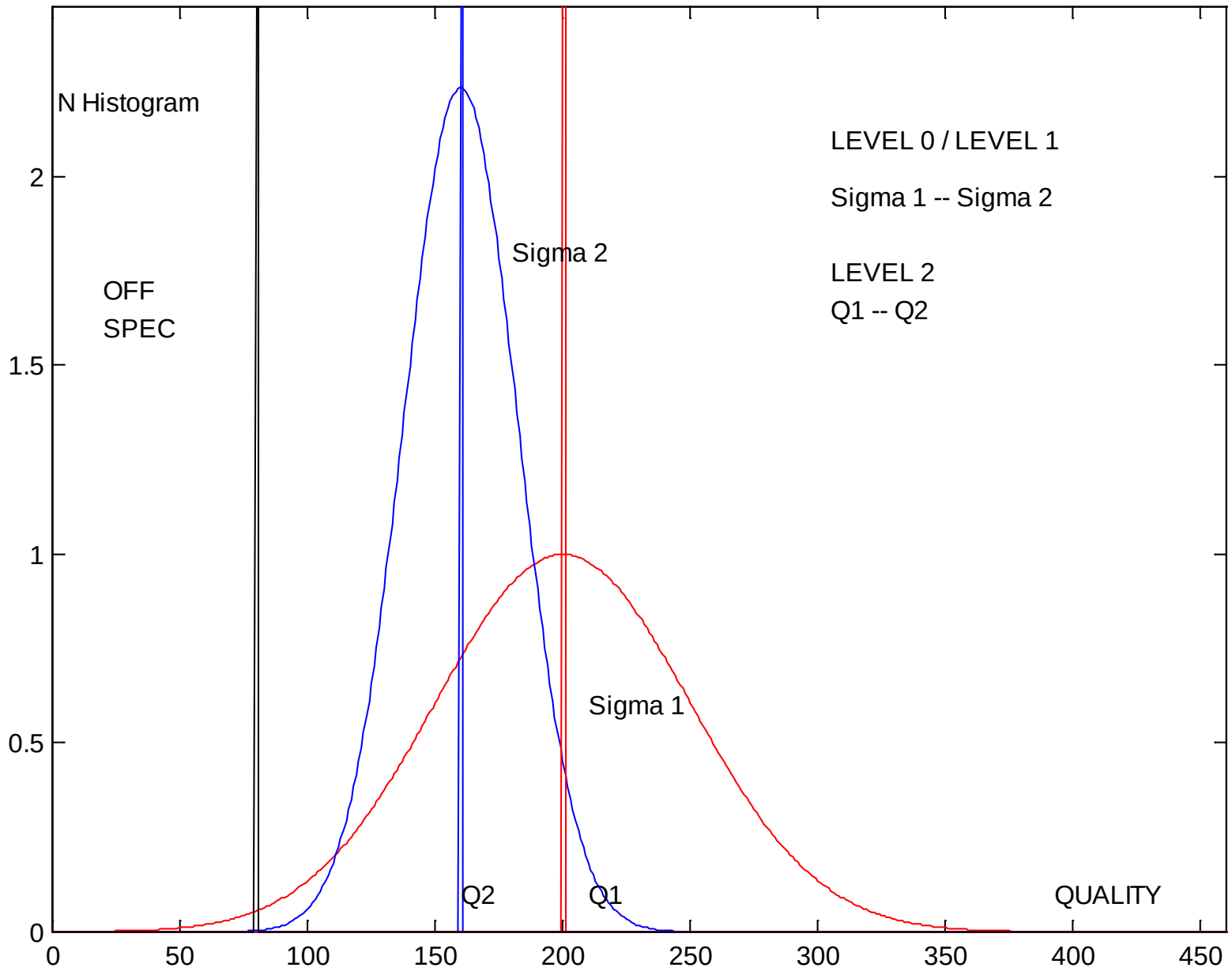
N Histogram
OFF
SPEC
LEVEL 0 / LEVEL 1
Sigma 1 -- Sigma 2
LEVEL 2
Q1 -- Q2
Sigma 2
Sigma 1
Q2
Q1
QUALITY
0
0.5
1
1.5
2
0
50
100
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200
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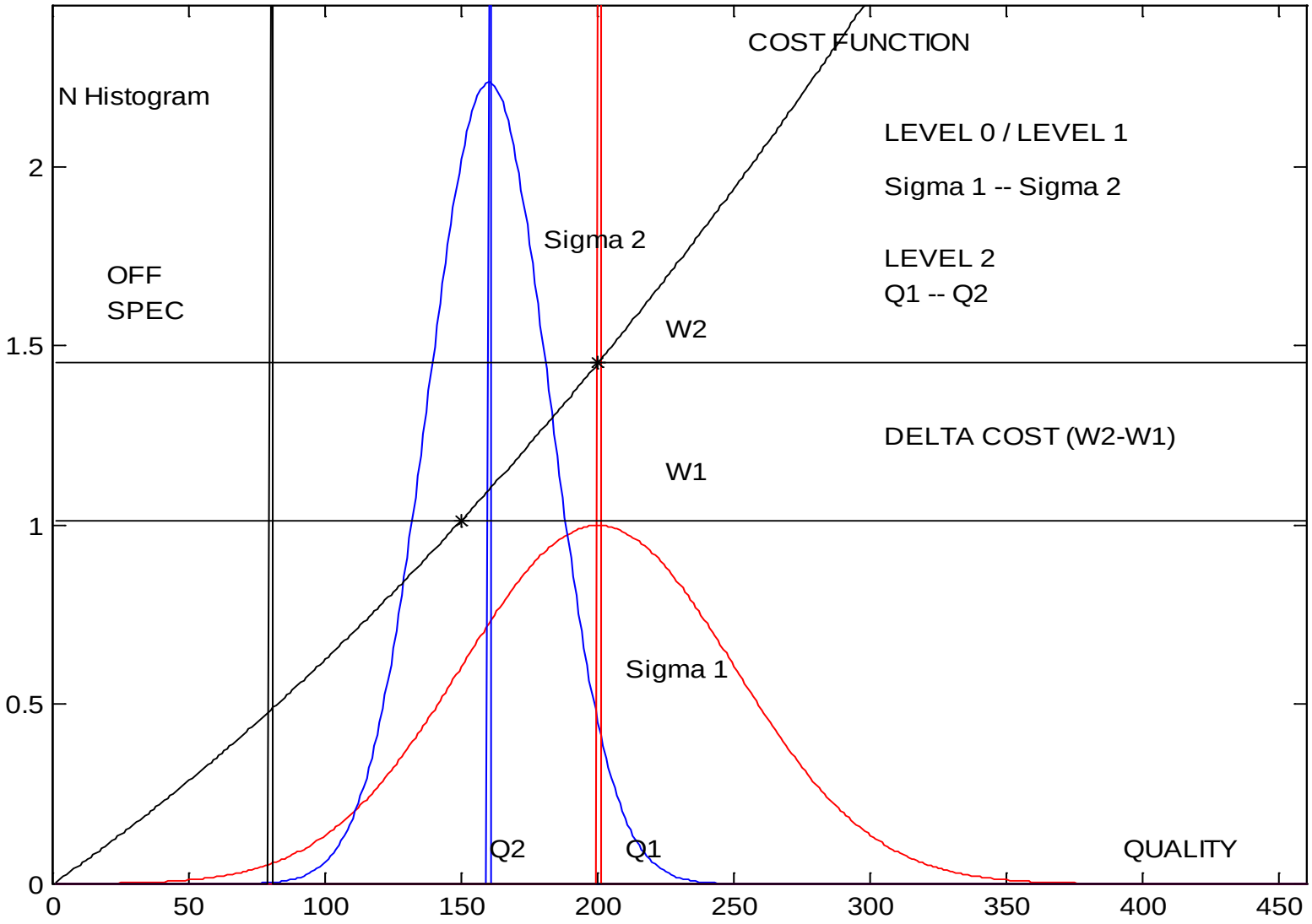
400
450

« SQUEEZE AND SHIFT 1972 !»



TARGETED PERFORMANCES

. Control « all » types of processes: time delay, unstable, non-minimum phase, some non-linear ,

. Handles all constraints on the MV and on internal variables of the process CV.

. No lag error on dynamic set points with no integrator

. Transparent and Cascade Control with transfer of constraints from inner loop to outer controller (« Back Calculation »)

. True feed-forward

. Split-range control with different dynamics (reactors!)

. Control with 2 cooperative MV's, e.g., big valve / small valve

. Extendable to 3 MV/ 3 CV…..

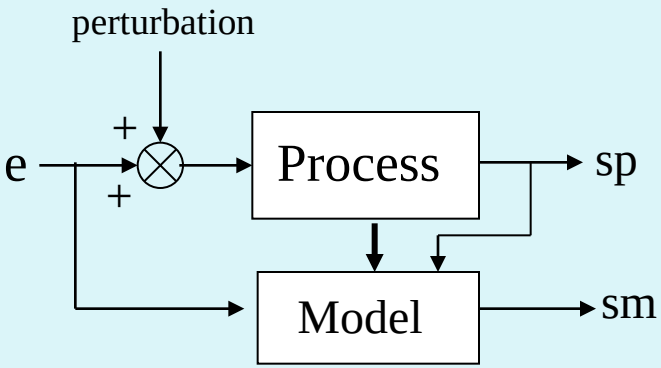
. Dual control: total elimination of harmonic disturbances

. Full Robustness analysis: easy trade-off ,

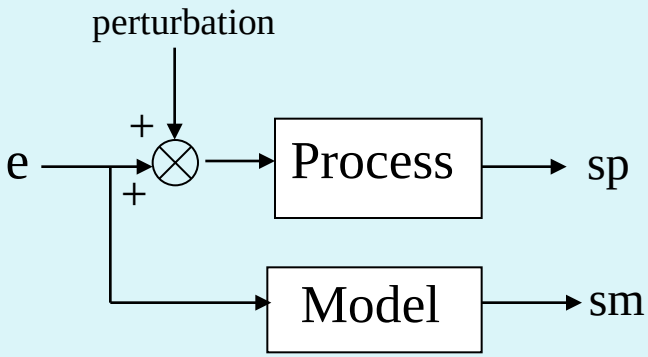
. Immediate tuning / Open technology

Etc…..

2 TYPES OF MODELS



Re-aligned Model



Independent Model

Independent models are selected:

. Input /Output models valid for all math. structures

. No permanent errors in steady-state modes!
(never mix process variables with model parameters..)

TEST PROTOCOL OPTIMIZATION

APPLY AN « OPTIMAL » TEST INPUT SIGNAL TO VALIDATE A MODEL OF THE PROCESS ?
: SEQUENCE OF TESTS OF DIFFERENT DURATIONS

- **LIMITED AMPLITUDE : BETWEEN +M /- M ?**

- **LIMITED DURATION H : H< NEGOCIATED TIME ?**

- **SENSITYZING SPECTRUM DEPENDING ON THE BAND PASS OF THE PROCESS ?**

IT IS POSSIBLE TO OPTIMIZE THE PROTOCOL : MINIMUM UNCERTAINTY OF THE PARAMETERS OF THE PROCESS IF WE KNOW THE PROCESS:

Solution ? : ITERATIVE TEST PROCEDURE

PRBN :not realistic !

Solver

- **The future MV is projected on a Functional Basis:**
  - **e.g. Taylor expansion / Polynomials**
- **Thus, the MV is restricted *a priori* and not damped afterwards….**
- **$MV(n+i) = \Sigma\ \mu j.\ Uj(i)$**
- **$U0(i) = 1$, $U1(i) = i$ $\underline{U2(i)= i^2 \quad etc}$ …**
- **Find the μj such that:**
  - **At a finite number of points, the predicted model output coincides with the desired reference trajectory**
    - **(i.e., coincidence points)**

Why structuring the future MV?

- **Computing all future MVs is of little benefit:**

  Computation time increases (PLC !)
- **Introduction of a damping term on the speed of the MV *a priori* is difficult to tune !**
- **So….**
- **Projection on « Eigen » MV functions of linear dynamic processes insures no lag error on dynamic set points**

ACCURACY

- **Basic Eigen Function property:**

- **If the set point can be projected on a polynomial basis of order N, and if the non integrative model is of order N, then there is no lag error…!**

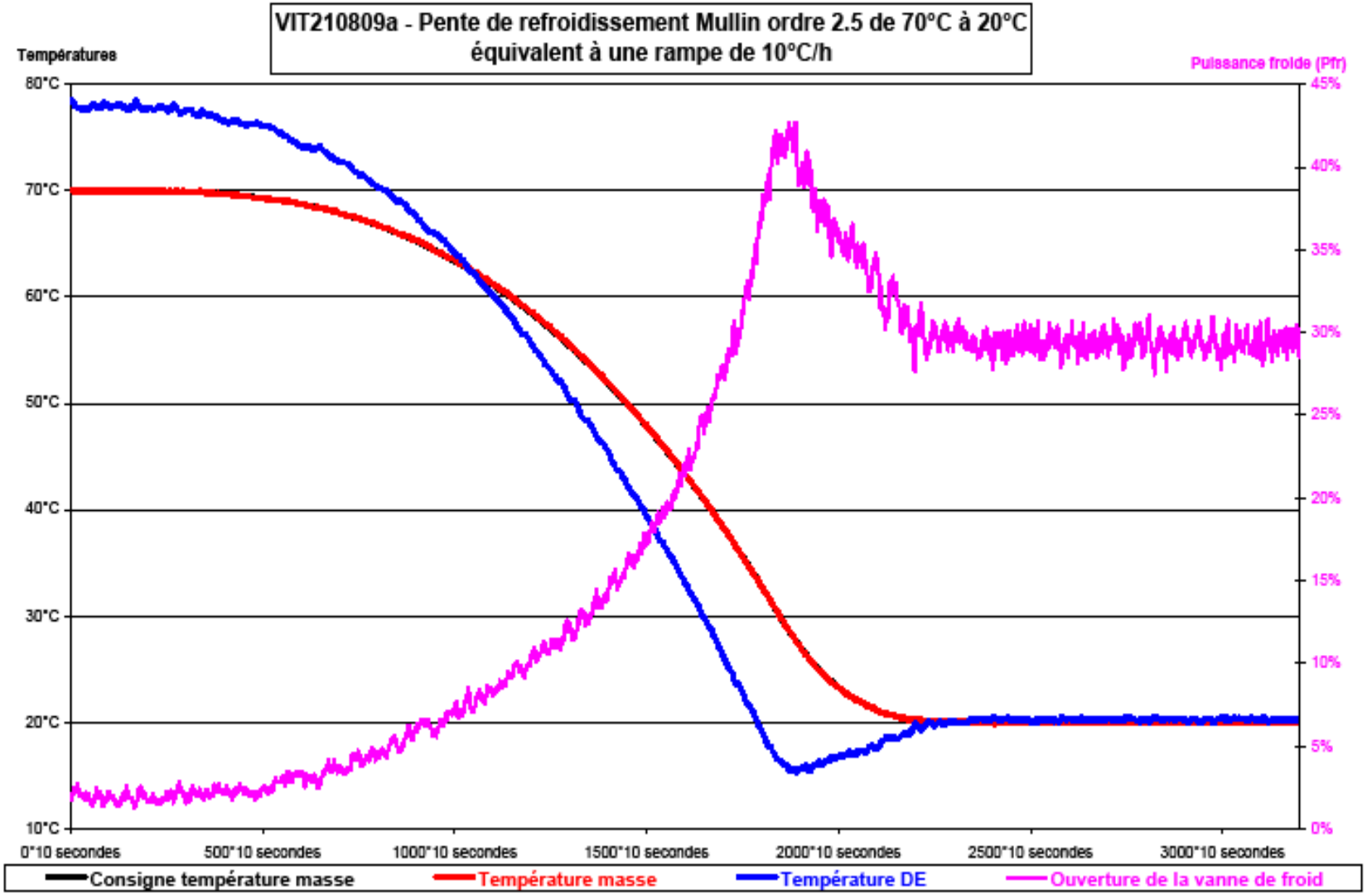
- **Accuracy depends on the choice of the functional basis and not on the "gain" of the controller….**

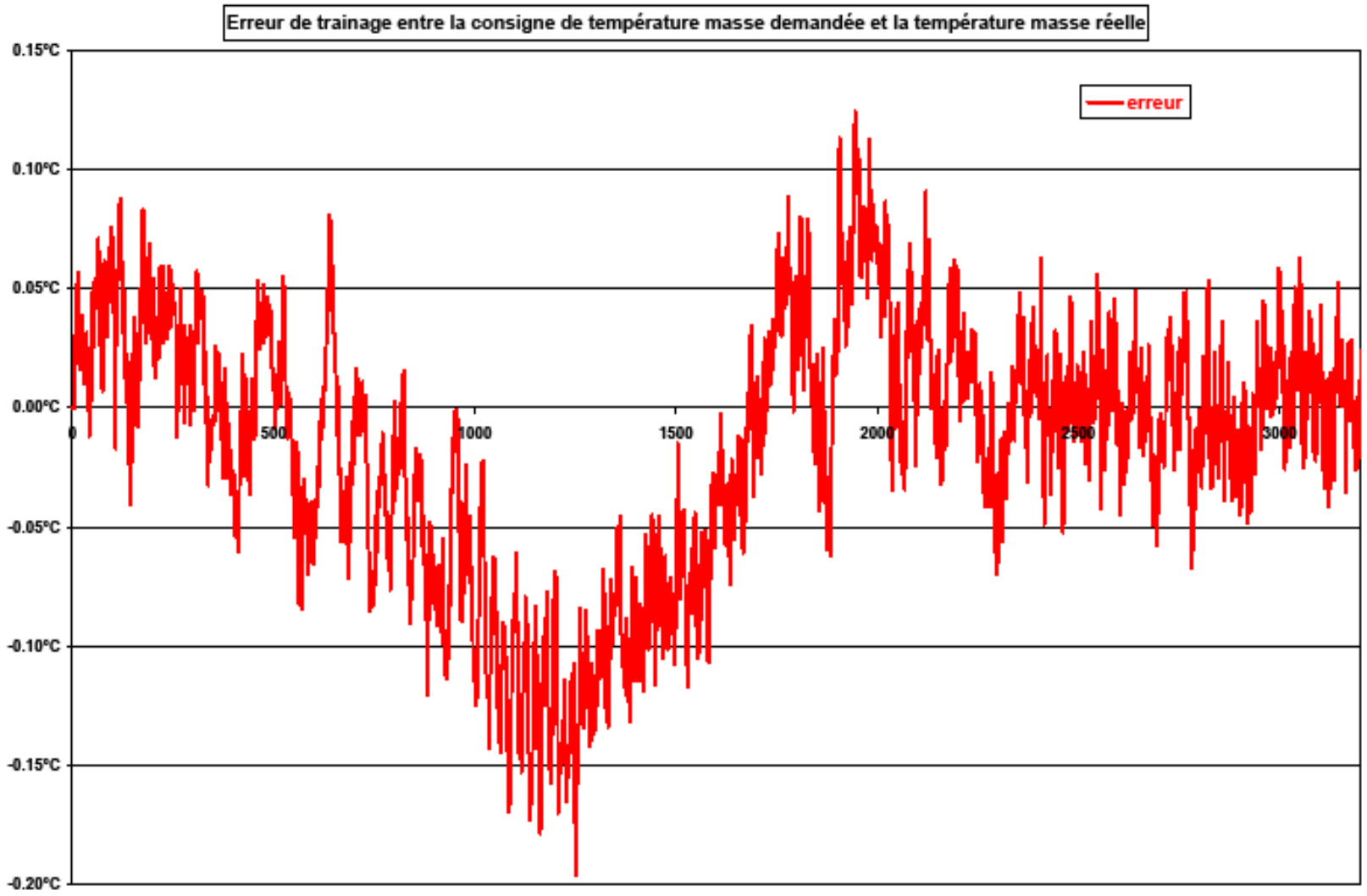
Let us take an exemple !

- 95% of pharma drugs are crystals !
- According to Professor's Mullin's theory the temperature time profile during crystalisation should be close to a cubic function !

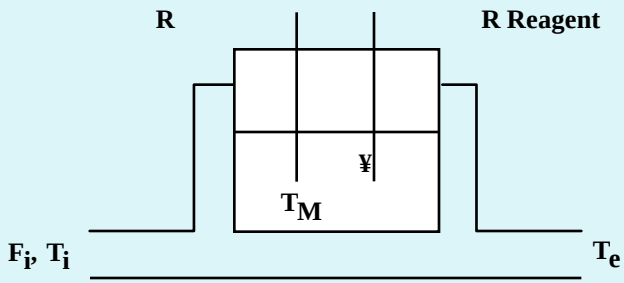
Challenge .. !

SANOFI : 6 production plants > 1200 PFC installed in different control PLC's


VIT210809a - Pente de refroidissement Mullin ordre 2.5 de 70°C à 20°C
équivalent à une rampe de 10°C/h
Températures
Puissance froide (Pfr)
80°C
70°C
60°C
50°C
40°C
30°C
20°C
10°C
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
0*10 secondes
500*10 secondes
1000*10 secondes
1500*10 secondes
2000*10 secondes
2500*10 secondes
3000*10 secondes
Consigne température masse
Température masse
Température DE
Ouverture de la vanne de froid


Erreur de trainage entre la consigne de température masse demandée et la température masse réelle
erreur
0.15°C
0.10°C
0.05°C
0.00°C
-0.05°C
-0.10°C
-0.15°C
-0.20°C
0
500
1000
1500
2000
2500
3000

4 CONTROL STRATEGIES OF BATCH REACTORS



$$r_M C_{PM} V_M \frac{dT_M}{dt} = UA\left(T_e - T_M\right) + DHx$$

$$r_e C_{Pe} V_e \frac{dT_e}{dt} = r_e F_i \left(T_i - T_e\right) + UA\left(T_M - T_e\right)$$

$$\boxed{q(F_i)\,\dot{T}_M + T_M = \overrightarrow{T_i}}$$

1) Fi =ct /MV= Ti CV=TM / level 0 =Ti ? :PFC

2) Ti =ct (!) MV=Fi Parametric Control non linear :PPC

3) MV : Ti and Fi : Enthaplic control (power) :PPC+

4) MV : Pressure of reactor :PFC

The Tea Pot theory

- **Heat transfer with heat loss ?:**
- **What to do ?**

« To heat up slowly during a long time

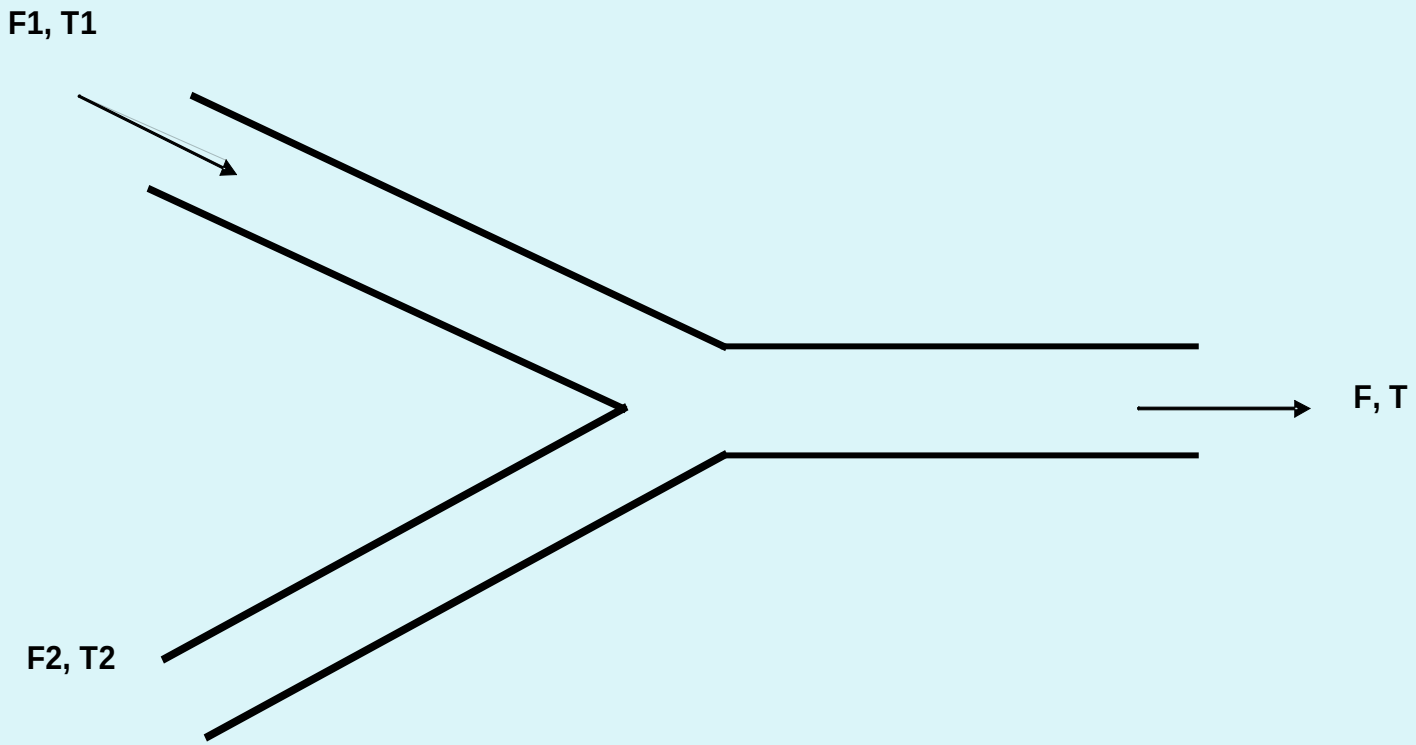
or

abruptly during a short time «

- **« Energy consumption is minimum**

if Power is maximum »

Convexity Theorem



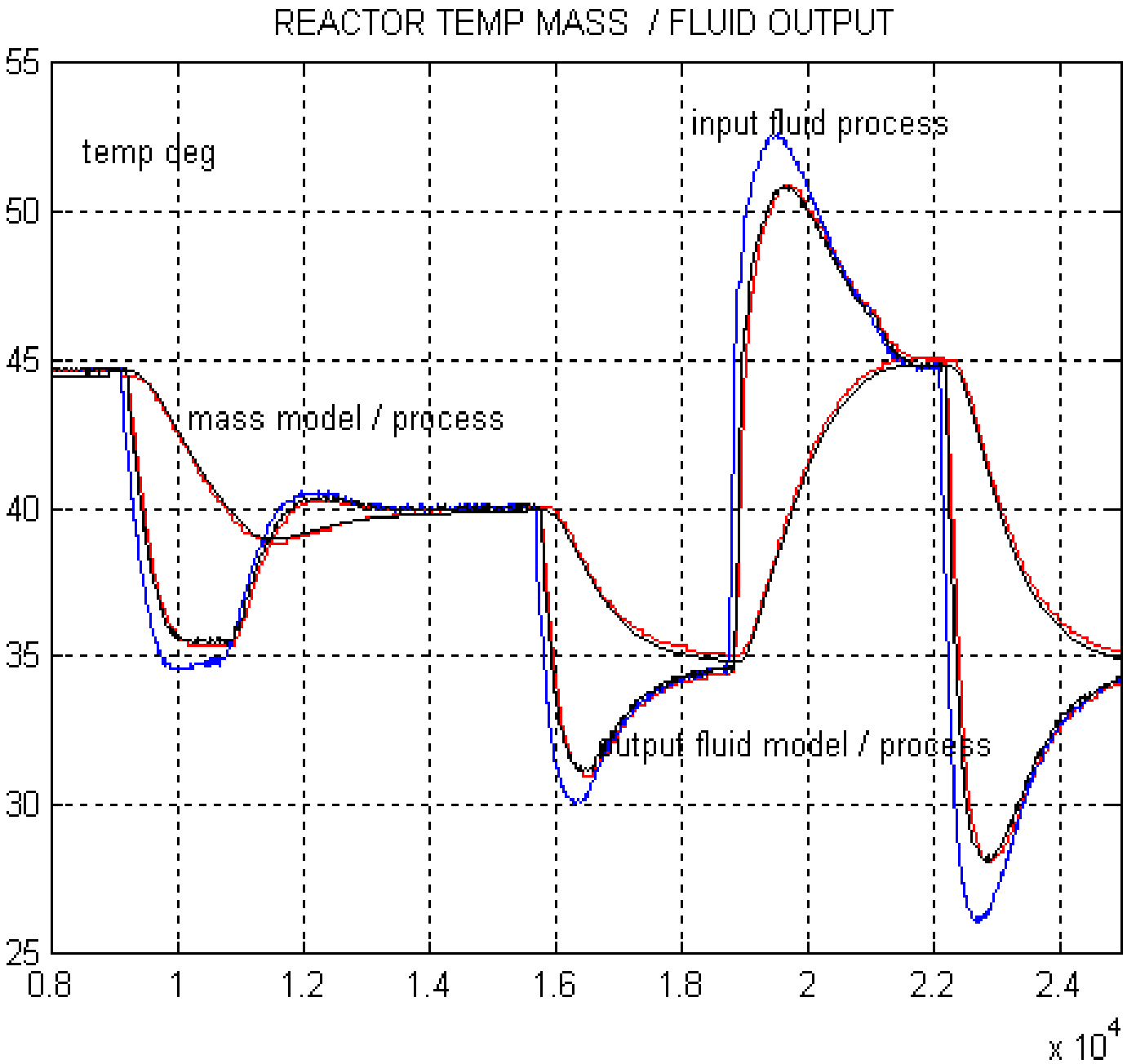
$$F.T = F1.T1 + F2.T2 \qquad T = \lambda.T1 + (1-\lambda).T2$$

$$\lambda = F1/(F1+F2) \quad 0 \le \lambda \le 1$$ **Hyperbolic function**

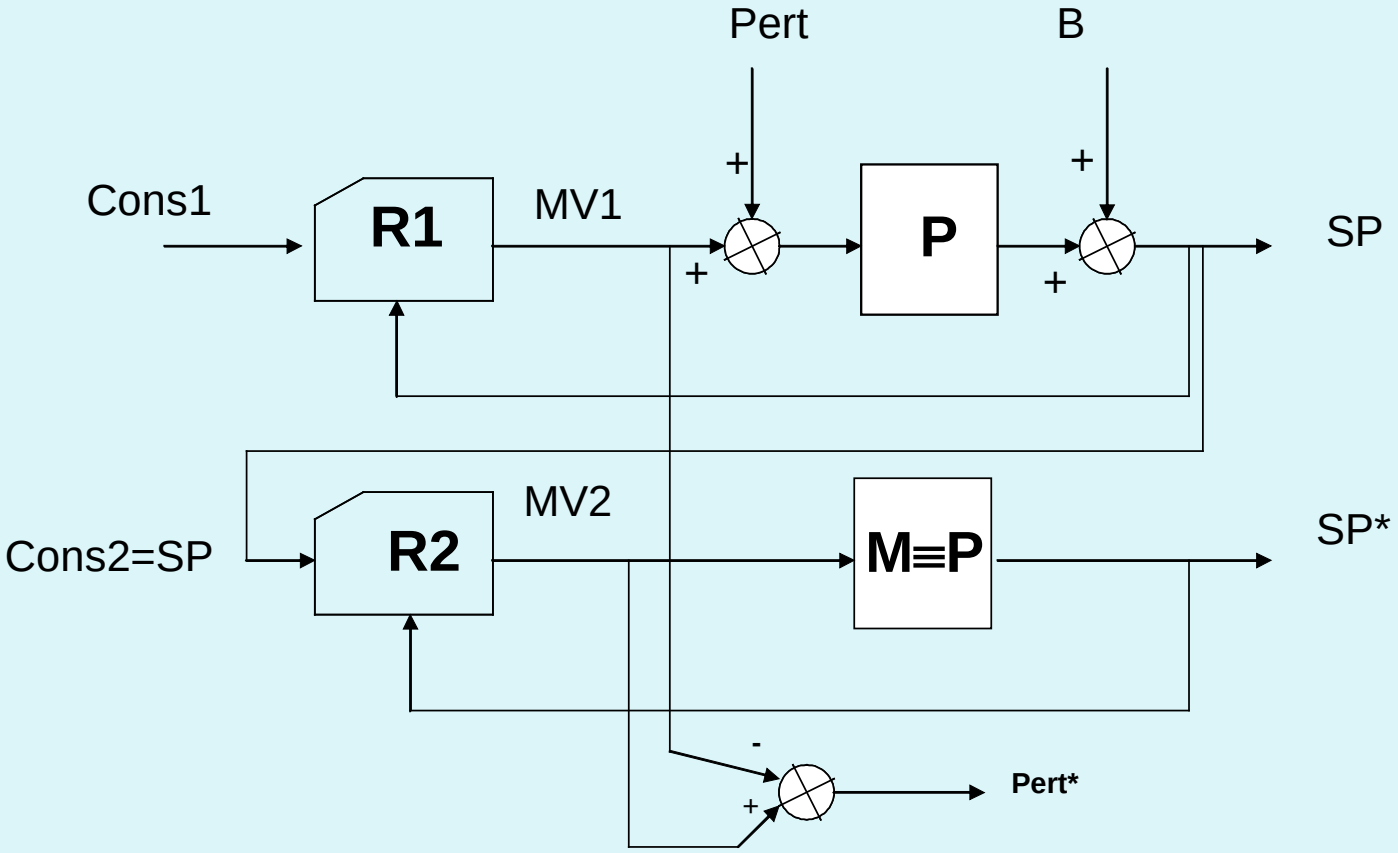
$$\Gamma(\mathbf{Qf}) = \frac{1 - \exp[-\mathbf{U.A}(\frac{1}{\mathbf{Fp}} - \frac{1}{\mathbf{Ff}})]}{1 - \frac{\mathbf{Fp}}{\mathbf{Ff}}\exp[-\mathbf{U.A}(\frac{1}{\mathbf{Fp}} - \frac{1}{\mathbf{Ff}})]}$$

Fp, Ff : Thermal flows

$Fp = (\rho.Cp)_p.Qp$ $\quad$ $Ff = (\rho.Cp)_f.Qf.$


REACTOR TEMP MASS / FLUID OUTPUT
temp deg
input fluid process
mass model / process
output fluid model / process
55
50
45
40
35
30
25
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
x 10^4

EXOTHERMICITY ESTIMATOR
by Global estimator



STRUCTURE and STATE DISTURBANCES

- On line global estimator: an example!

DV (n) = actual disturbance

DV*(n) = estimated disturbance

Gp = 1/ gain of process

Gm = 1/ gain of model (same dynamics…)

DV* (n)= DV(n) +Setpoint.(Gm-Gp)

State and structure mismatches in the same equation !

BAYER

$Vm = 42.3\ m^3$

$F = 250 m^3/H$ $A = 85\ m^2$ $U = 450\ W/m^2/K$

NUT =.135

$\Theta_s = 610$ sec $\tau m = 5370$ sec

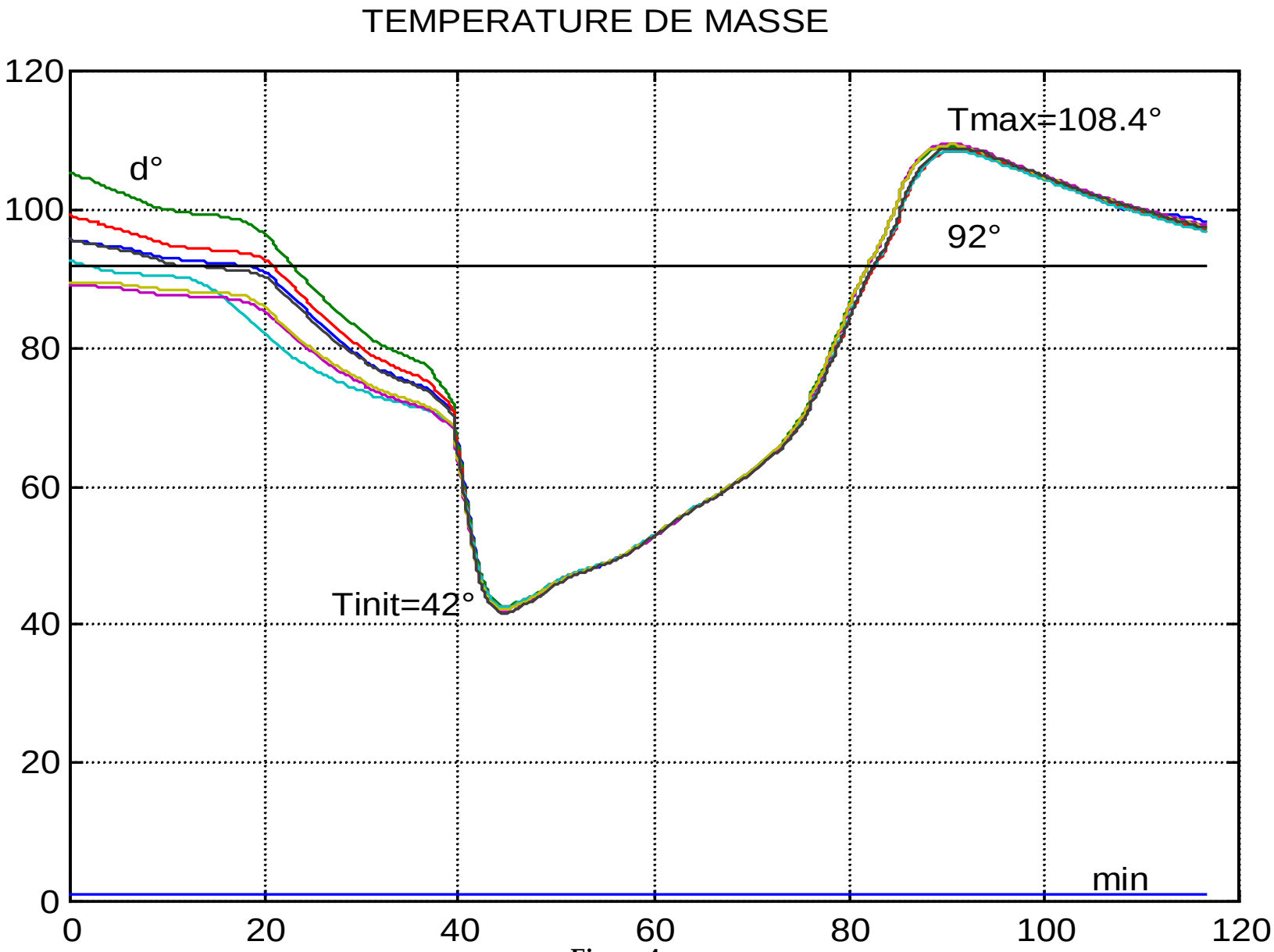

TEMPERATURE DE MASSE
120
100
80
60
40
20
0
0
20
40
60
80
100
120
d°
Tmax=108.4°
92°
Tinit=42°
min

Figure 4

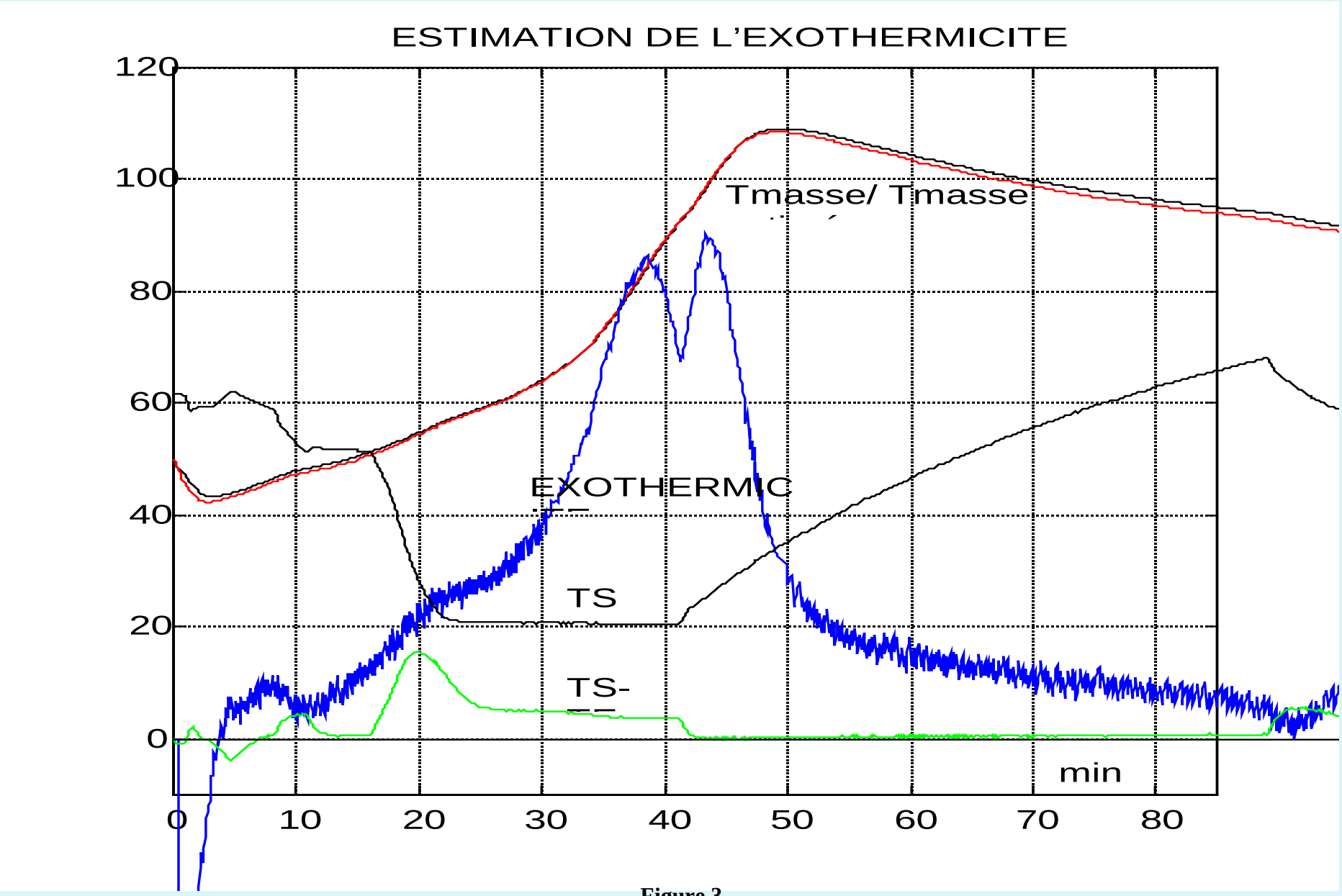

ESTIMATION DE L'EXOTHERMICITE
120
100
80
60
40
20
0
Tmasse/ Tmasse
EXOTHERMIC
TS
TS-
min
0
10
20
30
40
50
60
70
80

Figure 3

SANOFI PHARMA

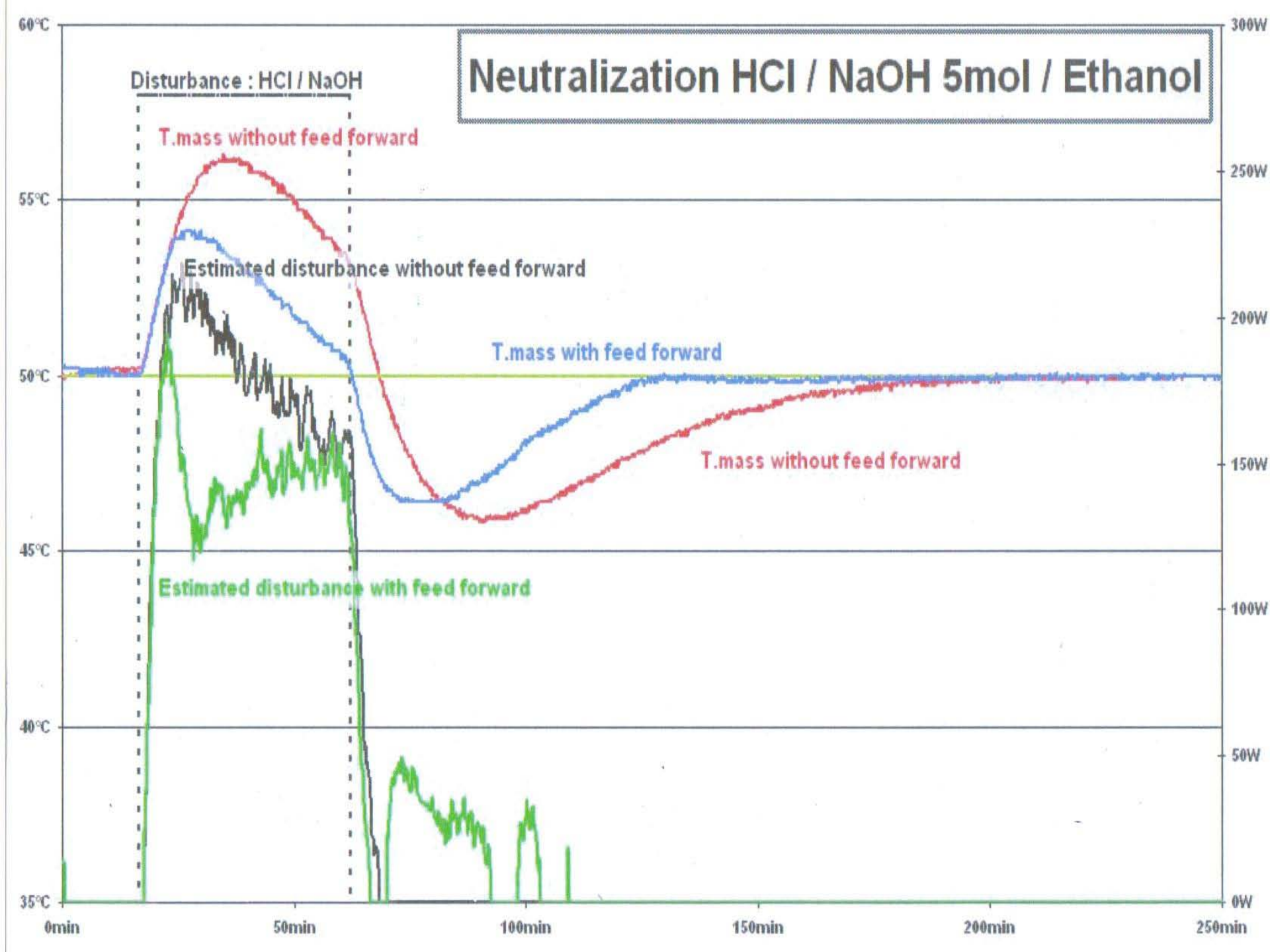
NEUTRALISATION WITH ON LINE ESTIMATOR OF EXOTHERMICITY TAKEN INTO ACCOUNT A S A FEED FORWARD VARIABLE

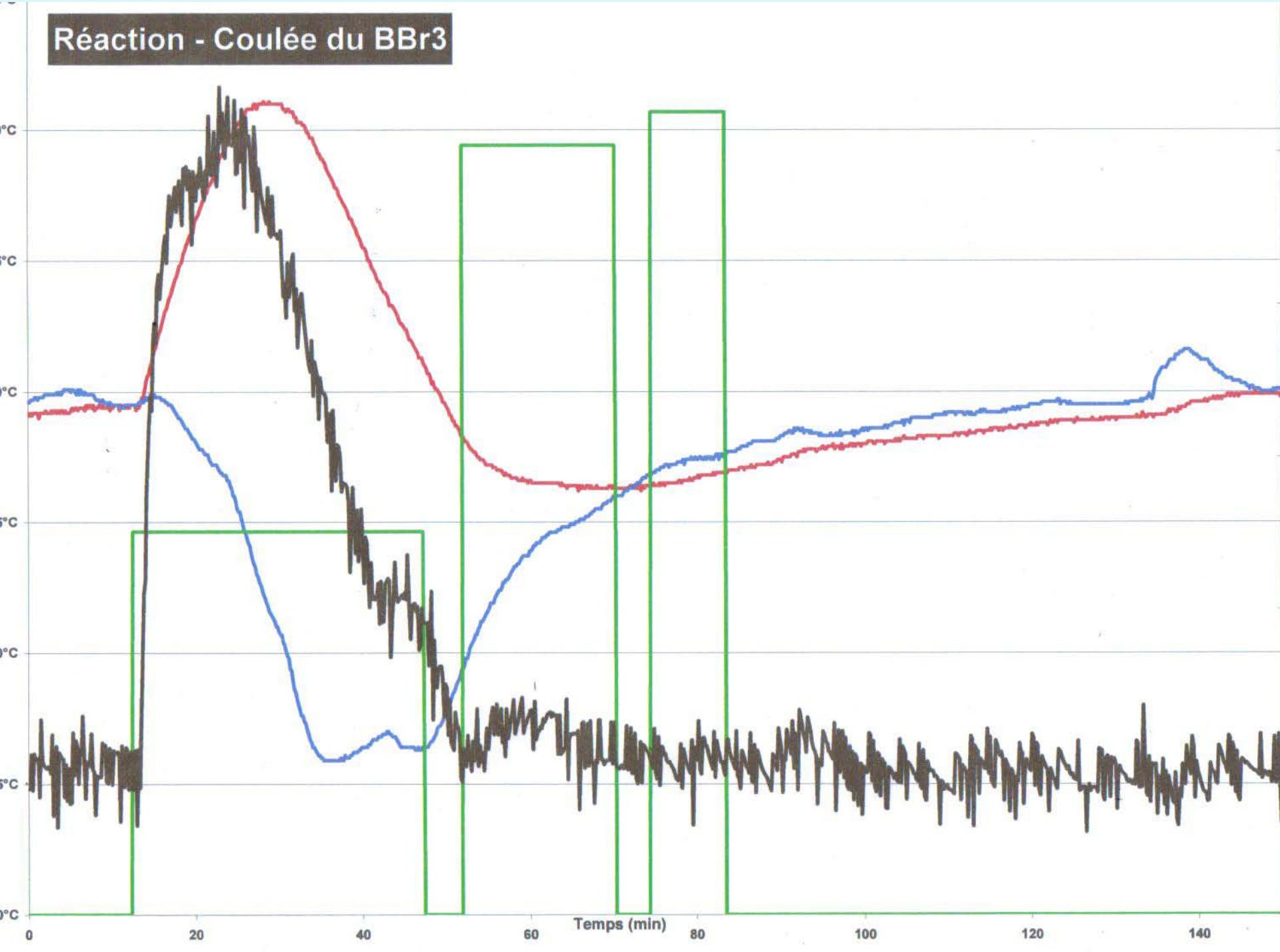
2 CONTROLLERS ARE ACTIVE:

- **ONE TO CONTROL THE TEMPERATURE … AS USUAL…**

- **ONE TO CONTROL THE REACTION ACTIVITY MEASURED BY THE ON LINE ESTIMATOR OF POWER ACTING ON THE FLOW OF REACTANT……..**

soft sensor…!


Neutralization HCl / NaOH 5mol / Ethanol
Disturbance : HCl / NaOH
T.mass without feed forward
Estimated disturbance without feed forward
T.mass with feed forward
T.mass without feed forward
Estimated disturbance with feed forward
60°C
55°C
50°C
45°C
40°C
35°C
300W
250W
200W
150W
100W
50W
0W
0min
50min
100min
150min
200min
250min

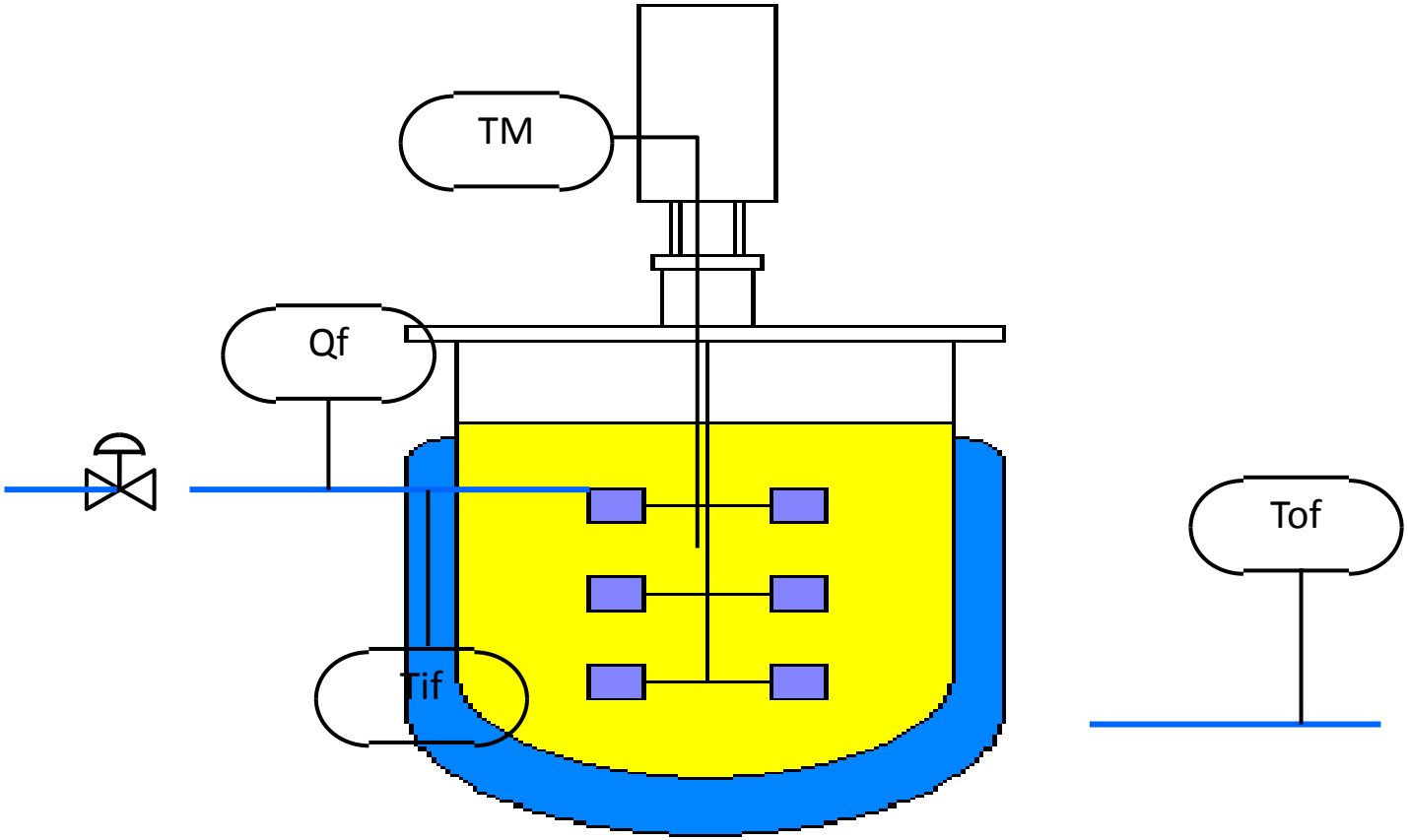

Réaction - Coulée du BBr3
°C
°C
°C
°C
°C
°C
°C
0
20
40
60
Temps (min)
80
100
120
140

PFC / PPC :DEGUSSA EVONIC

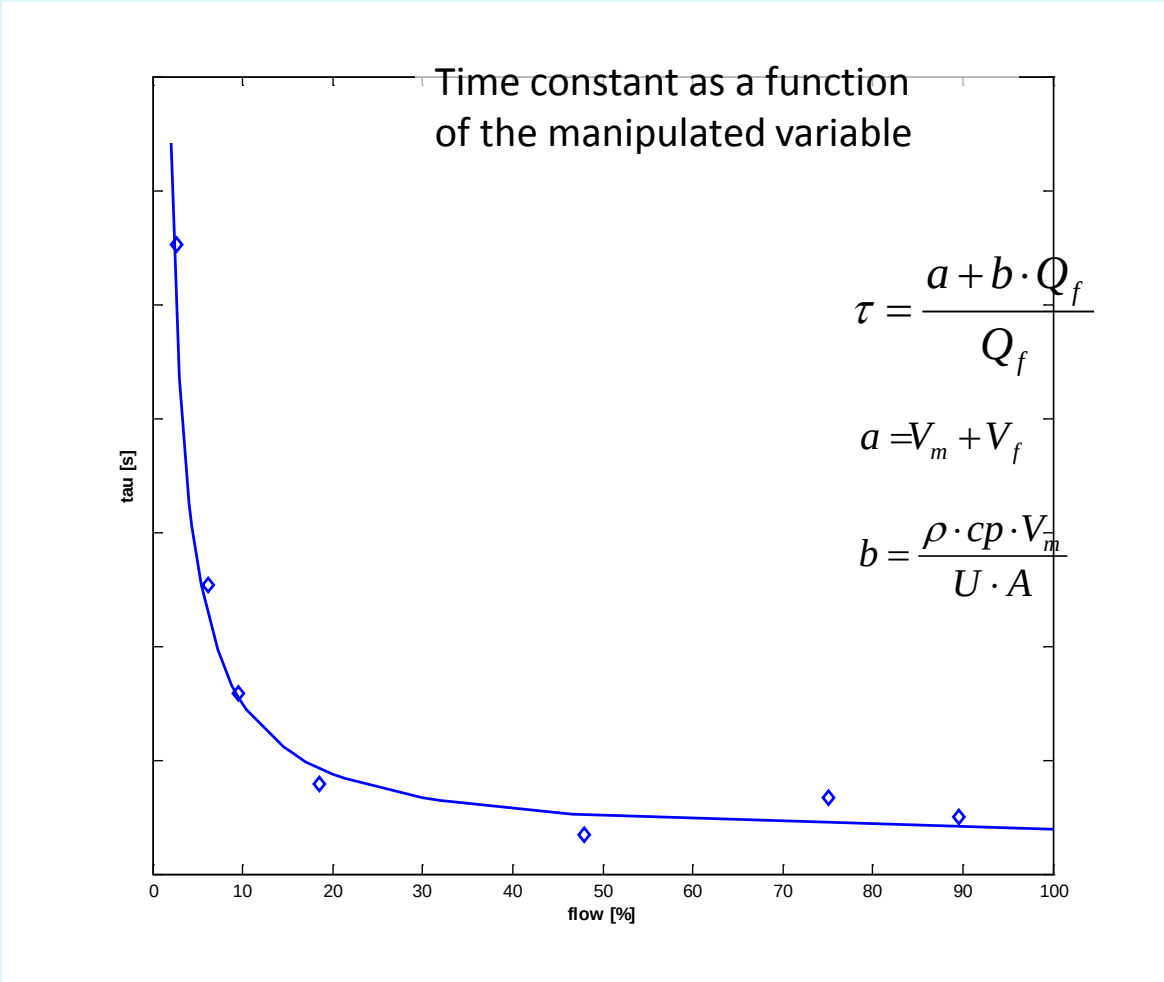
- **Esterification : Batch time reduced approx. 10%**
- **Polymerisation: Time duration 15% shorter**
- **Quality .Reproducability increased**
- **Less energy consumption**
- **Implemented in all types of PLCs**

01/12/2011 > 300 processes in several plants in different countries

Batch Reactor Control by Jacket flow as MV



Identification of characteristics



$$\tau = \frac{a + b \cdot Q_f}{Q_f}$$

$$a = V_m + V_f$$

$$b = \frac{\rho \cdot cp \cdot V_m}{U \cdot A}$$

Q_f: flow

V_m: mass volume

V_f: jacket volume

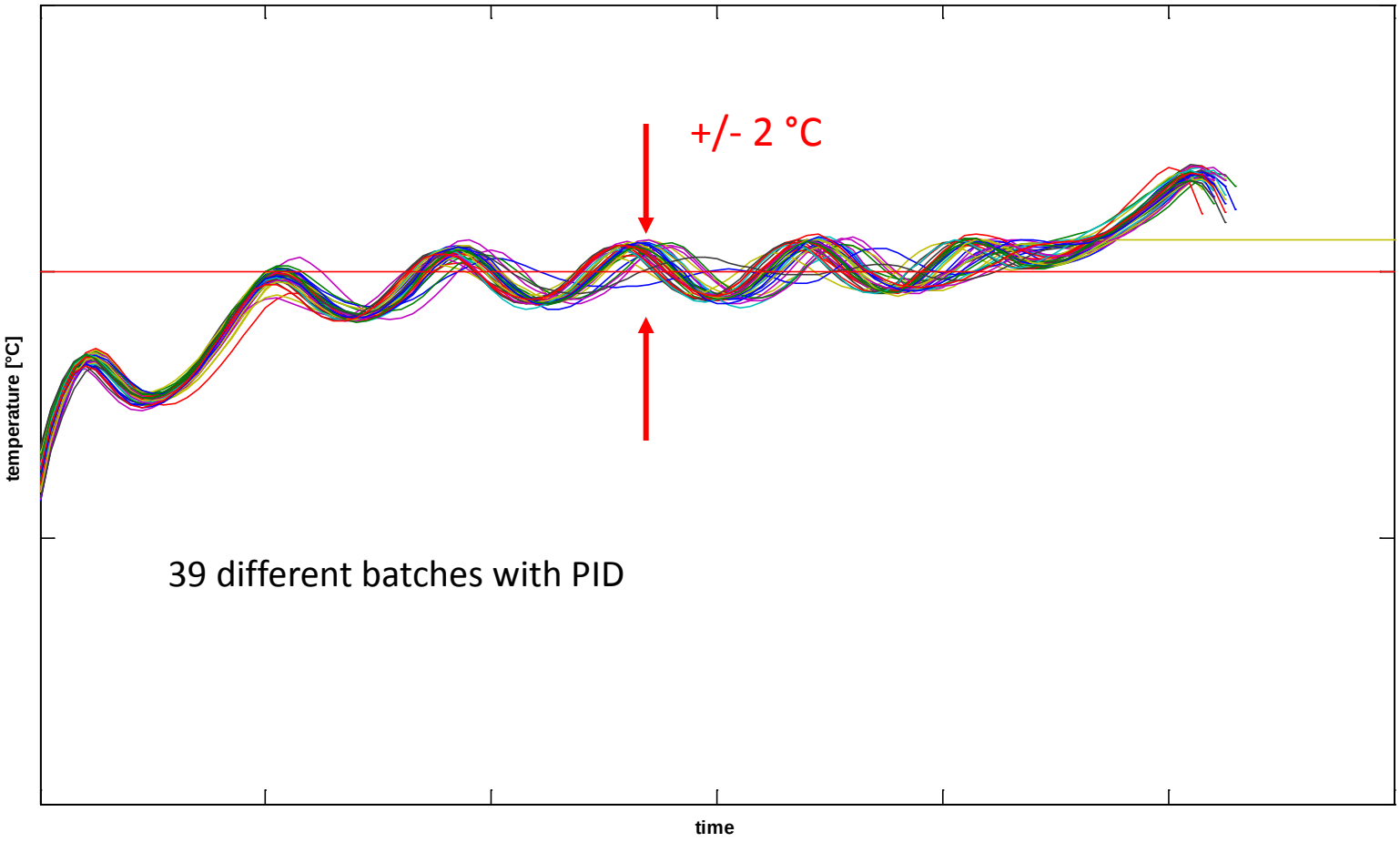
r: density

cp: heat capacity

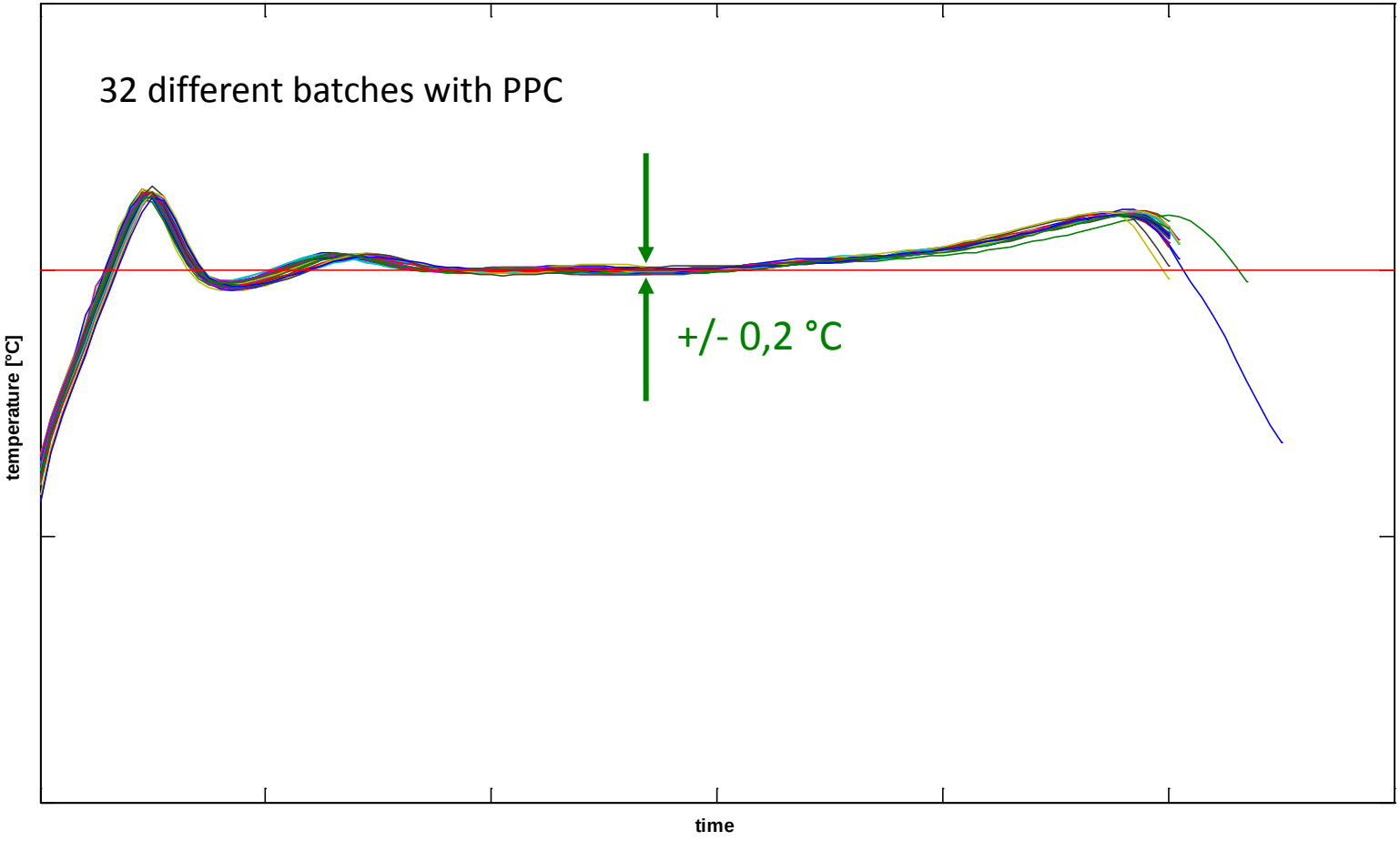
U: constant

A: heat transfer surface

Control with PID



Process control with PPC



ARCELOR.MITTAL

Continuous casting

. Level control :

.Known as a difficult and dangerous process

.Harmonic swell of steel in the extraction cooling section called « Bulging »

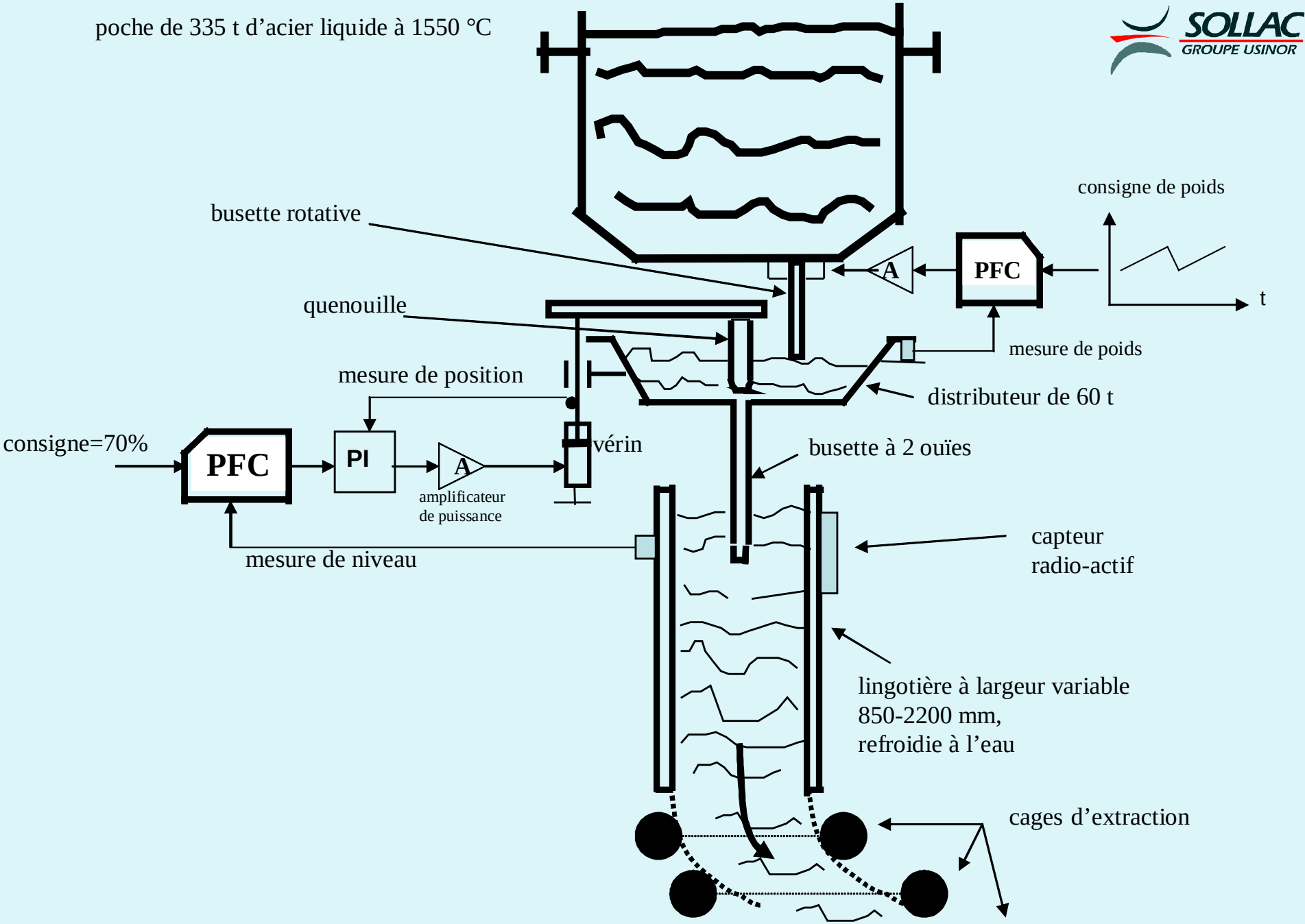
.Solution:

.Implementation of complex algebra in the PLC

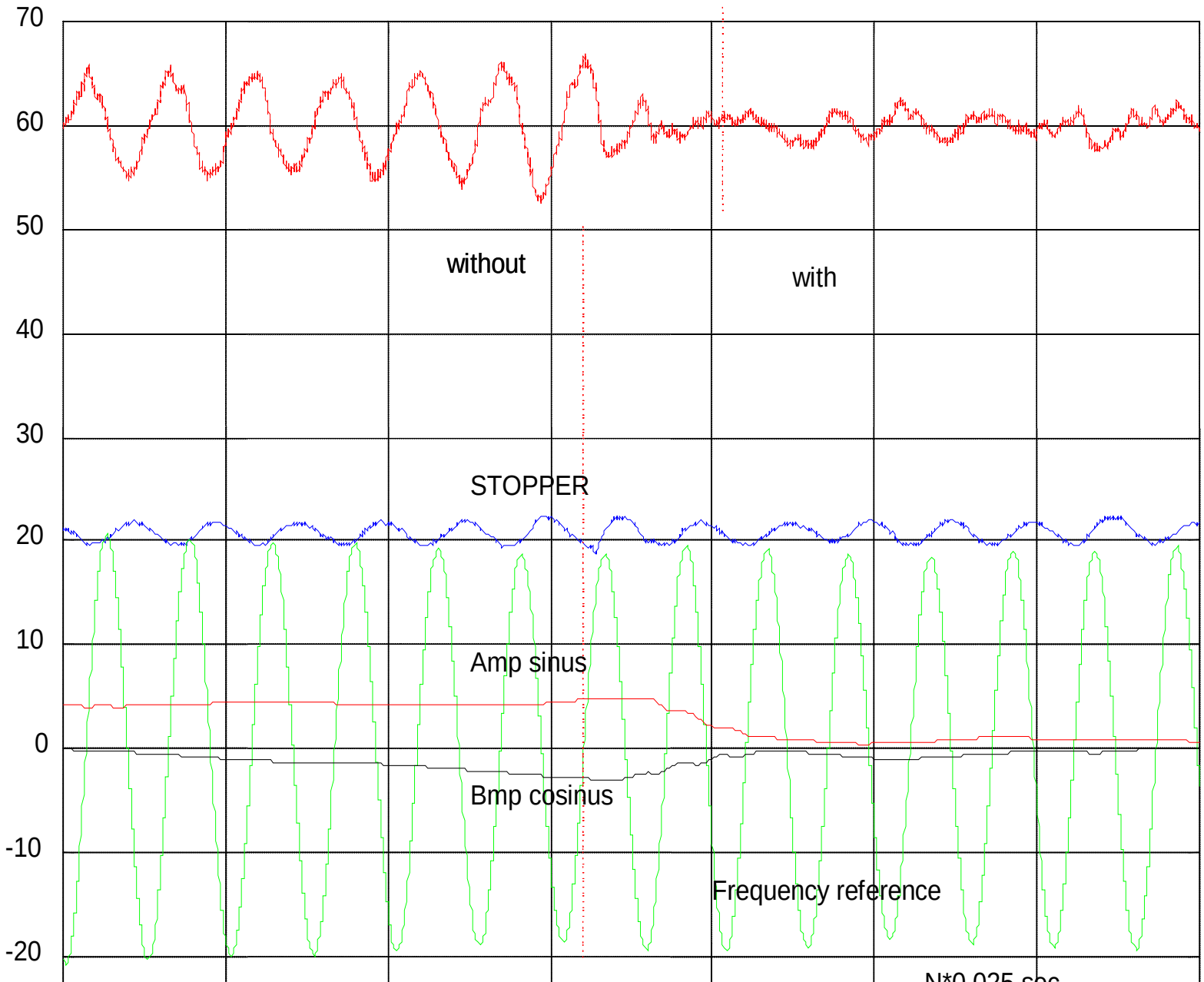
.to control with only one « complex PFC » the

.sinusoidal disturbance .!

.Simplification of the controller …


poche de 335 t d'acier liquide à 1550 °C
busette rotative
quenouille
mesure de position
consigne=70%
PFC
PI
A
amplificateur
de puissance
vérin
mesure de niveau
A
PFC
consigne de poids
t
mesure de poids
distributeur de 60 t
busette à 2 ouïes
capteur
radio-actif
lingotière à largeur variable
850-2200 mm,
refroidie à l'eau
cages d'extraction

BULGING COMPLEX CONTROL

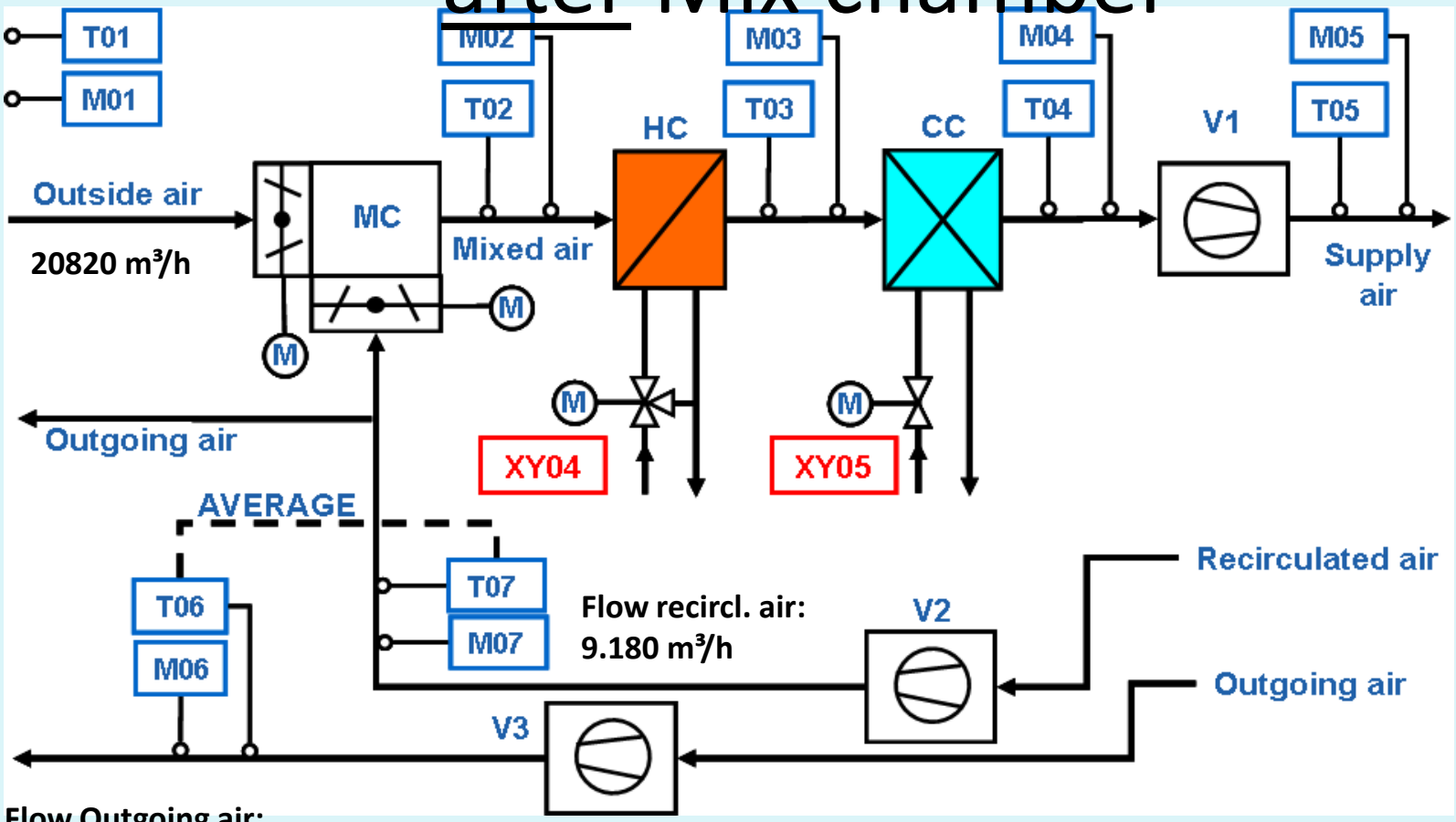


Teaching Control in Technical schools

- **39 Technical schools in France**
- ≠ 660 Young technicians per year
- PFC was taught to 23 profs of Tech. schools
- Lectures and laboratory works on PLCs and laboratories processes.
- The first 125 young technicians went out to industry in 2007, completely at ease with PFC…
- **22 profs of German Fachhochschule were trained on PFC in 2009**

THANK YOU FOR YOUR ATTENTION

Scheme AHU LT22: Treatment of Air after Mix chamber



Flow Outgoing air:
18.580 m³/h

Flow fresh air: 20.000 m³/h??? Flow recirculated air : 10.000 m³/h???