Introduction to the assessment of thermal process safety

Module 2
ENG 431: Safety of chemical Processes

Annik Nanchen

Content Module 2

- Thermal Risks
  - Heat Balance
  - Failure Scenario

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WILEY-VCH
Thermal Safety of Chemical Processes
Risk Assessment and Process Design

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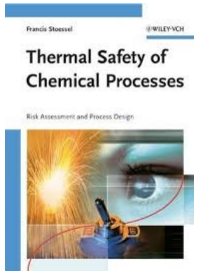
Risk Assessment and Process Design
Second, Completely Revised and Extended Edition

Chapters 2 and 3

- Criticality

- Assessment Procedure

- Assessment of the energy potential
  - Energy
  - Pressure



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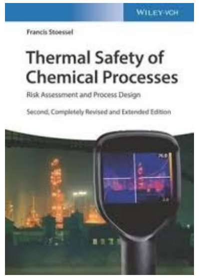
Chapter 2



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Chapters 2 and 5

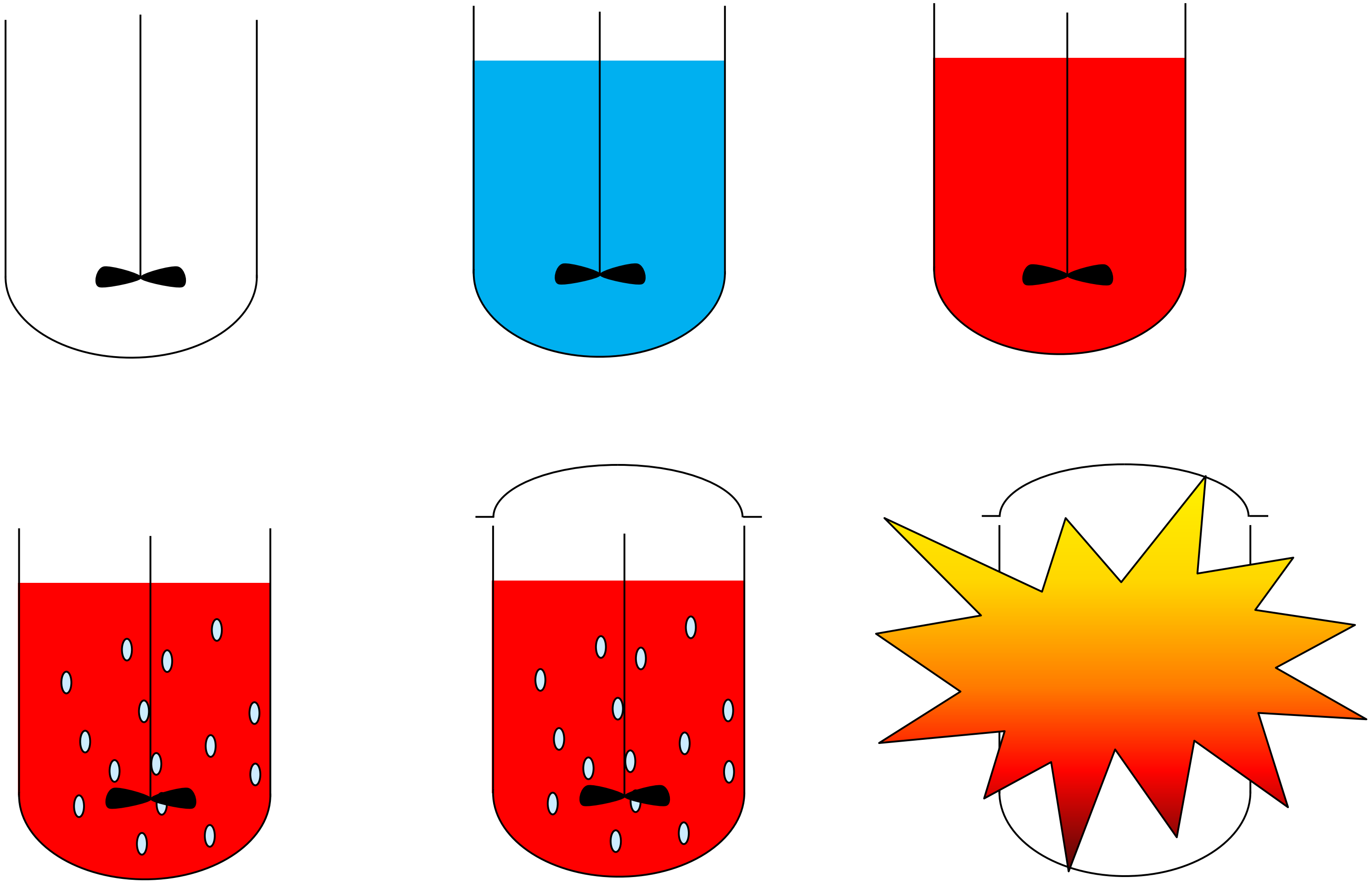
Potential hazard

- Exothermic reaction
  - Heat produced must be removed
  - Otherwise Temperature increase
  - At higher temperatures, secondary reactions
  - Boiling point: vapour produced

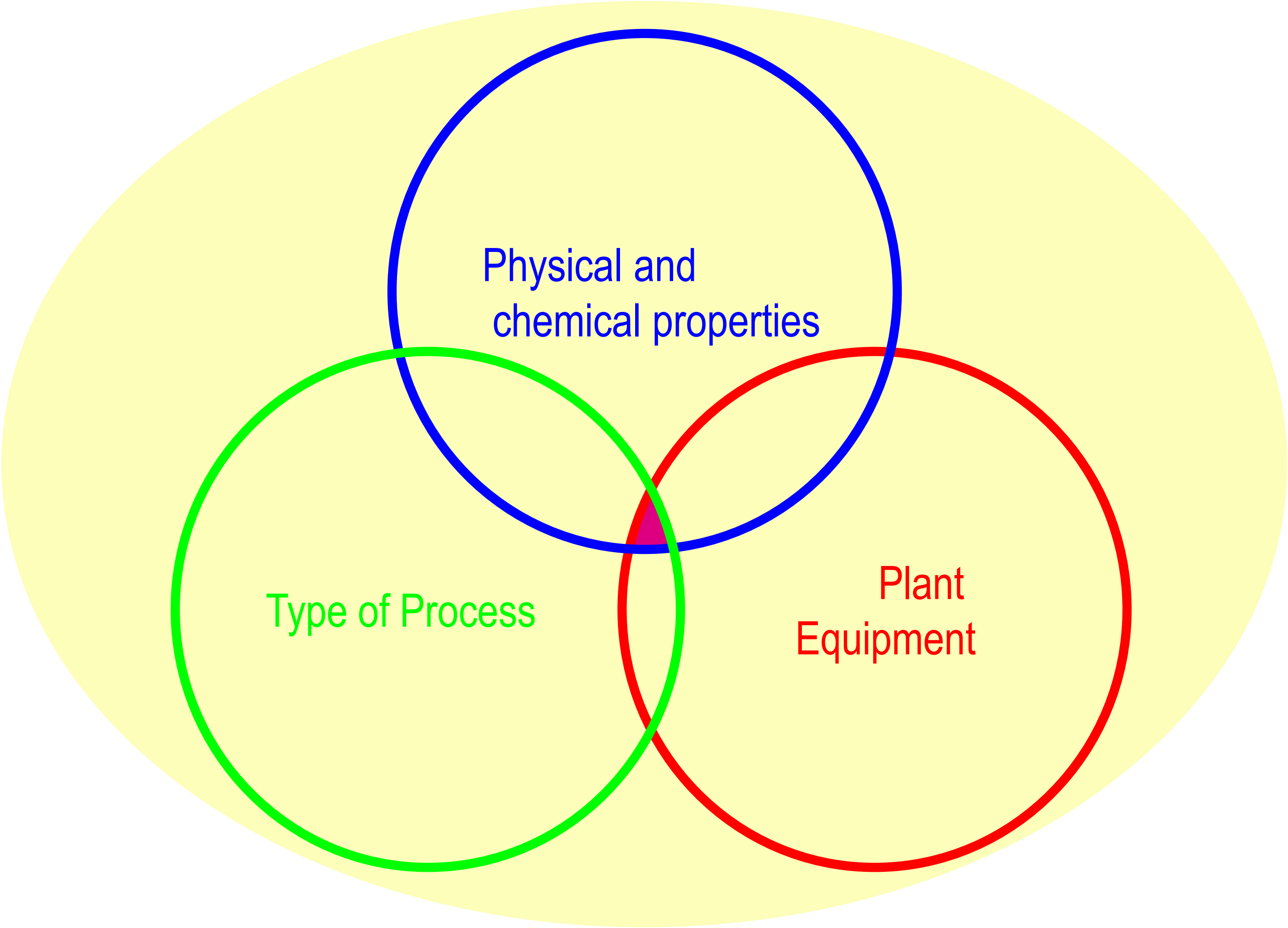
- Secondary reactions:
  - Heat production
  - Gas production

- Hazard: thermal runaway

Accidents - Hazard



Assesment of Thermal Process Safety



Content Module 2

- Video/ introduction to the hazard
- Thermal Risks
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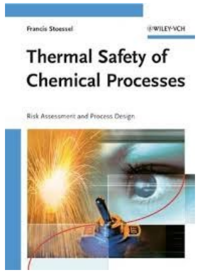

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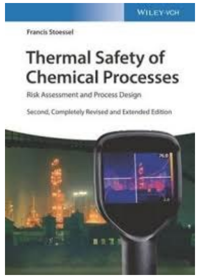

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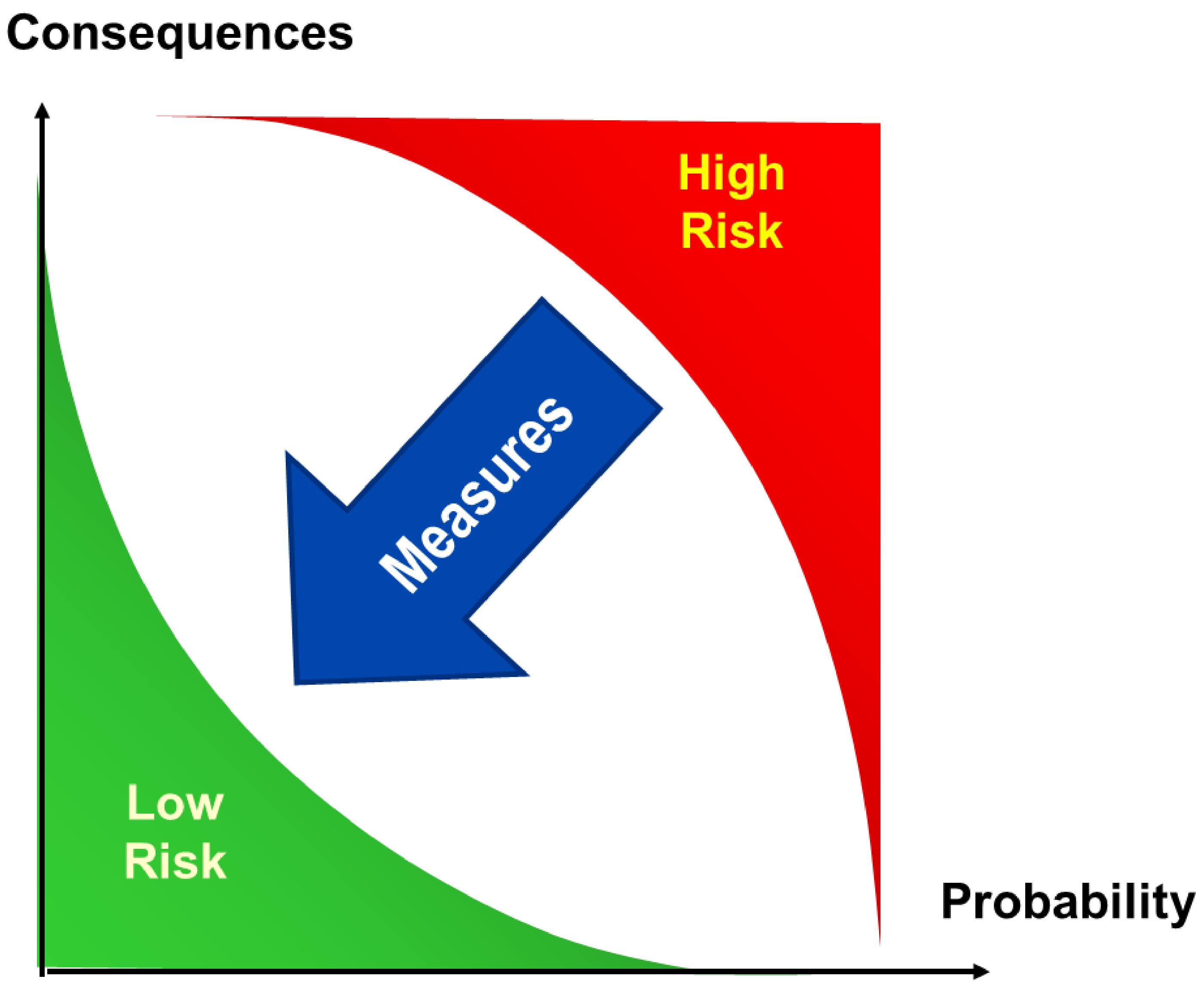
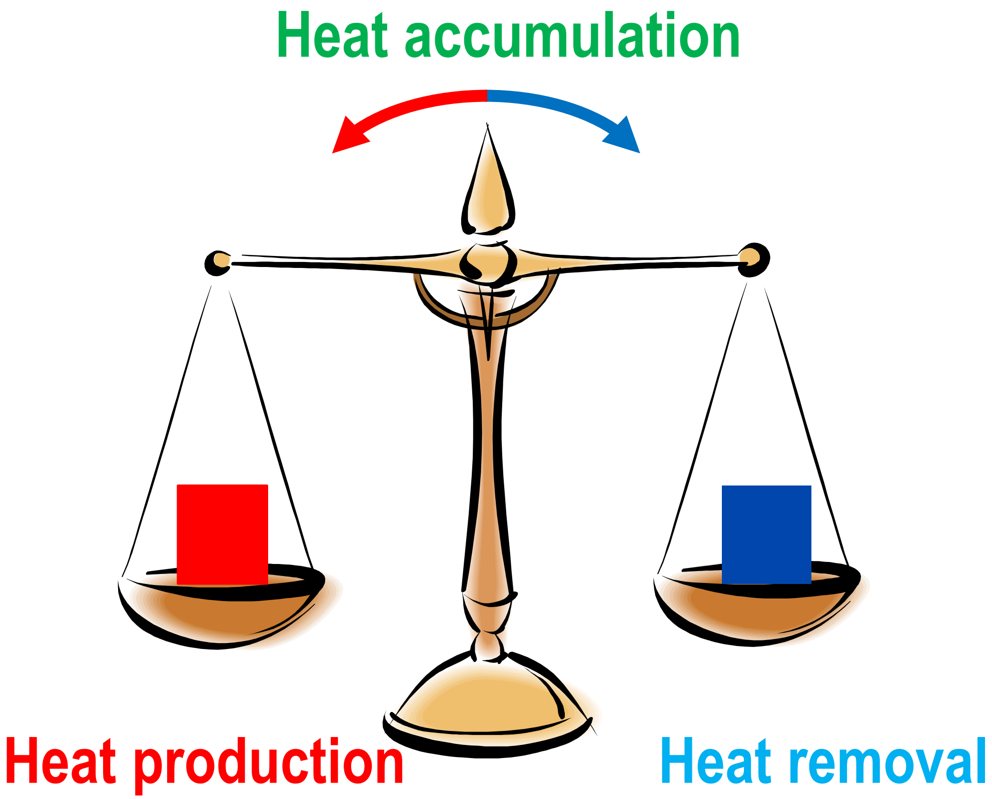
Chapters 2 and 3

Risik-Diagram



Effect of Scale on Heat Balance



$$\frac{dT}{dt} = k(1-X_A)^n c_{A0}^{n-1}\Delta T_{ad} - \frac{UA(T-T_C)}{\rho V c'_p}$$

T: temperature	K
t: time	s
k: rate constant	$s^{-1}mol^{1-n}\,l^{n-1}$
X: conversion	-
n: order of the reaction	-
c_{A0}: starting concentration of A	mol/l
ΔT_{ad}: adiabatic temperature rise	K or °C
U: heat transfer coefficient	$W/(m^2 \cdot K)$
A: heat exchange area	m^2
Tc: temperature cooling media	K
ρ: density	kg/l
c'_p: specific heat capacity	$J/(kg \cdot K)$
V: volume	l

Heat Balance

$$q_{acc} = M \cdot c'_P \cdot \frac{dT}{dt} = q_{rx} - q_{ex}$$

$$q_{rx} = k_0 \cdot e^{-E/RT} \cdot C_0 (1 - X) \cdot V \cdot (-\Delta H_r)$$

1st order reaction

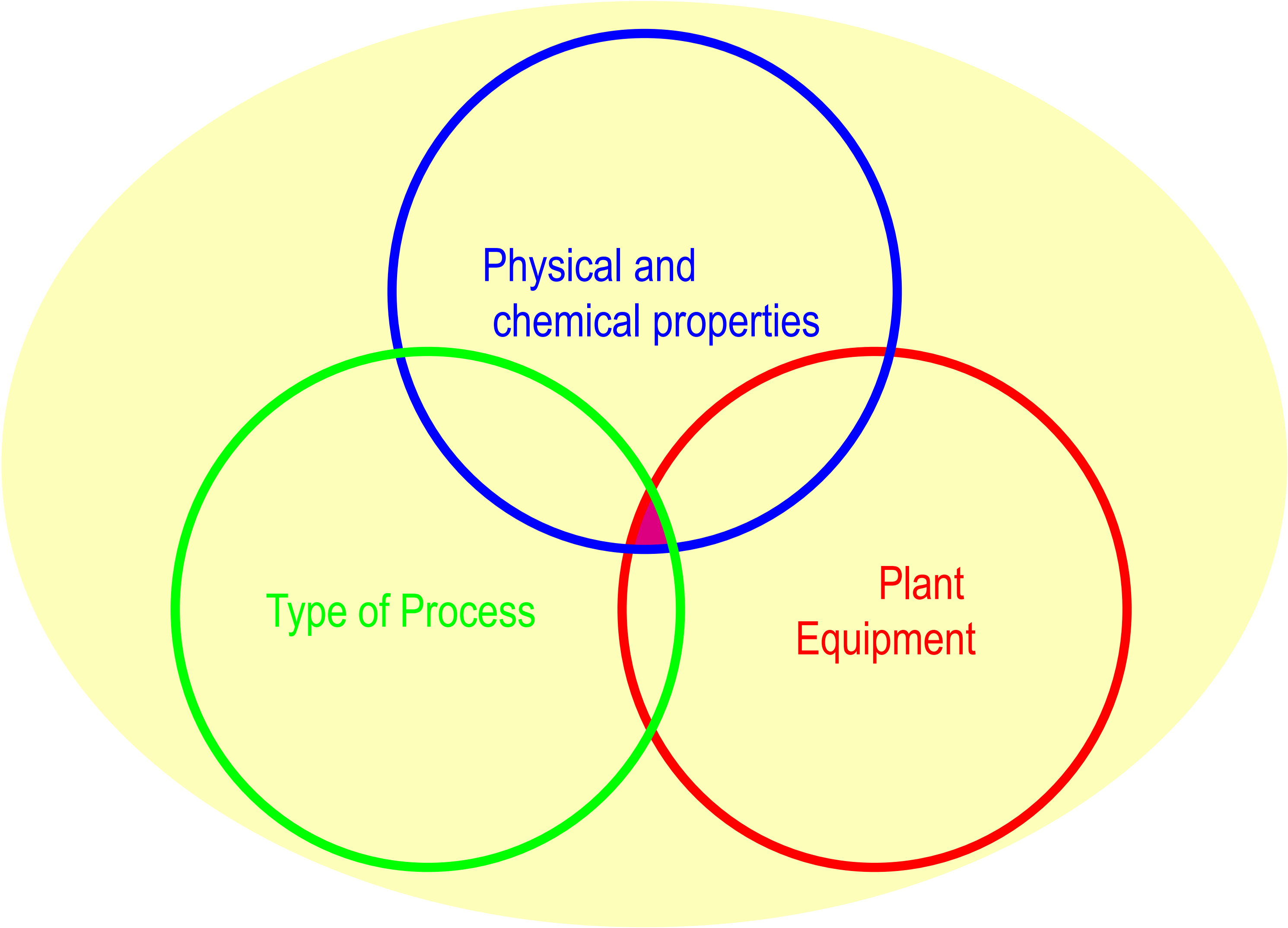
$$q_{ex} = U \cdot A \cdot (T - T_c)$$

acc: accumulation
rx: reaction
ex: exchange

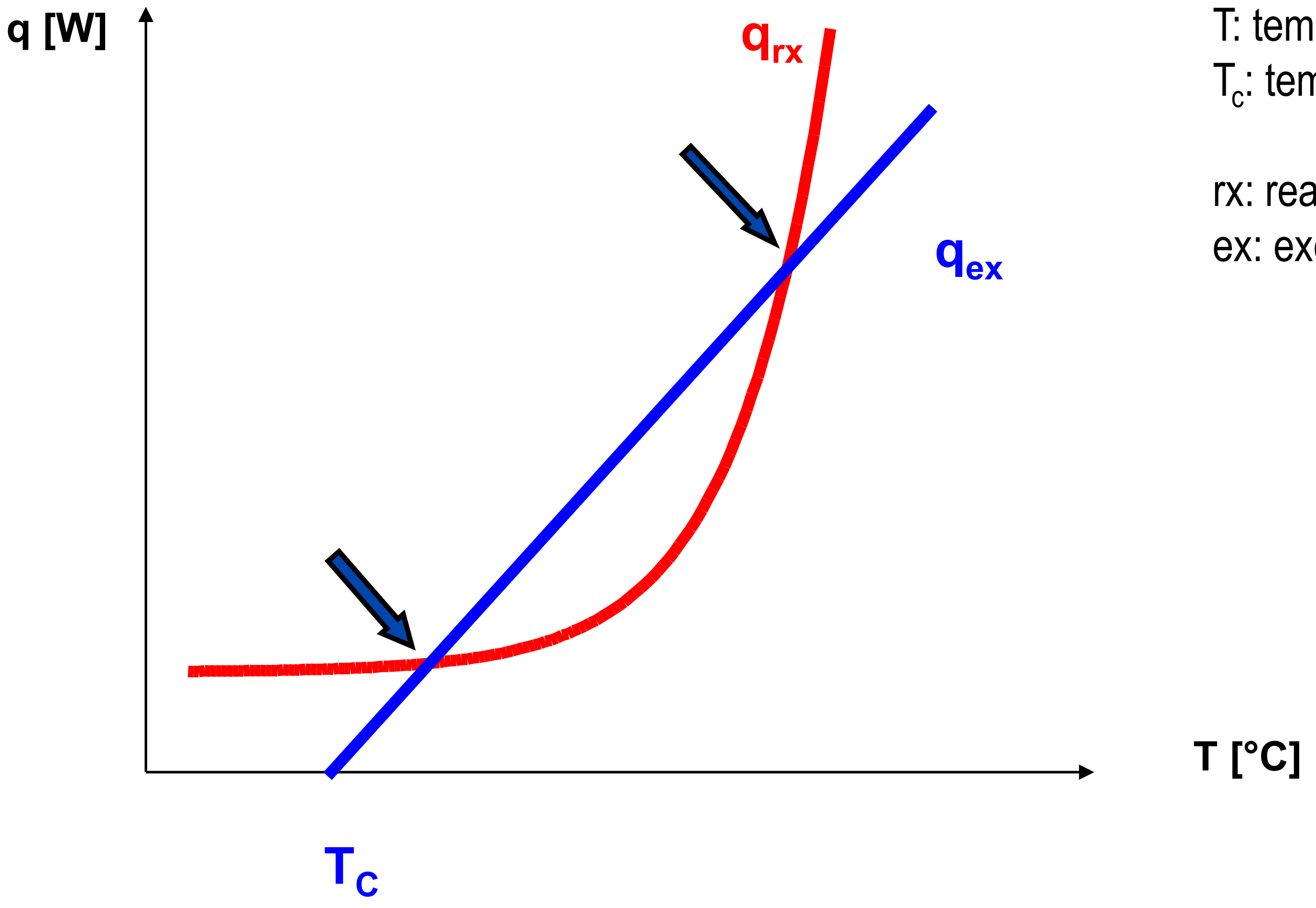
q: heat flow	W
M: mass	kg
c'_p: specific heat capacity	J/(kg·K)
T: temperature	K

t: time	s
k_0: pre-exponential factor	s^{-1}
E: activation energy	J/mol
c: concentration	mol/l
X: conversion	-
V: volume	l
ΔH_r: molar reaction enthalpy	J/mol
U: heat transfer coefficient	W/(m^2·K)
A: heat exchange area	m^2
T_c: temperature cooling media	K

Assesment of Thermal Process Safety



Semenov-Plot – normal operating conditions

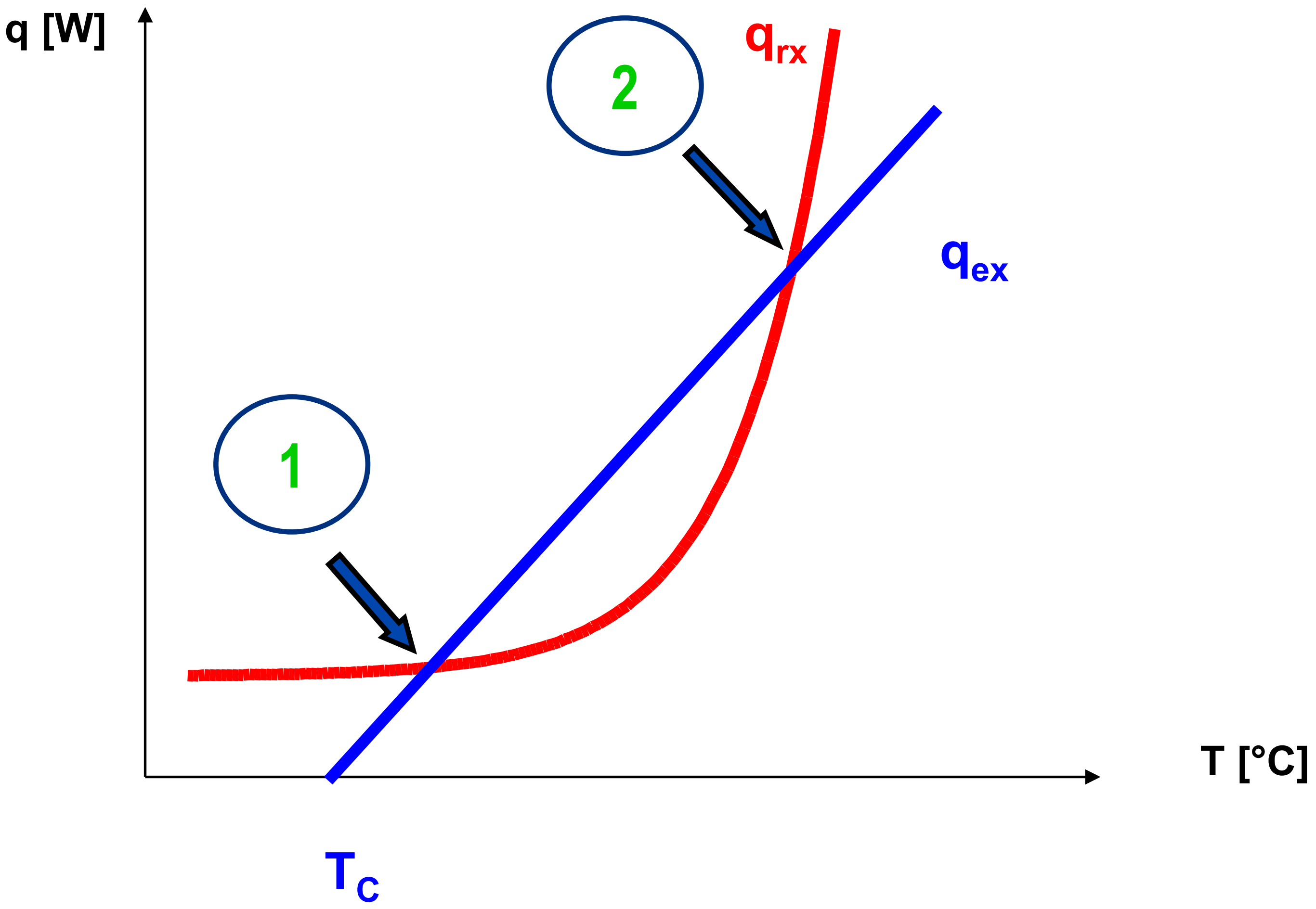


q: heat flow	W
T: temperature	°C/K
T_c: temperature cooling media	°C/K

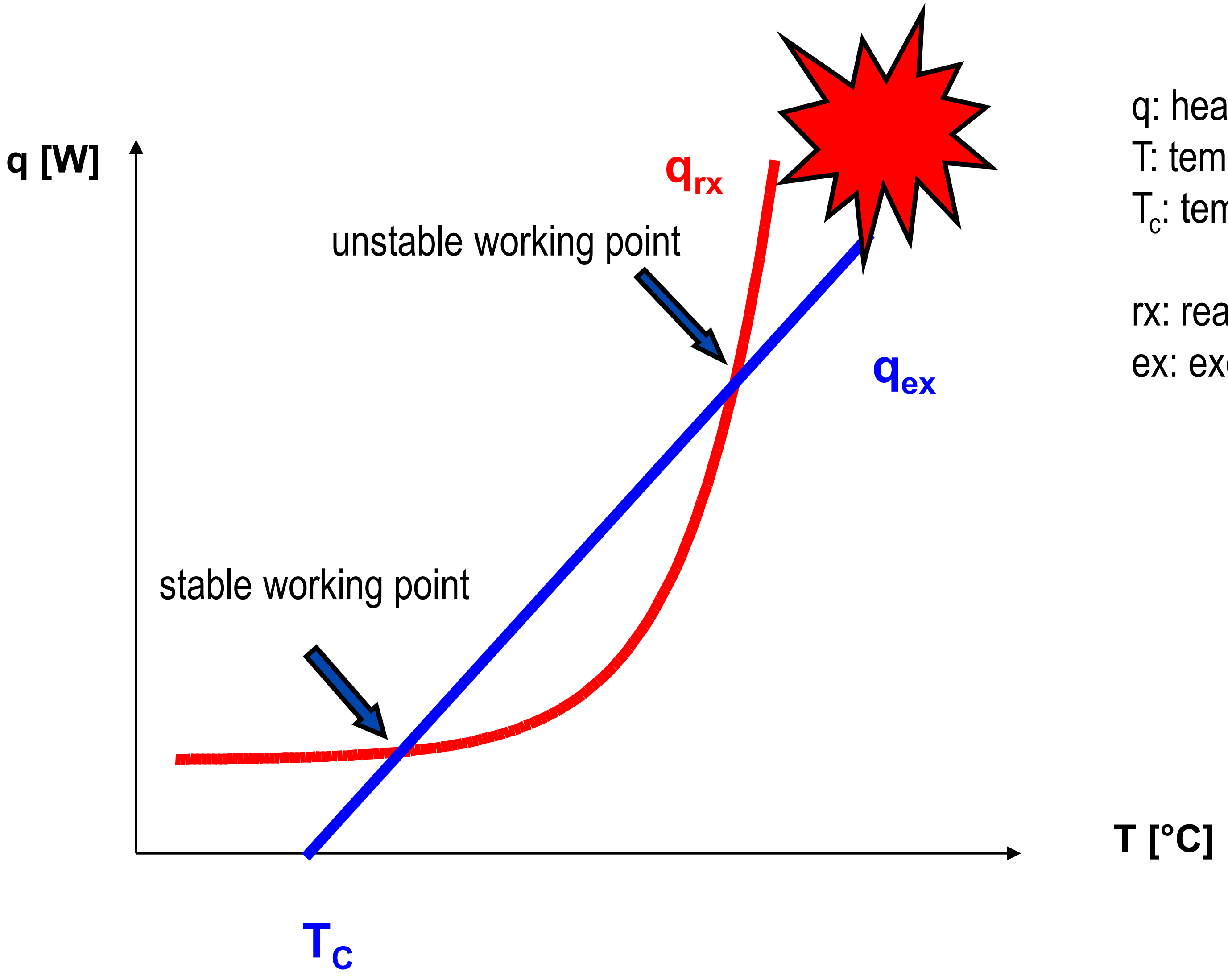
rx: reaction
ex: exchange

Semenov-Plot – normal operating conditions

- What is the difference between the two working points?
- Which one would you choose and why?
  - A. Point 1
  - B. Point 2
  - C. Point 1 or 2, makes no difference
- Think about it a few minutes



Semenov-Plot – normal operating conditions

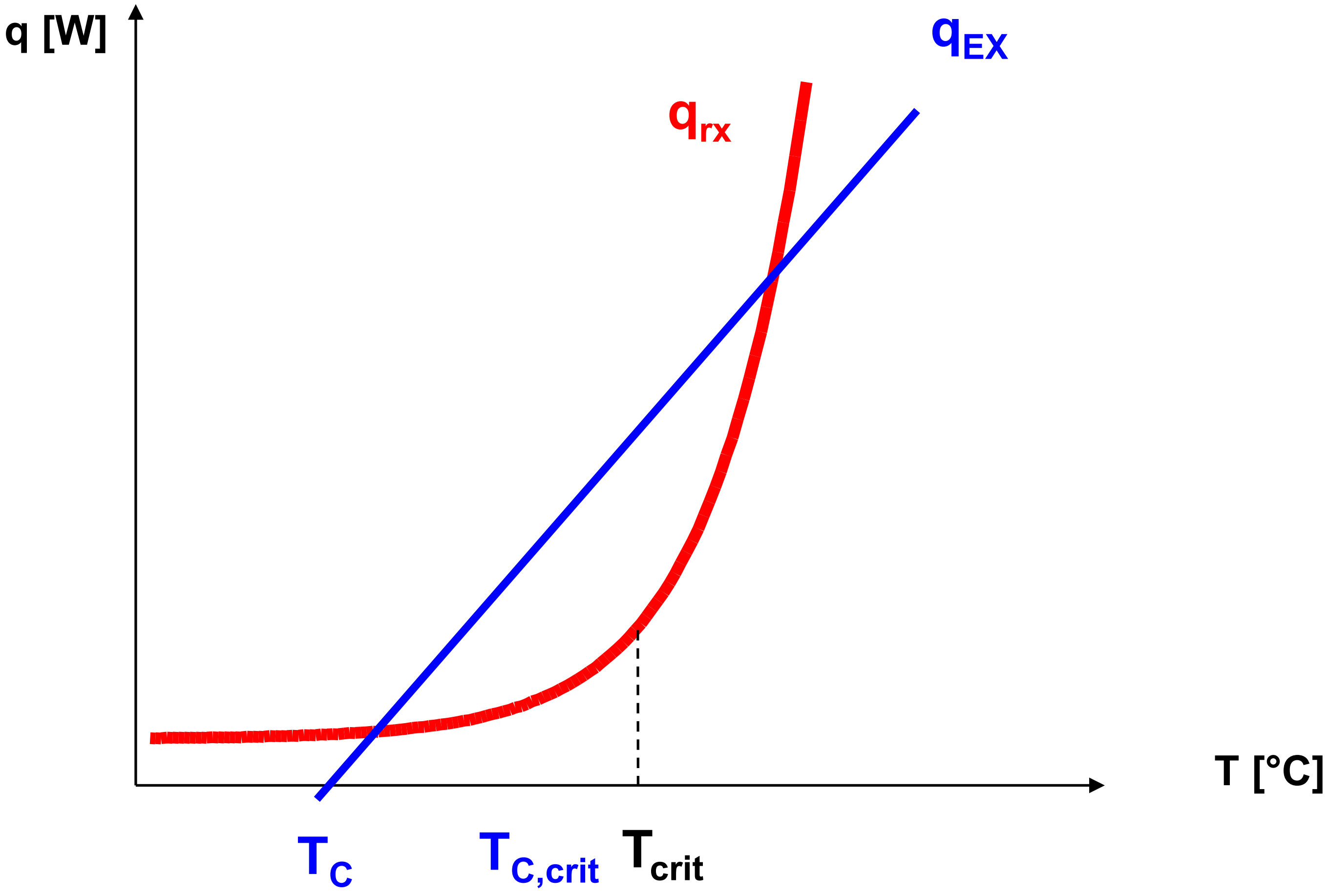


q: heat flow	W
T: temperature	°C/K
T_c: temperature cooling media	°C/K

rx: reaction
ex: exchange

Semenov-Plot – normal operating conditions

$$q_{EX} = UA\left(T_C - T\right)$$

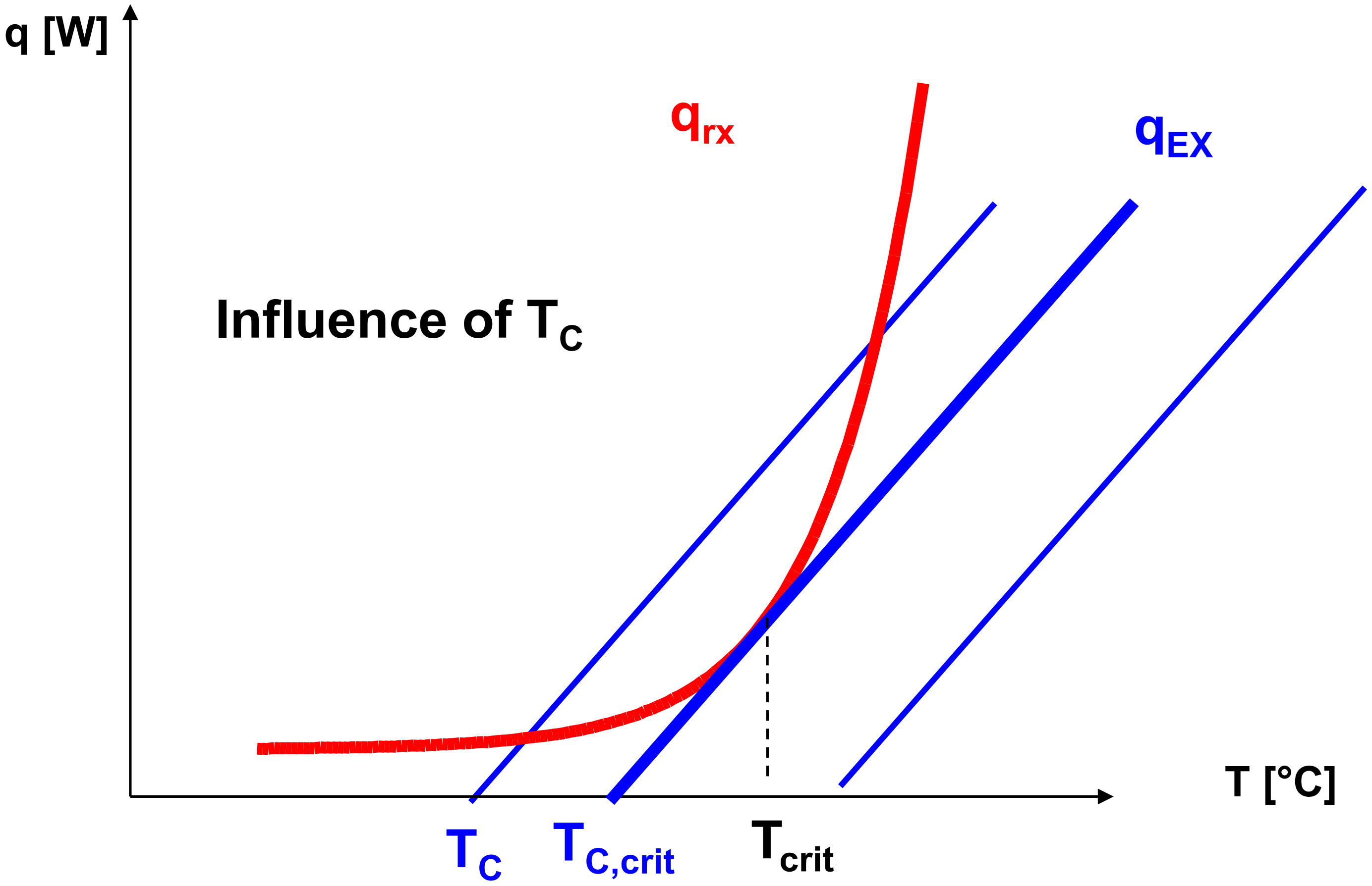


q: heat flow	W
T: temperature	°C/K
T_c: temperature cooling media	°C/K
$T_{c,crit}$: critical cooling media temperature	°C/K
T_{crit}: critical process temperature	°C/K
U: heat transfer coefficient	$W/(m^2 \cdot K)$
A: heat exchange area	m^2

rx: reaction
ex: exchange

Semenov-Plot – normal operating conditions

$$q_{EX} = UA\left(T_C - T\right)$$



q: heat flow	W
T: temperature	°C/K
T_c: temperature cooling media	°C/K
$T_{c,crit}$: critical cooling media temperature	°C/K
T_{crit}: critical process temperature °C/K	
U: heat transfer coefficient	$W/(m^2 \cdot K)$
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rx: reaction
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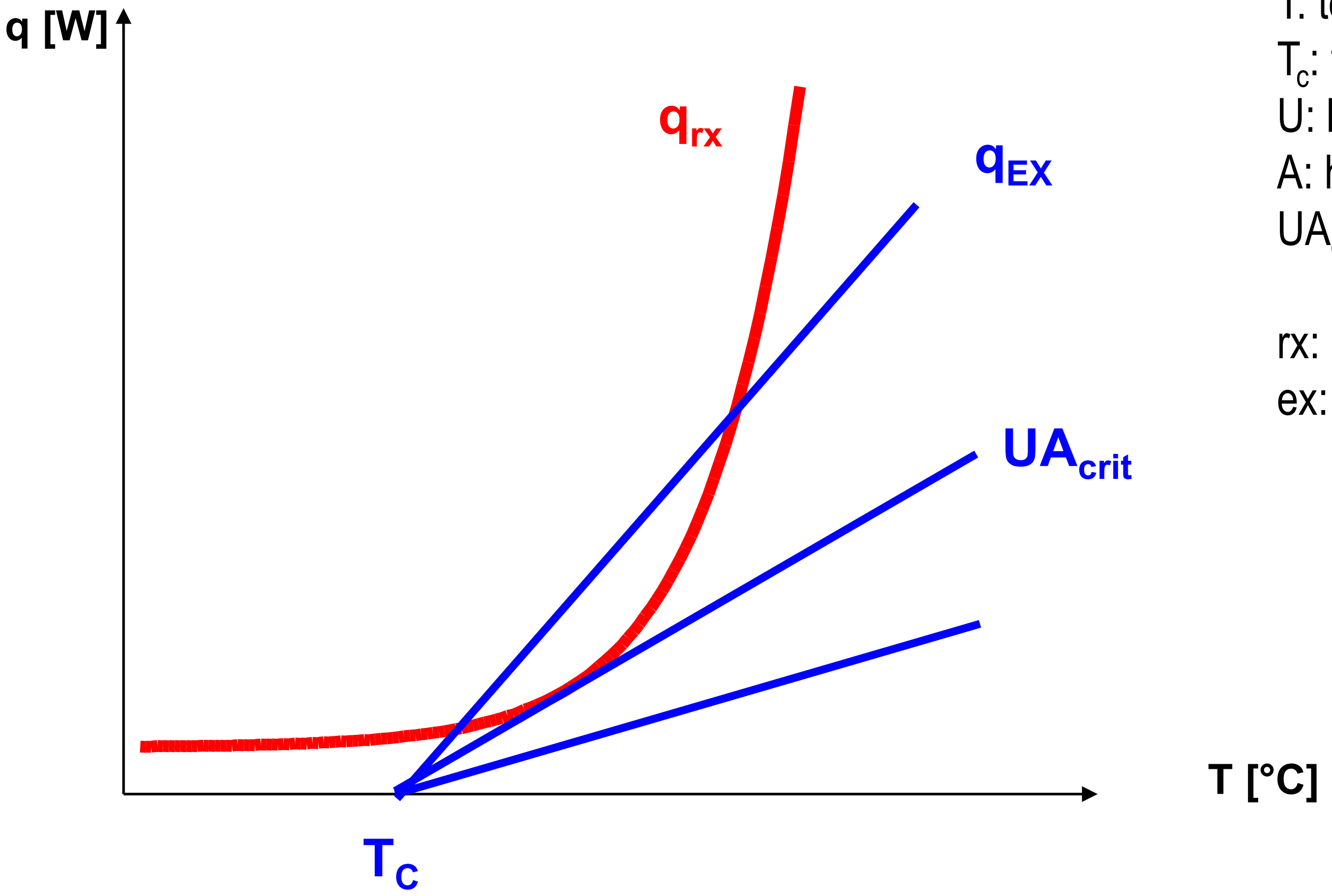
Semenov-Plot

$$q_{EX} = UA\left(T_C - T\right)$$



q: heat flow	W
T: temperature	°C/K
T_c: temperature cooling media	
U: heat transfer coefficient	$W/(m^2 \cdot K)$
A: heat exchange area	m^2
UA_{crit}: critical heat transfer coefficient-heat area	W/K

rx: reaction
ex: exchange

Key aspects Semenov Plot: normal operating conditions

- Heat production depends exponentially on T
- Heat removal depends linearly on T

→ Cooling capacity

- Heat production depends on V
- Heat removal depends on A

→ SCALE-UP

- Under normal operating conditions there is a stable and an unstable working point → need to work at the stable working point

- Influence of UA (fouling, change of scale) and Tc (winter - summer)

https://youtu.be/sRuz9bzBrtY

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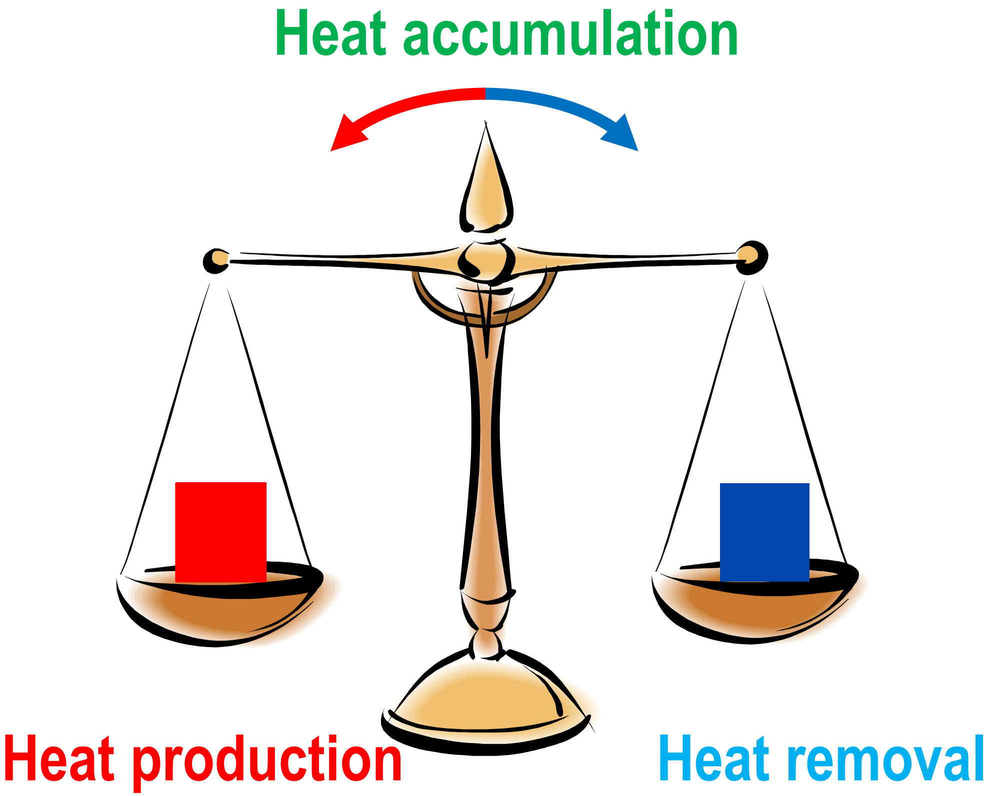
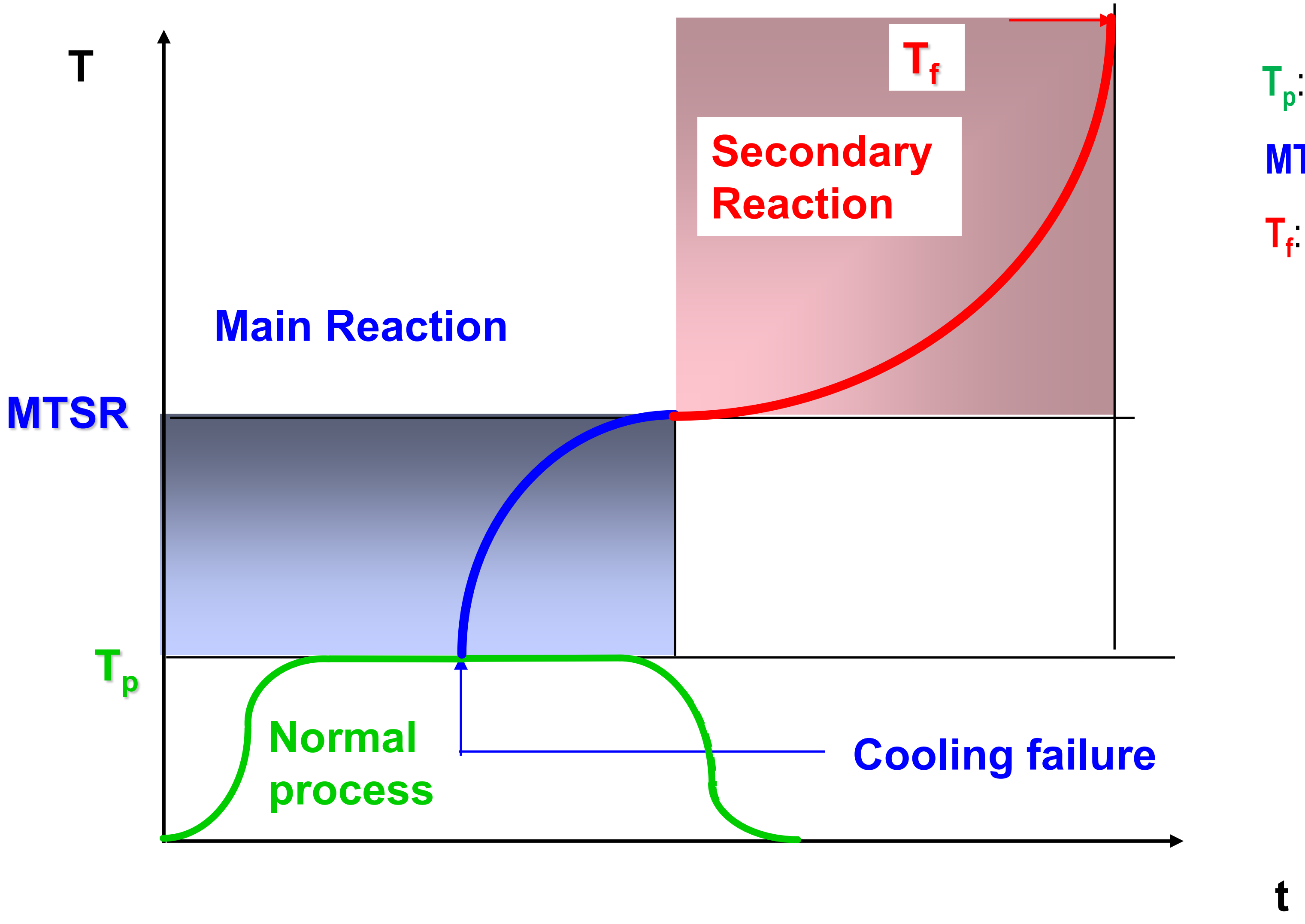
Heat Balance



$$\frac{dT}{dt} = k(1-X_A)^n c_{A0}^{n-1}\Delta T_{ad} - \frac{UA(T-T_C)}{\rho V c'_p}$$

T: temperature	K
t: time	s
k: rate constant	$s^{-1} mol^{1-n} l^{n-1}$
X: conversion	-
n: order of the reaction	-
c_{A0}: starting concentration of A	mol/l
ΔT_{ad}: adiabatic temperature rise	K or °C
U: heat transfer coefficient	$W/(m^2 \cdot K)$
A: heat exchange area	m^2
Tc: temperature cooling media	K
ρ: density	kg/l
c'_p: specific heat capacity	$J/(kg \cdot K)$
V: volume	l

Batch Process

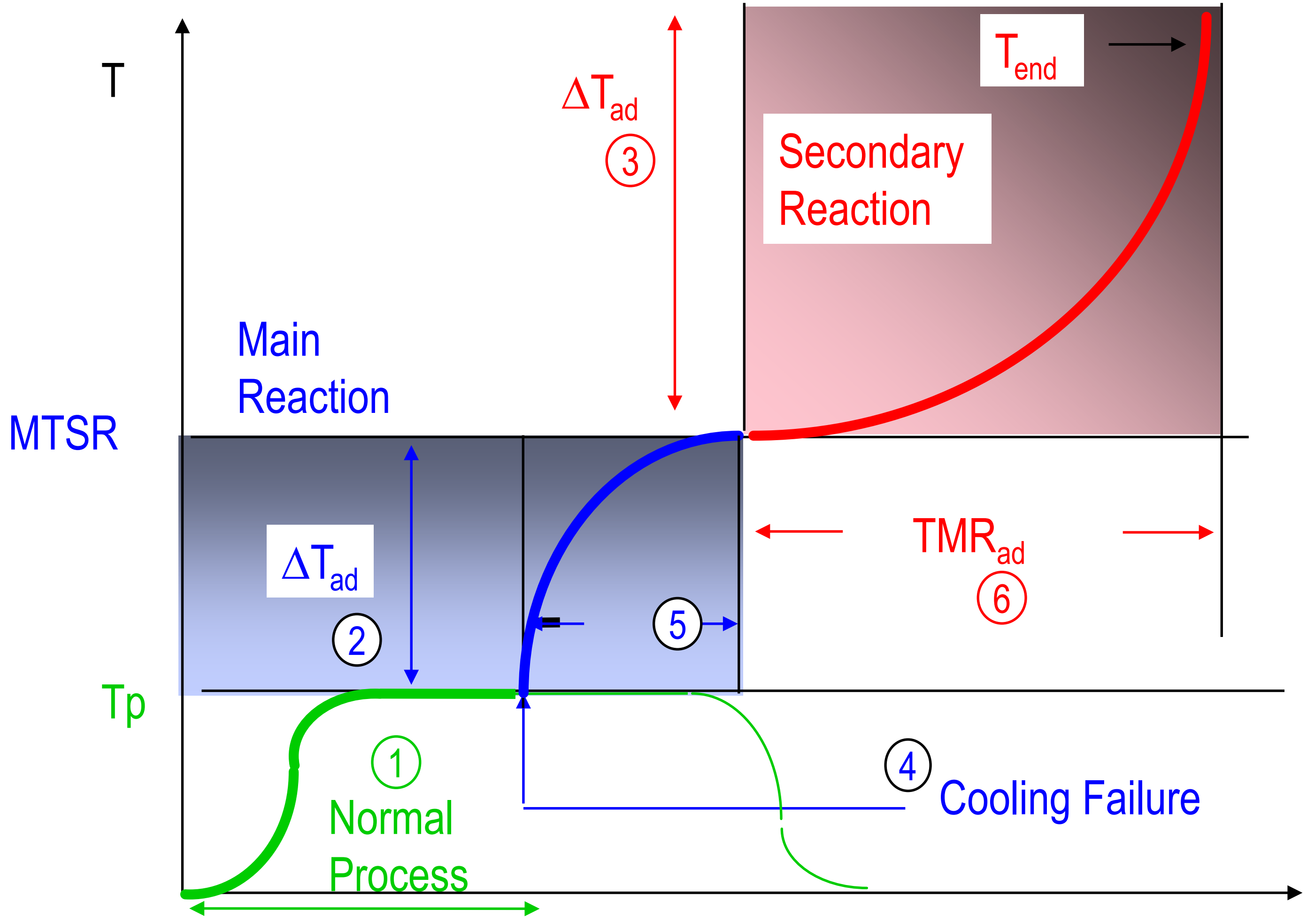


T_p: process temperature

MTSR: **M**aximal **T**emperature of the **S**ynthesis **R**eaction

T_f: final temperature or end temperature T_{end}

Cooling Failure Scenario



T_p: process temperature

MTSR: **M**aximal **T**emperature of the **S**ynthesis **R**eaction
ΔTad: adiabatic temperature rise

T_f: final temperature or end temperature **T_{end}**
TMR_{ad}: **T**ime to **M**aximum **R**ate under **ad**iabatic conditions

Adiabatic conditions: no heat exchange with the surrounding, the whole energy stays in the system (reaction mass) and leads to a temperature increase
→ neglecting heat losses of a real system during a cooling failure.

Cooling Failure Scenario: Key Questions

1 Is the **cooling capacity** sufficient to remove the heat released by the reaction under normal operating conditions?

2 What **temperature** may be reached after runaway of the **main reaction**?

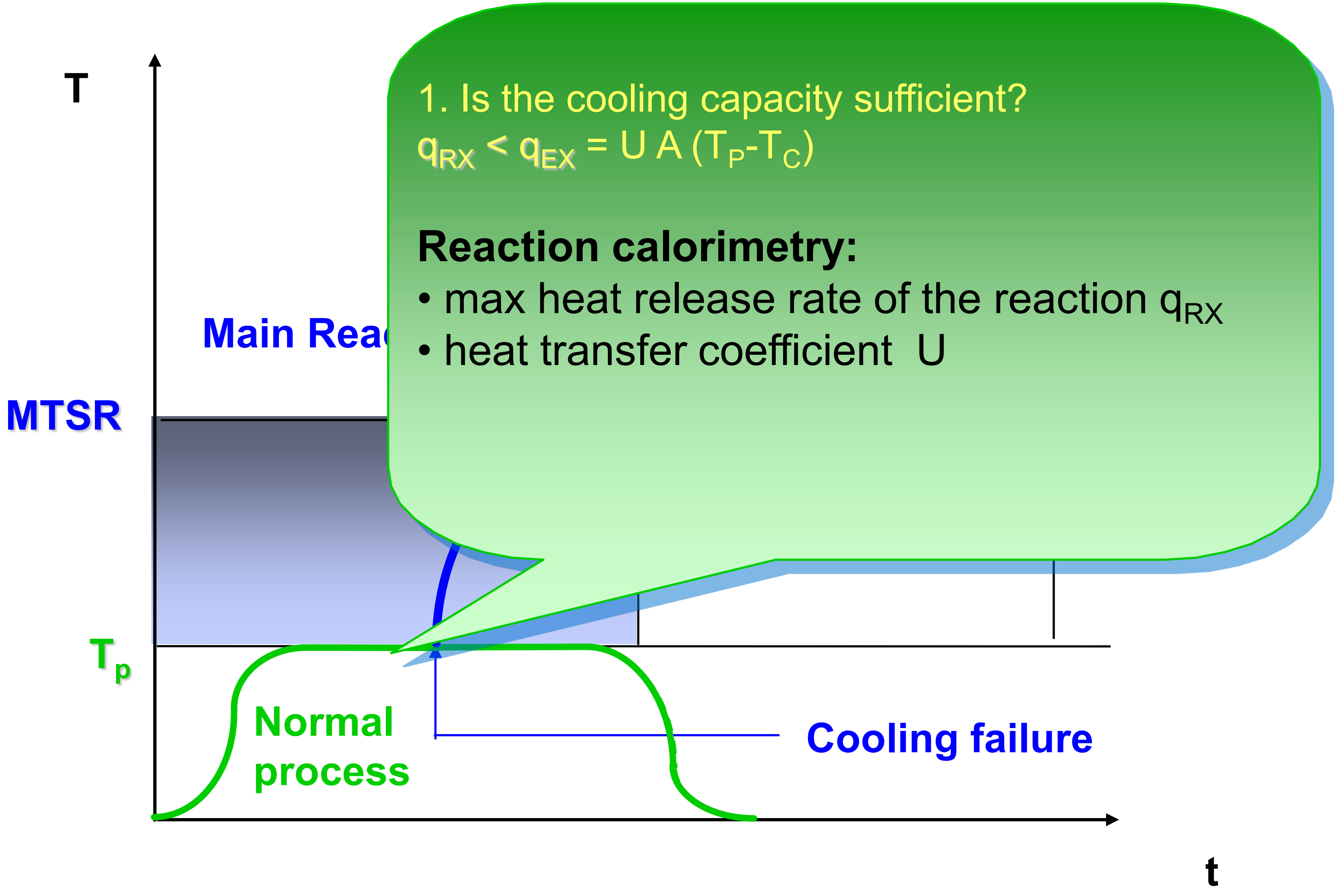
3 What **temperature** may be reached after runaway of **secondary reaction**

4 **When** does the cooling failure have the worst consequences?

5 **How long** does the runaway of the main reaction take?

6 **How long** does the runaway of the secondary reaction take?

Batch Process



1. Is the cooling capacity sufficient?

$q_{RX} < q_{EX} = U\,A\,(T_P - T_C)$

Reaction calorimetry:

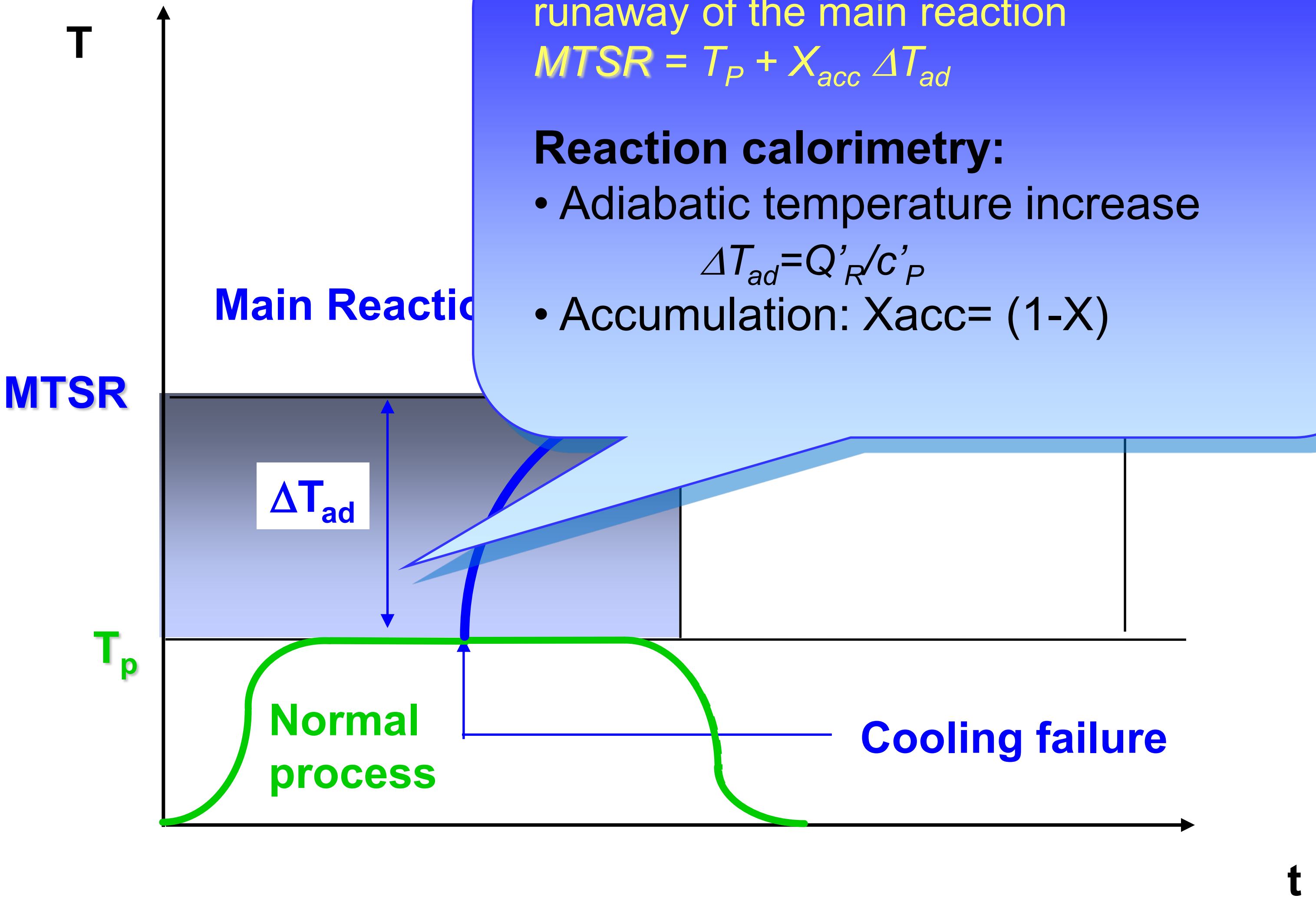
- max heat release rate of the reaction q_{RX}
- heat transfer coefficient U

T_p: process temperature	°C/K
T_c: temperature cooling media	°C/K
q: heat flow	W
U: heat transfer coefficient	$W/(m^2 \cdot K)$
A: heat exchange area	m^2

RX: reaction

EX: exchange

Batch Process



2. Which temperature can be reached after runaway of the main reaction

$MTSR = T_P + X_{acc}\,\Delta T_{ad}$

Reaction calorimetry:

- Adiabatic temperature increase

$$\Delta T_{ad} = Q'_R / c'_P$$

- Accumulation: Xacc= (1-X)

MTSR: maximal temperature of the synthesis reaction	°C/K
T_p: process temperature	°C/K
X_{acc}: accumulation	-
ΔT_{ad}: adiabatic temperature rise	°C/K
Q'_R: specific reaction energy	kJ/kg
c'_p: specific heat capacity	kJ/(kg·K)
X: conversion	-

Severity: Temperature Scale

Adiabatic Temperature Rise

$$\Delta T_{ad} = \frac{Q'}{c_p{}'}$$

$$\left[\frac{kJ\cdot kg^{-1}}{kJ\cdot kg^{-1}\cdot K^{-1}}\right]$$

$$\Delta T_{ad} = \frac{\left(-\Delta H_R\right)\cdot c_{A0}}{\rho\cdot c_p'}$$

$$\left[\frac{kJ\cdot mol^{-1}\cdot mol\cdot m^{-3}}{kg\cdot m^{-3}\cdot kJ\cdot kg^{-1}\cdot K^{-1}}\right]$$

ΔTad: adiabatic temperature rise	°C/K
Q' : specific reaction energy	kJ/kg
c'_p: specific heat capacity	kJ/(kg·K)
ΔH_r: molar reaction enthalpy	kJ/mol
c_{A0}: starting cncentration of A	mol/m^3
ρ: density	kg/m^3

Conclusion: ΔTad is given for one concentration of starting material. If the concentration is changed, then the adiabatic temperature rise changes accordingly

Severity: Temperature Scale: Heat Capacity

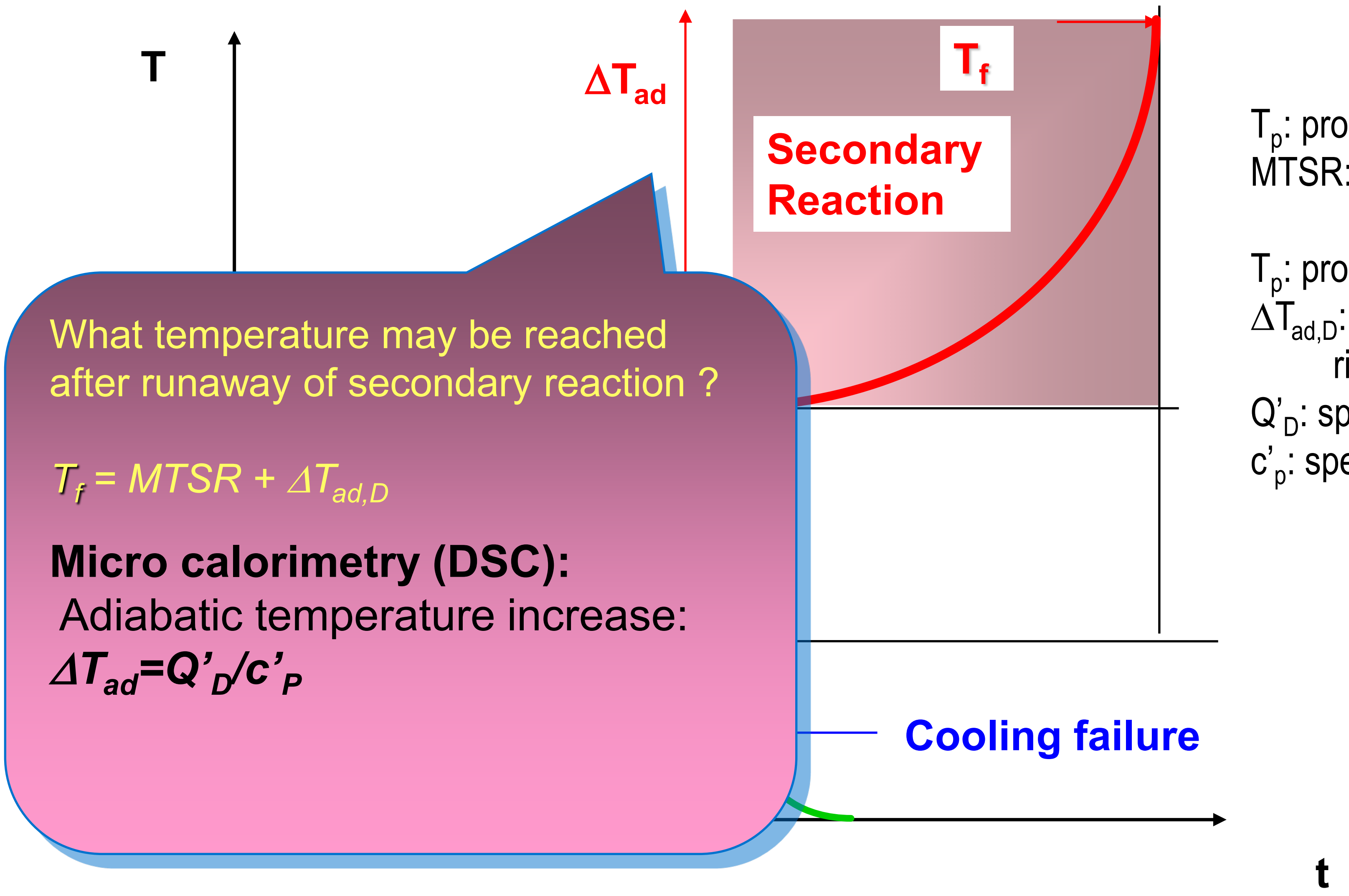
- Heat Capacity: $J.K^{-1}$
- Specific Heat Capacity: $J.kg^{-1}.K^{-1}$
- Mixture with i components and mass M_i

$$Cp' = \frac{\sum_i M_i \cdot Cp'_i}{\sum_i M_i}$$

- Typical values for heat capacity

Water:	4.2 $kJ.kg^{-1}.K^{-1}$
Liquid organic substances:	1.8 $kJ.kg^{-1}.K^{-1}$
Sulfuric acid:	1.3 $kJ.kg^{-1}.K^{-1}$
Solid organic substances:	1.3 $kJ.kg^{-1}.K^{-1}$

Batch Process



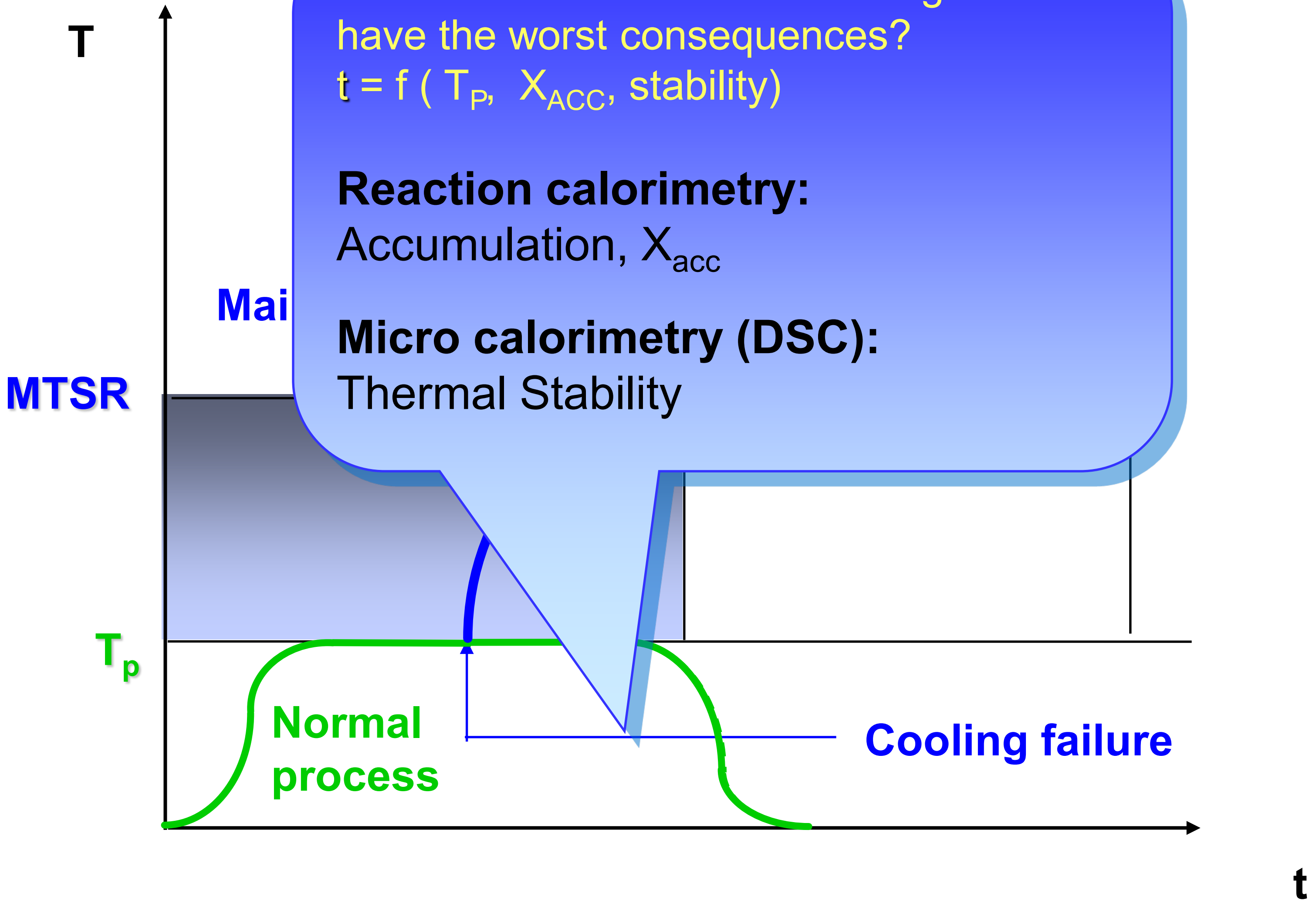
What temperature may be reached after runaway of secondary reaction ?

$T_f = MTSR + \Delta T_{ad,D}$

Micro calorimetry (DSC):
Adiabatic temperature increase:
$\Delta T_{ad} = Q'_D / c'_P$

T_p: process temperature	°C/K
MTSR: maximal temperature of the synthesis reaction	°C/K
T_p: process temperature	°C/K
$\Delta T_{ad,D}$: adiabatic temperature rise, for the decomposition	°C/K
Q'_D: specific decomposition energy	kJ/kg
c'_p: specific heat capacity	kJ/(kg·K)

Batch Process

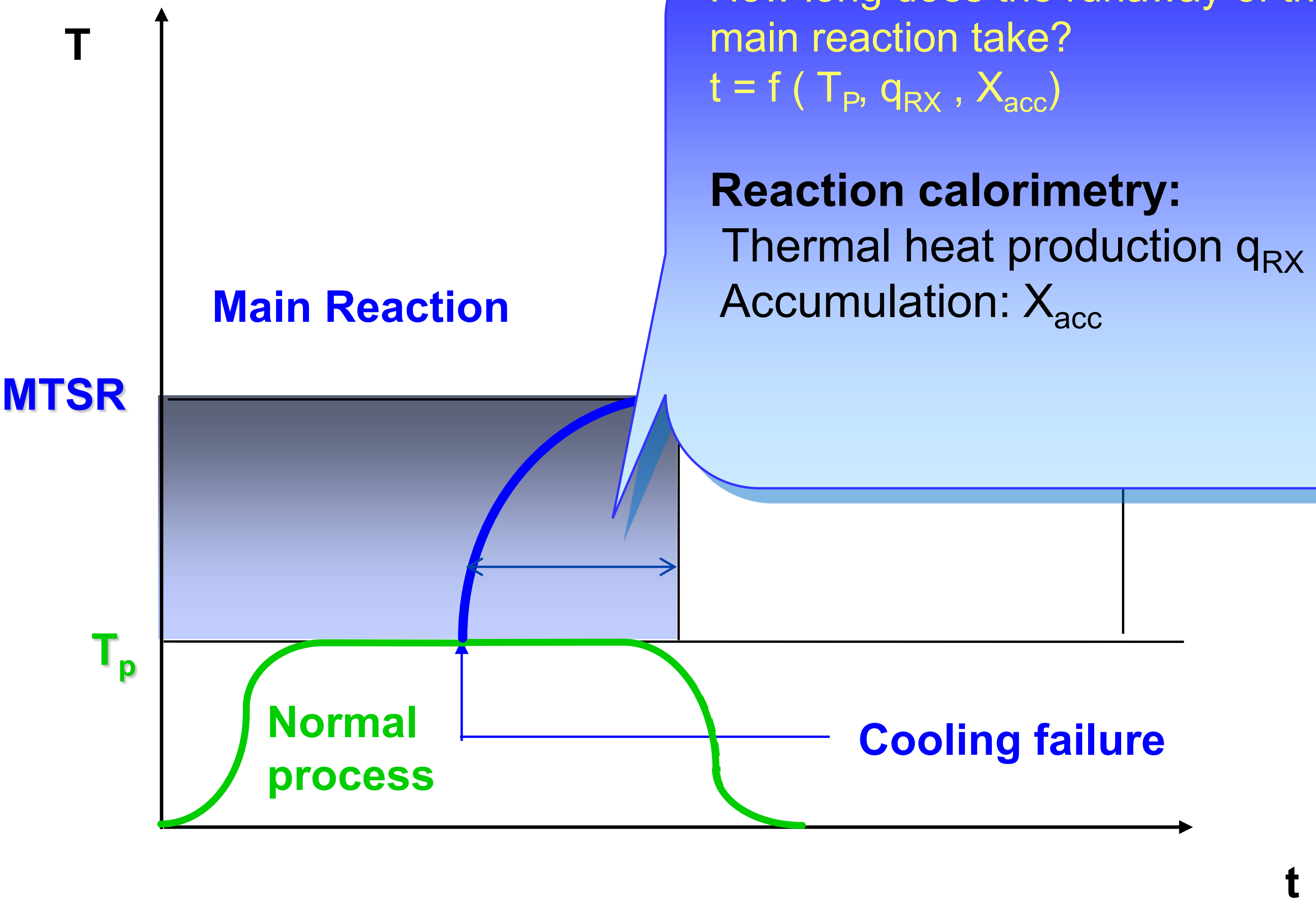


At which instant does the cooling failure have the worst consequences?
$t = f\ (T_P,\ X_{ACC},\ \text{stability})$

Reaction calorimetry:
Accumulation, X_{acc}

Micro calorimetry (DSC):
Thermal Stability

Batch Process



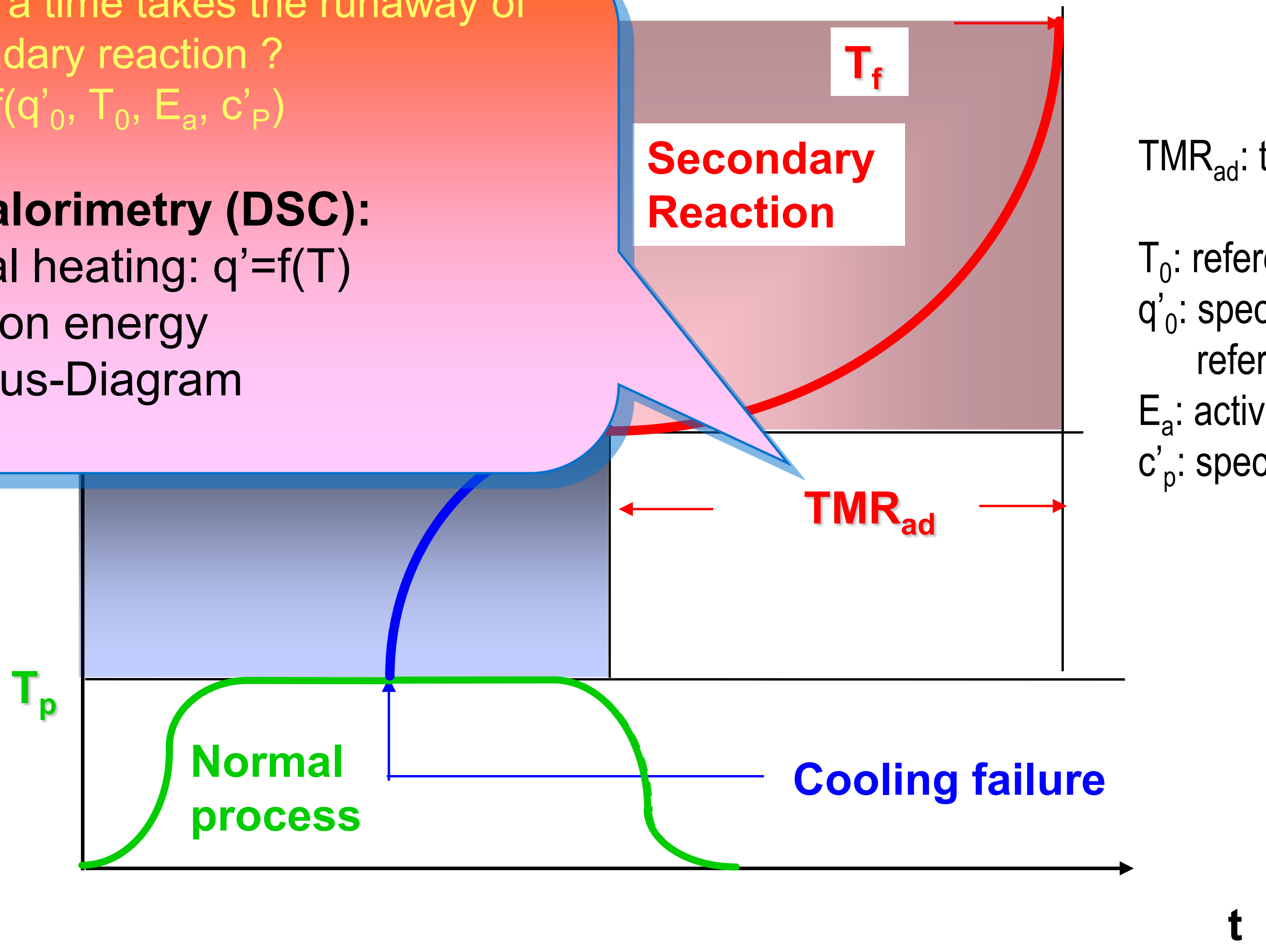
How long does the runaway of the main reaction take?
$t = f(T_P, q_{RX}, X_{acc})$

Reaction calorimetry:
Thermal heat production q_{RX}
Accumulation: X_{acc}

Batch Process

How long a time takes the runaway of the secondary reaction ?
$TMR_{ad} = f(q'_0, T_0, E_a, c'_P)$

Micro calorimetry (DSC):
- Thermal heating: q'=f(T)
- Activation energy
- Arrhenius-Diagram

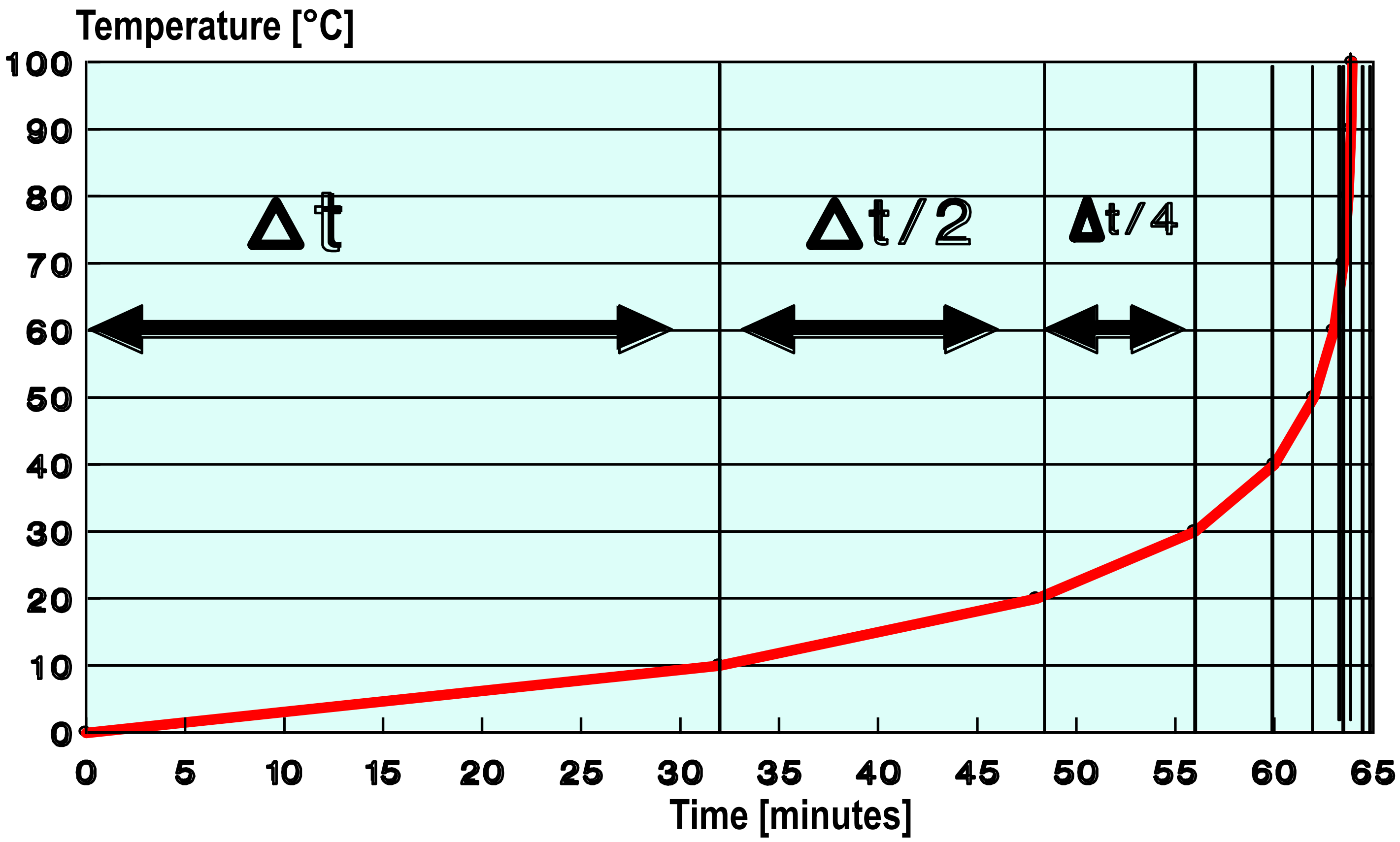


TMR_{ad}: time of maximum rate under adiabatic conditions	s or h
T_0: reference temperature	K
q'_0: specific heat release rate at the reference temperature	W/kg
E_a: activation energy	J/mol
c'_p: specific heat capacity	kJ/(kg·K)

Thermal explosion/ thermal runaway

Adiabatic temperature course

van't Hoff rule: doubling reaction rate each 10°C



Δt: initial time interval for an increase in temperature of 10 °C, in this case 32 minutes

Very useful rule for estimations of TMRad but it is not conservative

Time to Maximum Rate under Adiabatic Conditions: TMR_{ad}

Approximate estimation in seconds

$$TMR_{ad}(T_0) = \frac{c'_P \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E_a}$$

$TMR_{ad}(T_0)$	Time to maximum rate under adiabatic conditions at T_0
c_p'	specific heat capacity [J / kg / K]
R	universal gas constant 8.314 J /(mol. K)
T_0	considered temperature (K)
$q'_{(T0)}$	specific heat release rate at T_0 [W / kg]
E_a	activation energy [J / mol]

To draw the cooling failure scenario, the temperature T_0 that has to be considered is the MTSR

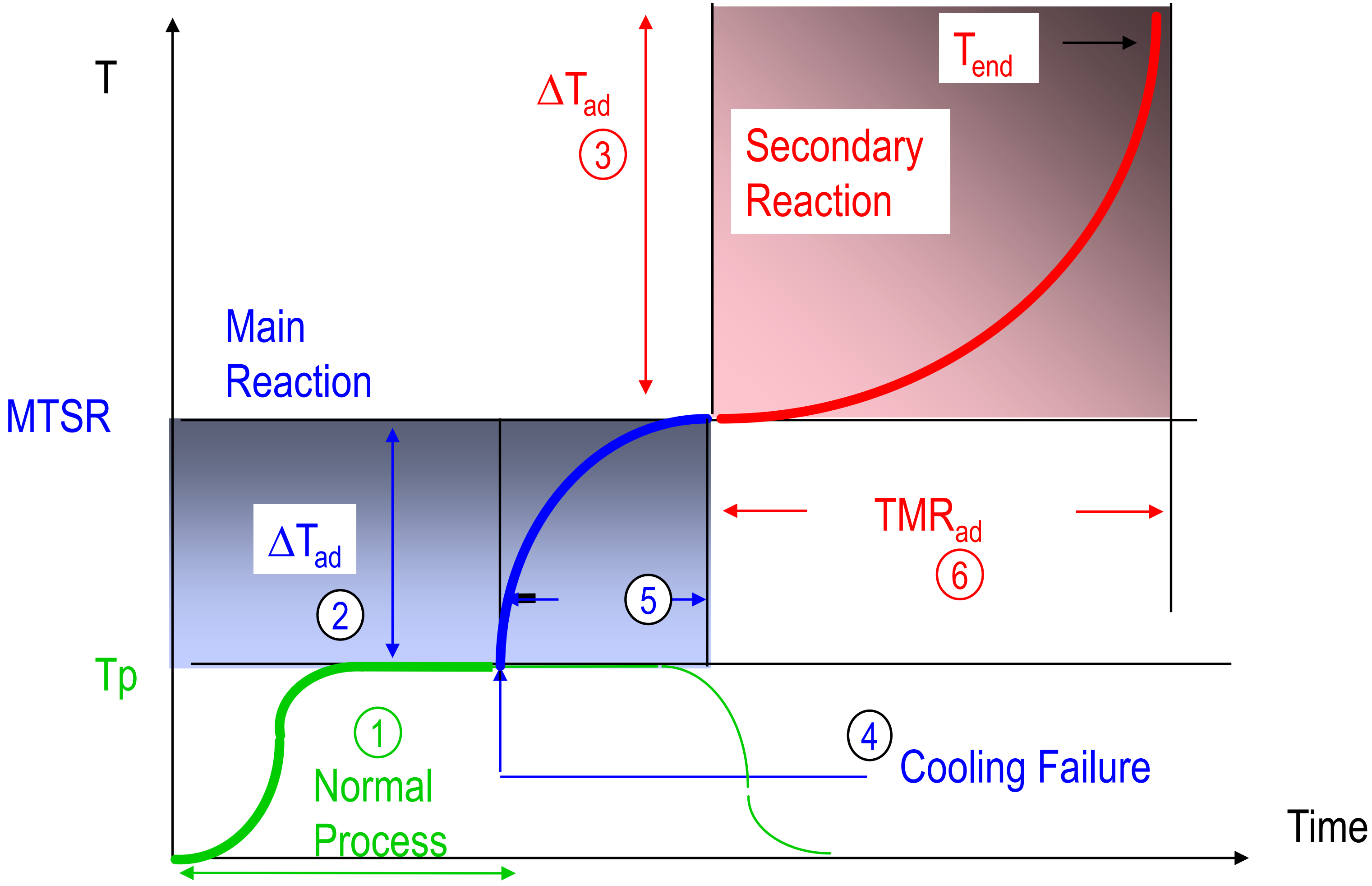
→ The TMRad is calculated for the MTSR

Thermal Risk and cooling failure scenario

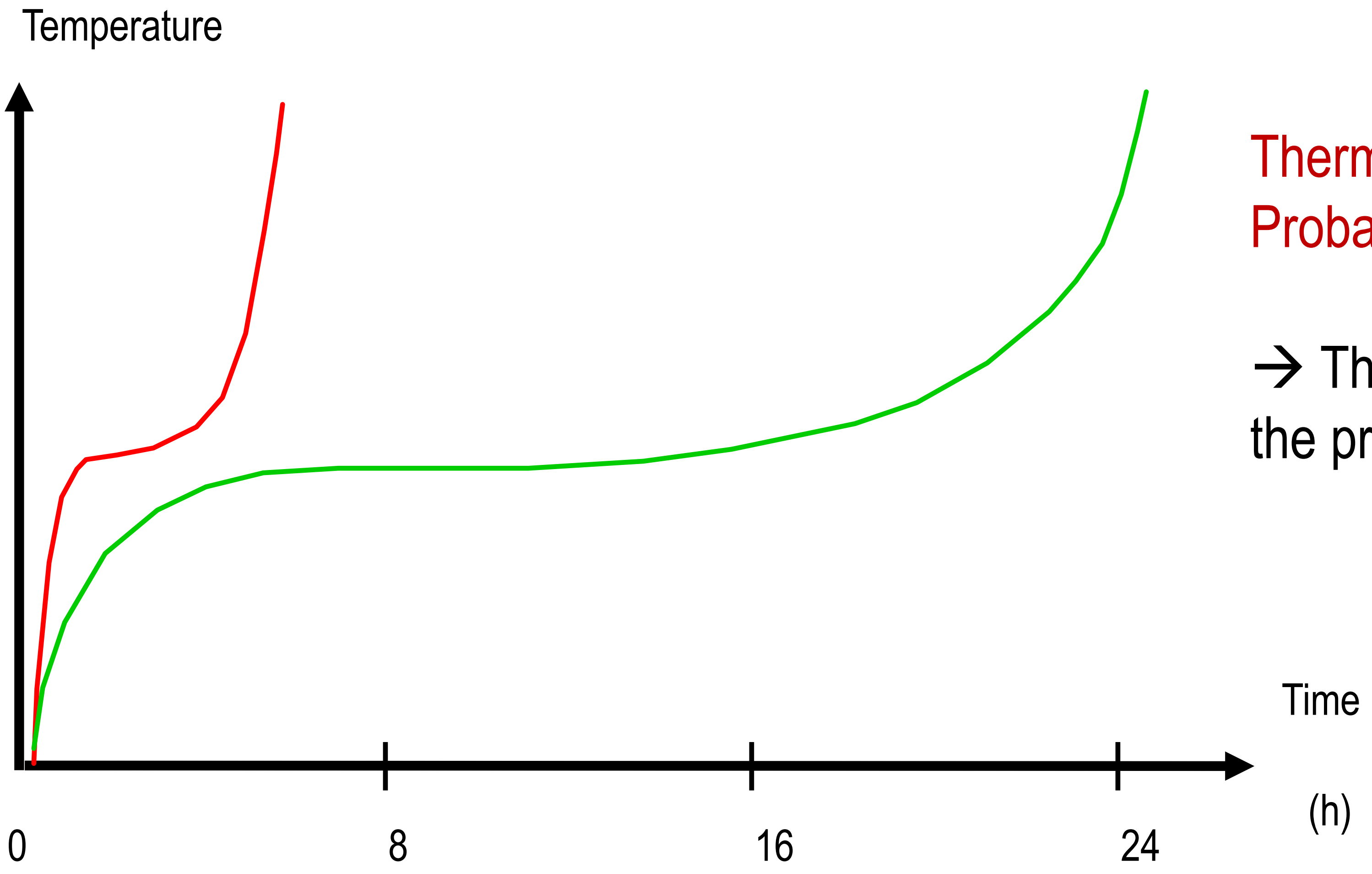
How can we evaluate the Thermal Risk?

Risk = probability x severity

Severity of a runaway = ?
Probability of a runaway = ?



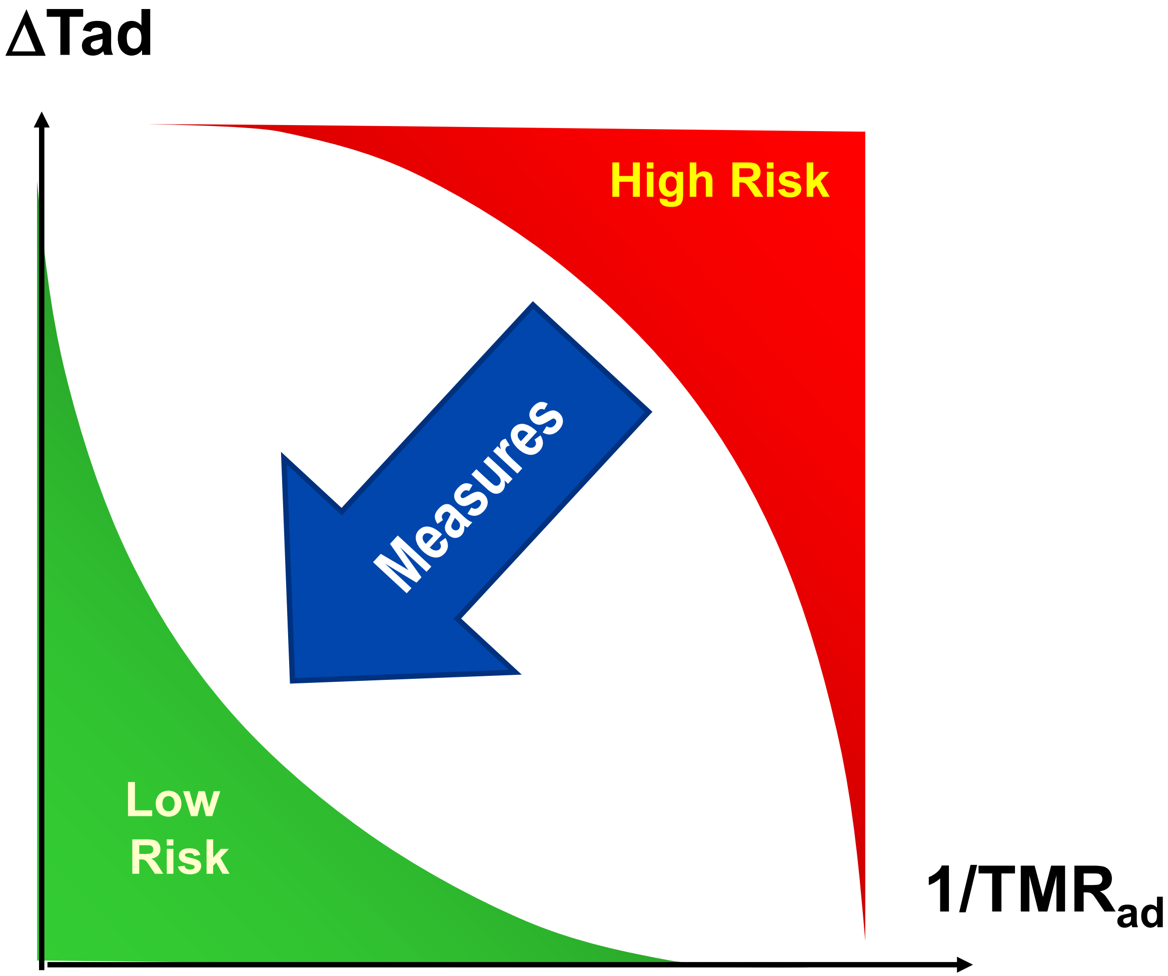
Thermal risk



Thermal Risk:
Probability of a runaway = Time Scale

→ The longer the TMRad, the lower the probability

Risk-Diagram



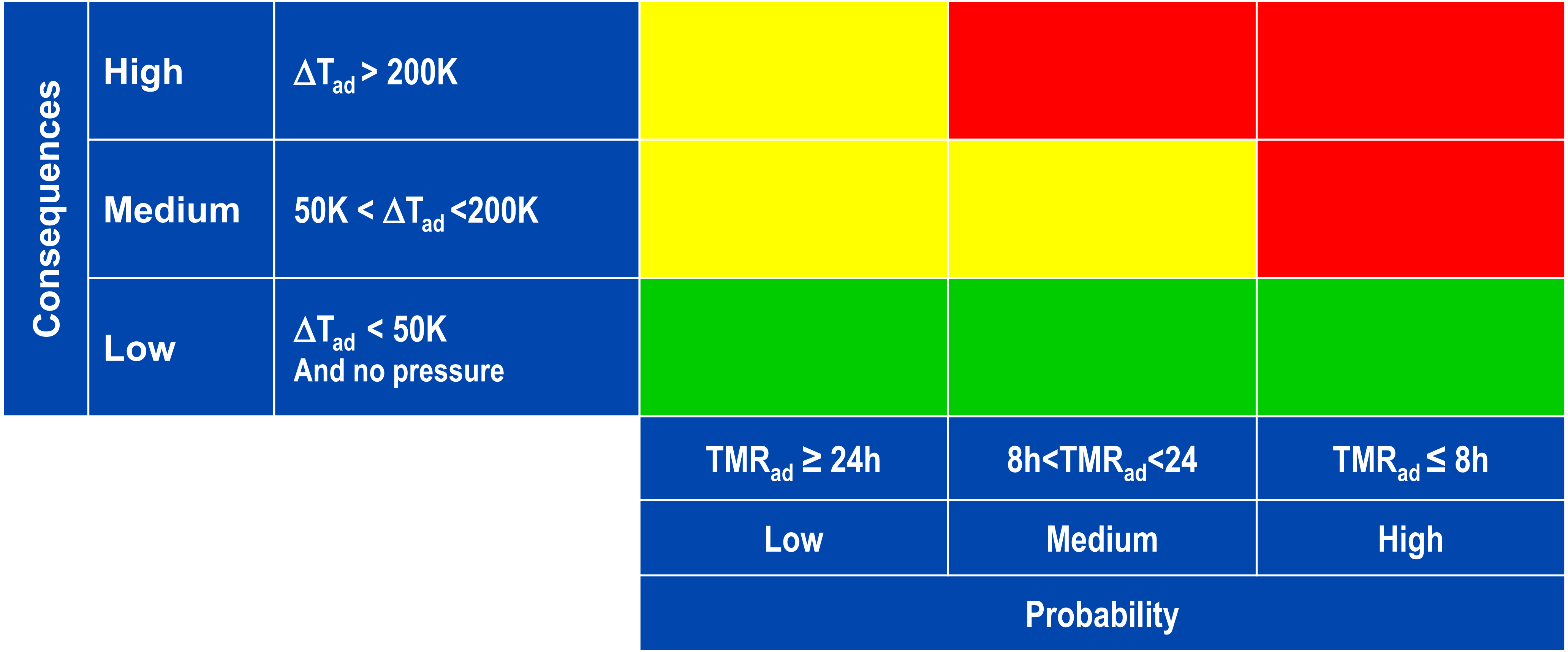
Criteria for probability and consequences

Criteria	Consequences	Probability
High	ΔTad > 200°C	TMRad < 8 h
Medium	50°C < ΔTad < 200°C	8 h < TMRad < 24 h
Low	ΔTad < 50°C and no pressure	TMRad > 24 h

Criteria based on experience

Criteria for the probability valid for controlled reaction masses (in reactors), not valid for example for storage or transport.

Criteria for risk evaluation



Consequences	**High**	$\Delta T_{ad} > 200K$	🟨	🟥	🟥
	Medium	$50K < \Delta T_{ad} < 200K$	🟨	🟨	🟥
	Low	$\Delta T_{ad} < 50K$ And no pressure	🟩	🟩	🟩
			$TMR_{ad} \geq 24h$	$8h < TMR_{ad} < 24$	$TMR_{ad} \leq 8h$
			Low	Medium	High
			Probability		

🟩	Low risk, risk acceptable
🟨	Medium risk. Apply ALARP principle (ALARP: as low as reasonable practicable)
🟥	High risk. Risk unaccpetable

Physical Chemical Data

- A decomposition reaction with a specific energy of 500 J/g releases 10 W/kg at a temperature of 150°C.

- Translating in terms of thermal risk:
  - Consequences: determine the adiabatic temperature increase: $\Delta T_{ad} = \frac{Q'}{c_p{}'}$
  - Probability: determine TMR_{ad}: $TMR_{ad}(T_0) = \frac{c'_P \cdot R \cdot T_0{}^2}{q'_{(T_0)} \cdot E_a}$

- A decomposition, able to raise the temperature by 250 °C, leads to a severe thermal explosion within less than one hour, starting from 150 °C.

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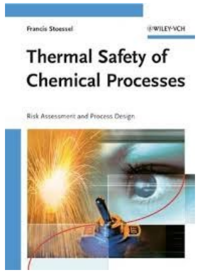

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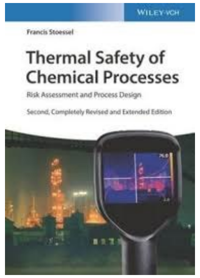

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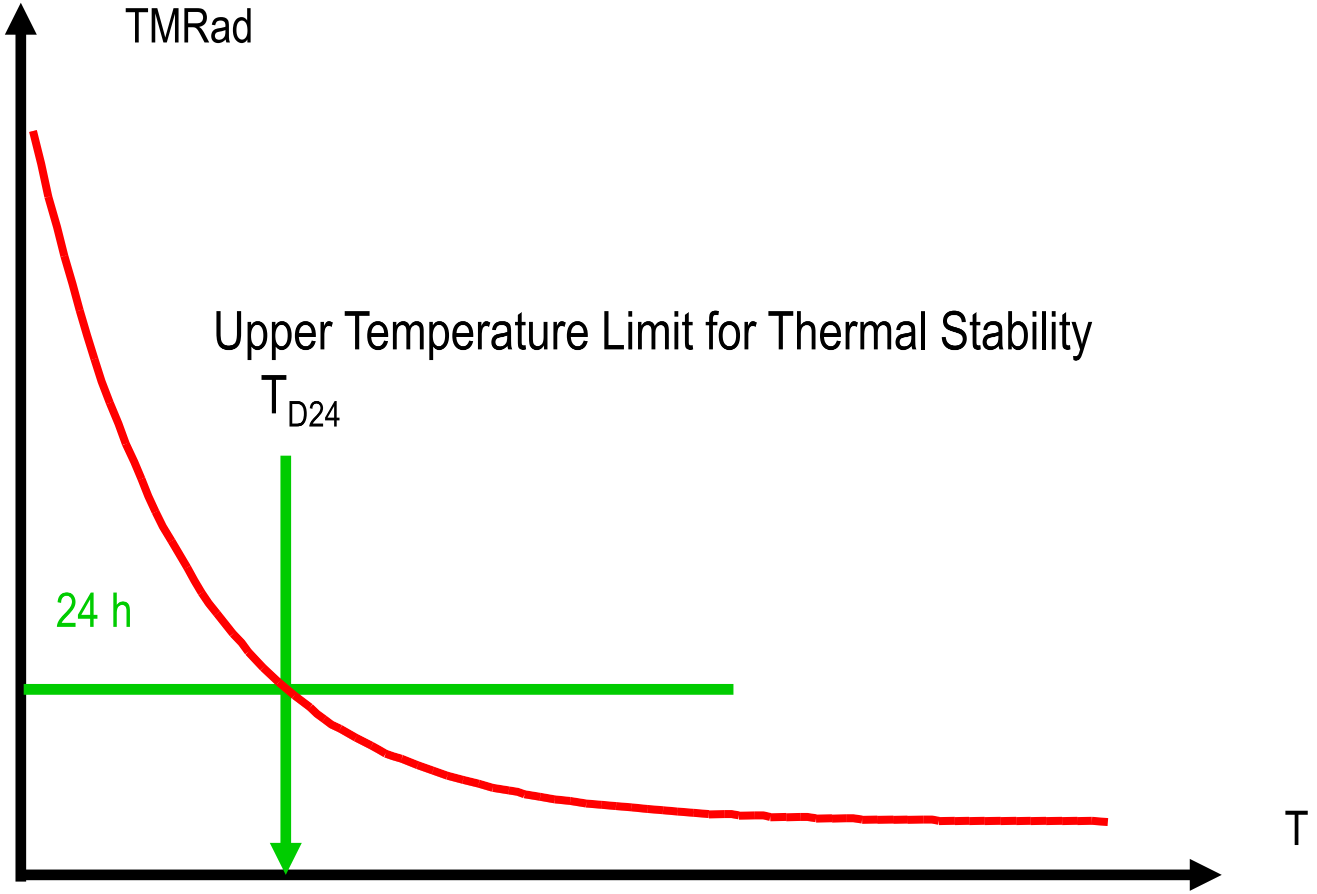
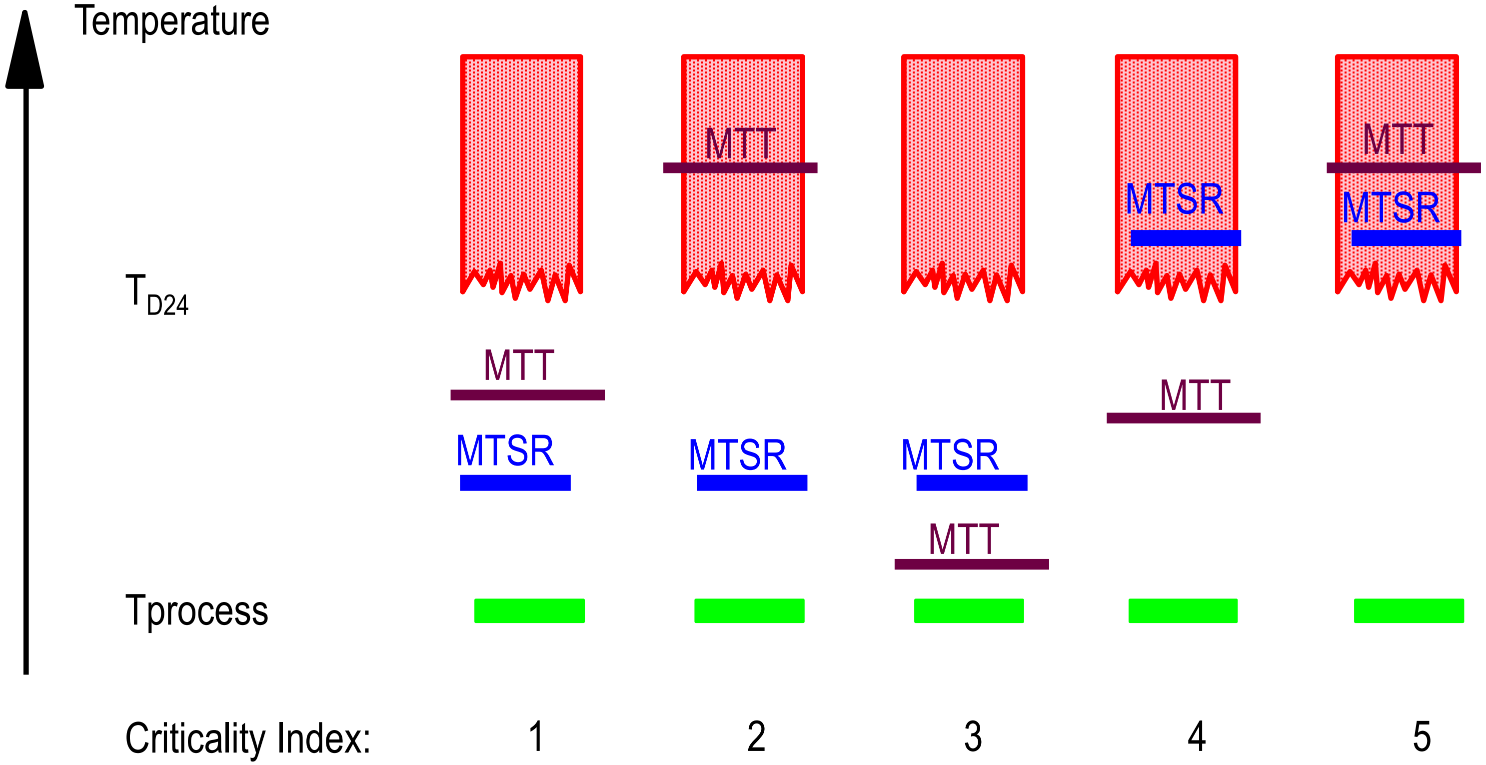
TMRad as a Function of Temperature



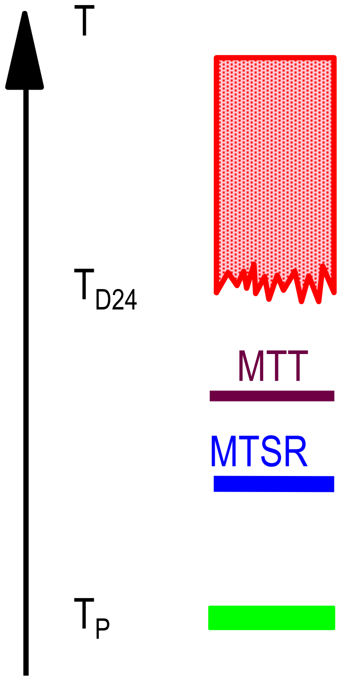
Characteristic Temperatures

- Tp : Process Temperature
  Defined by the mode of operation
- MTSR: Maximum Temperature of Synthesis Reaction
  Defined by the accumulation of reactants and Tp
- T_{D24}: Temperature at which the Decomposition becomes critical TMRad = 24 hrs
  Defined by the thermal stability of reaction mass
- MTT: Maximum Temperature for Technical Reasons
  Defined by the equipment

Classification of Scenarios



Criticality Class: 1



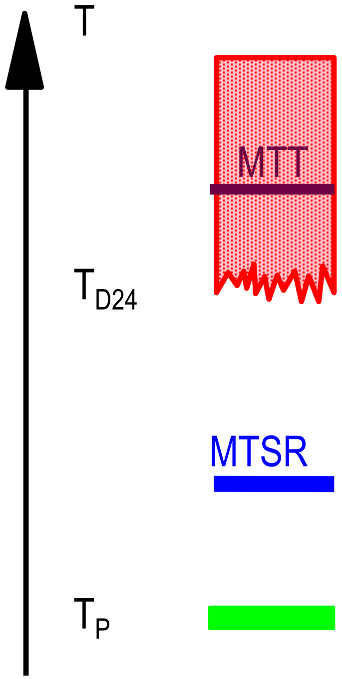
Decomposition is not triggered.

MTT is not reached

No special Measure required.

Boiling point could serve as a safety barrier

Criticality Class: 2



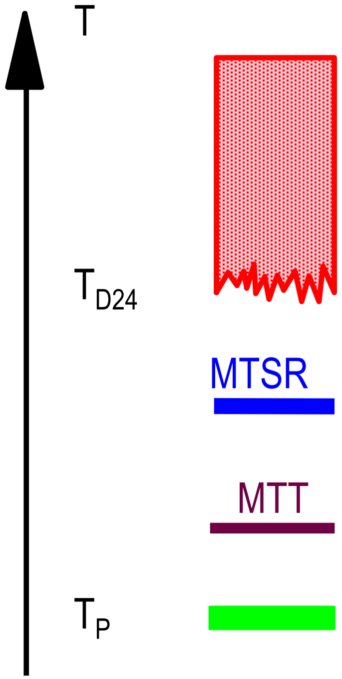
Decomposition is not triggered.

MTT is not reached

No special Measure required.

Avoid heat accumulation conditions
Boiling point could *not* serve as a safety barrier.

Criticality Class: 3



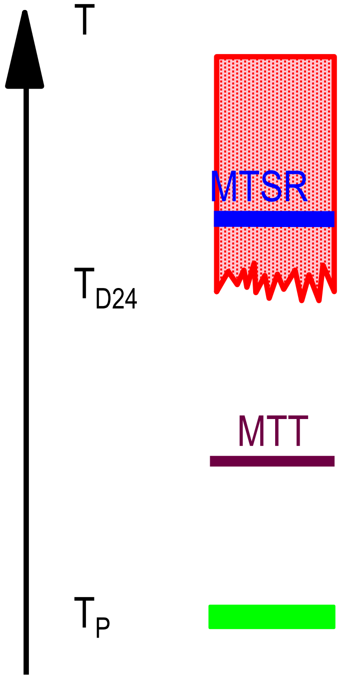
Decomposition is not triggered.

MTT is reached

Risk reducing measures are required.

Boiling point could serve as a safety barrier.
Design system for that purpose

Criticality Class: 4



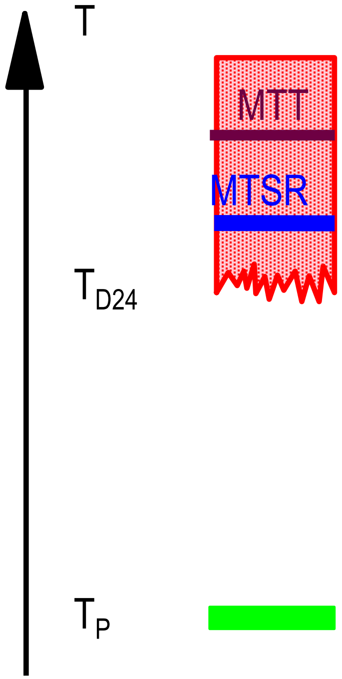
Decomposition could be triggered.

MTT is reached

Risk reducing measures required.

Boiling point could serve as a safety barrier to avoid triggering the decomposition reaction. Design system for that purpose

Criticality Class: 5



Decomposition is triggered.

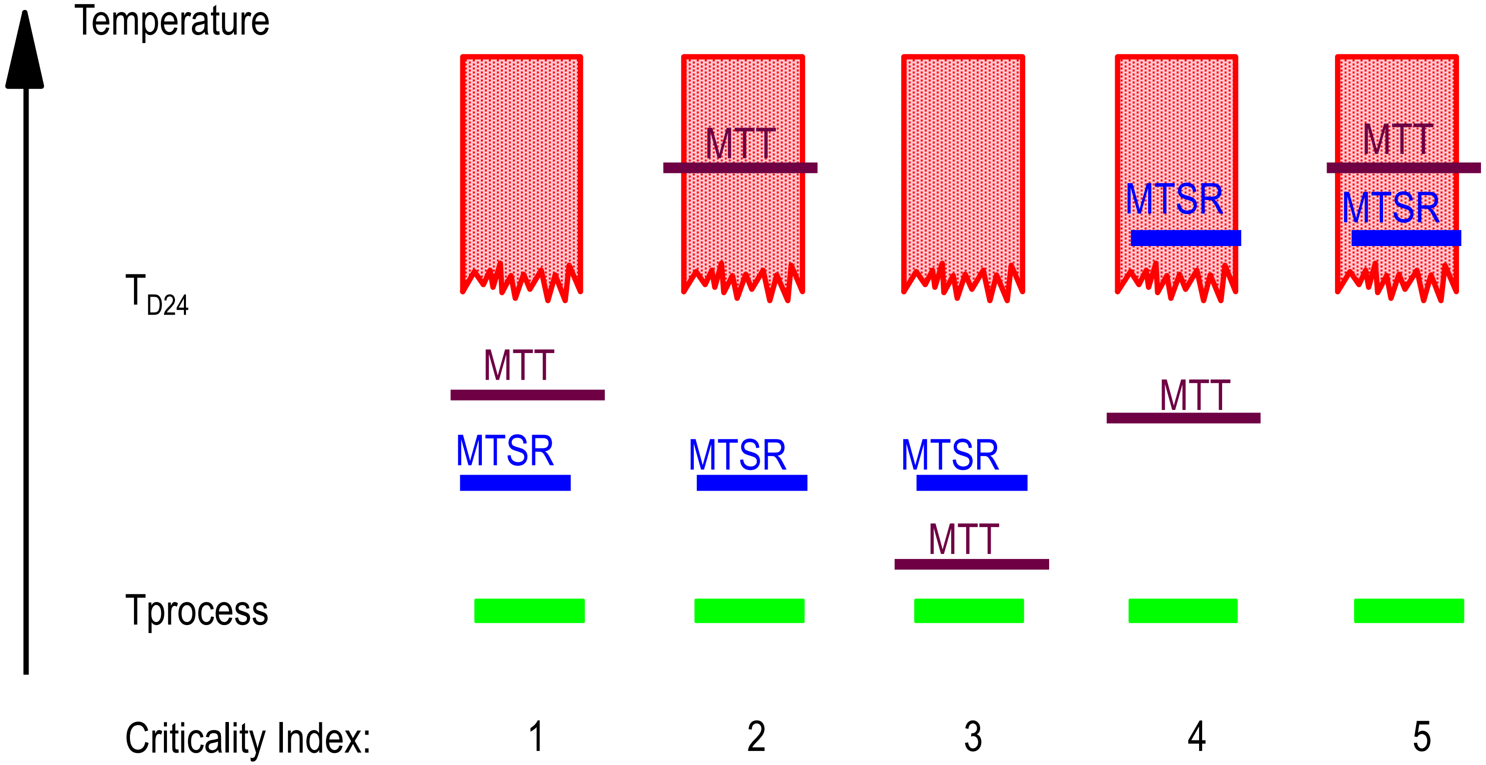
MTT is reached

Risk reducing measures required.

Emergency measures required.

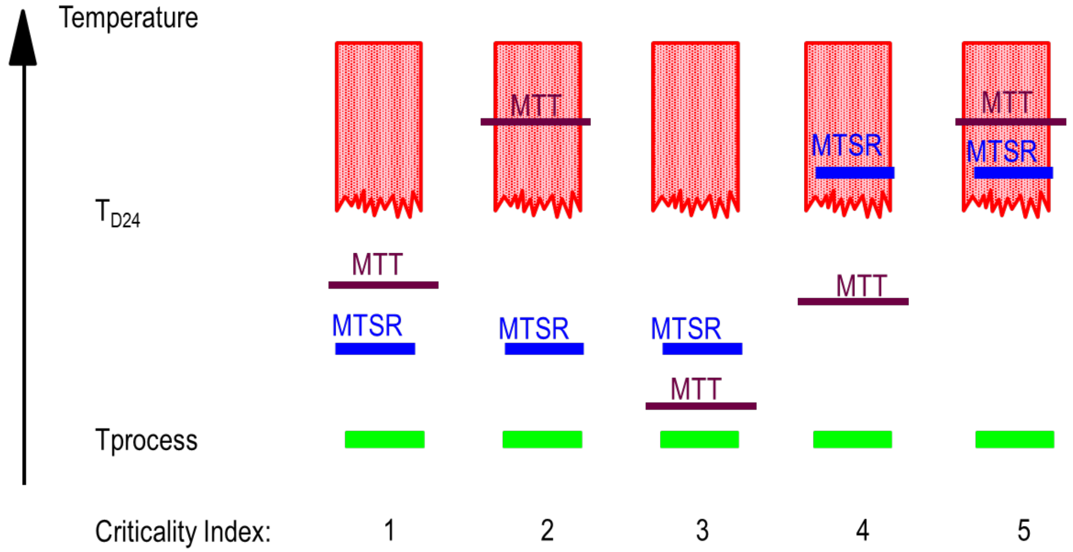
Consider redesigning the process

Criticality classes



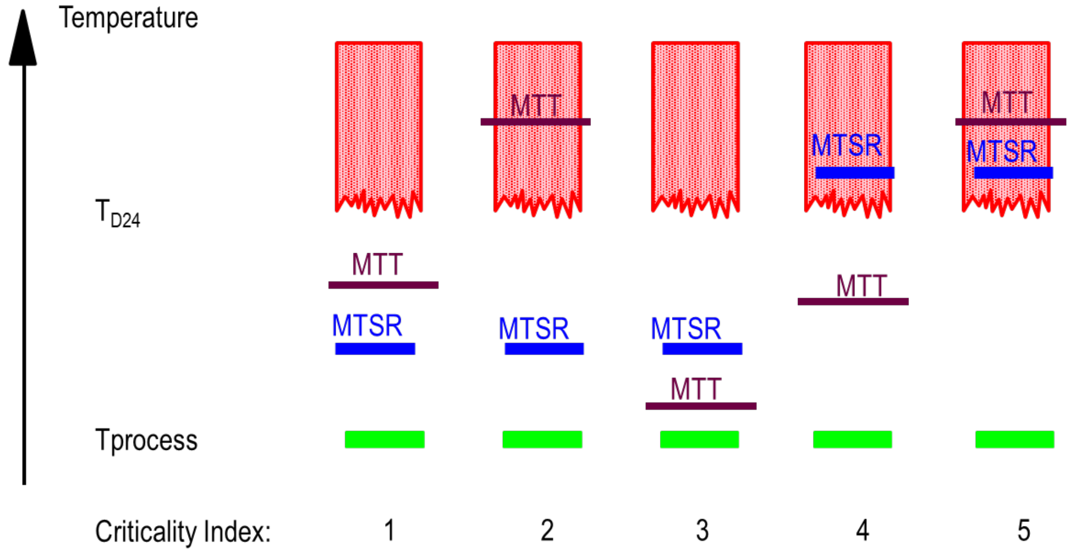
Criticality classes

- If you have a criticality class 5 process, what can you change to make it less hazardous?
- Write down 3 possible changes



Criticality classes

- What is the hazard linked with criticality 3 processes?
- What are the benefits and disadvantages of having a boiling temperature (MTT) close to Tprocess?
- What are the benefits and disadvantages of having a boiling temperature (MTT) close to MTSR?
- So what is best, a boiling temperature close to Tprocess or to MTSR?

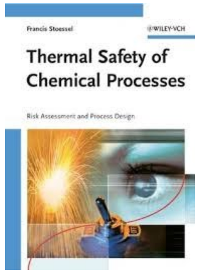


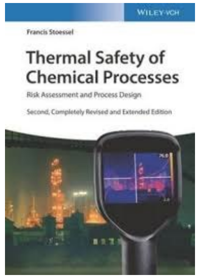
Content Module 2

- Video/ introduction to the hazard
- Thermal Risks
  - Heat Balance
  - Failure Scenario

- Criticality

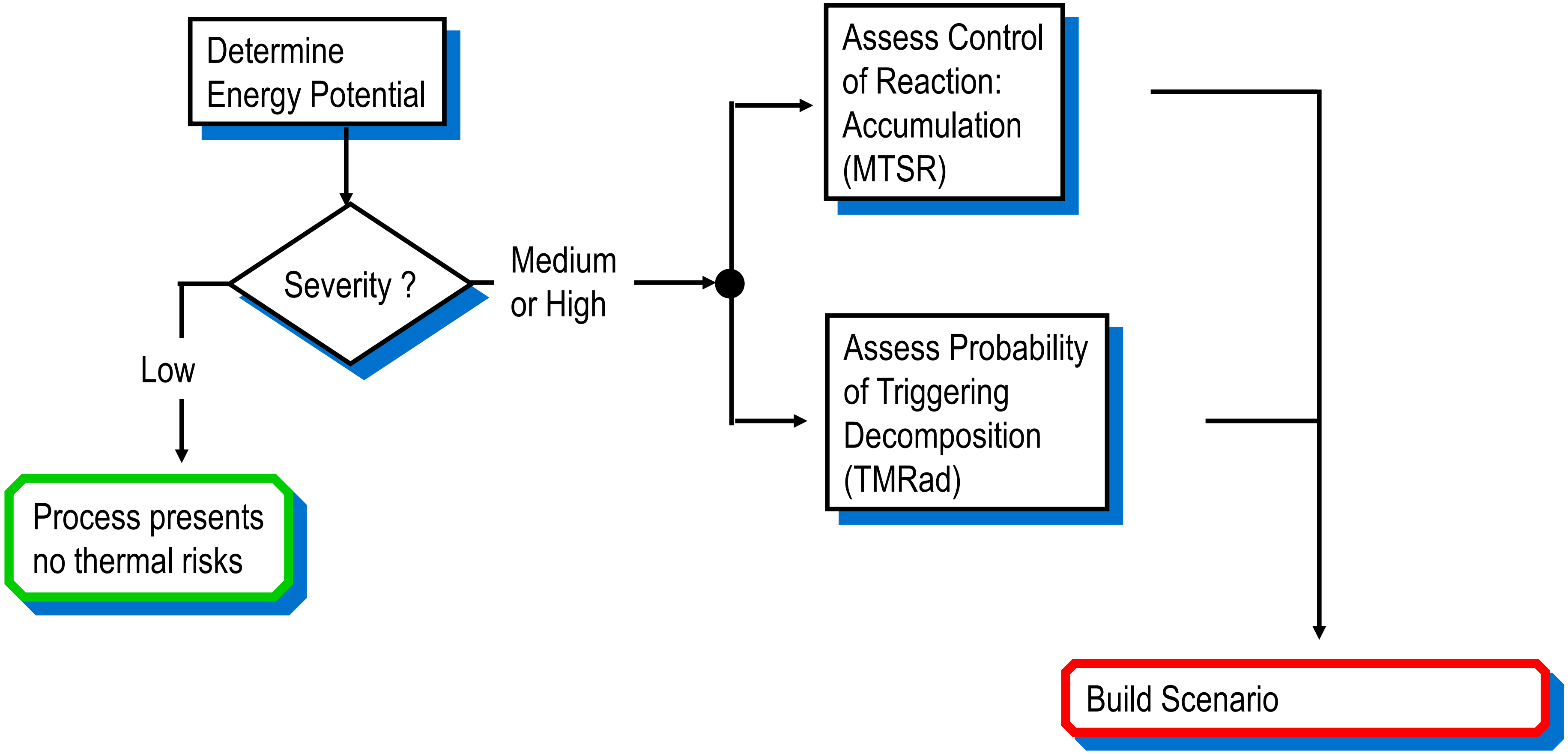
- Assessment Procedure



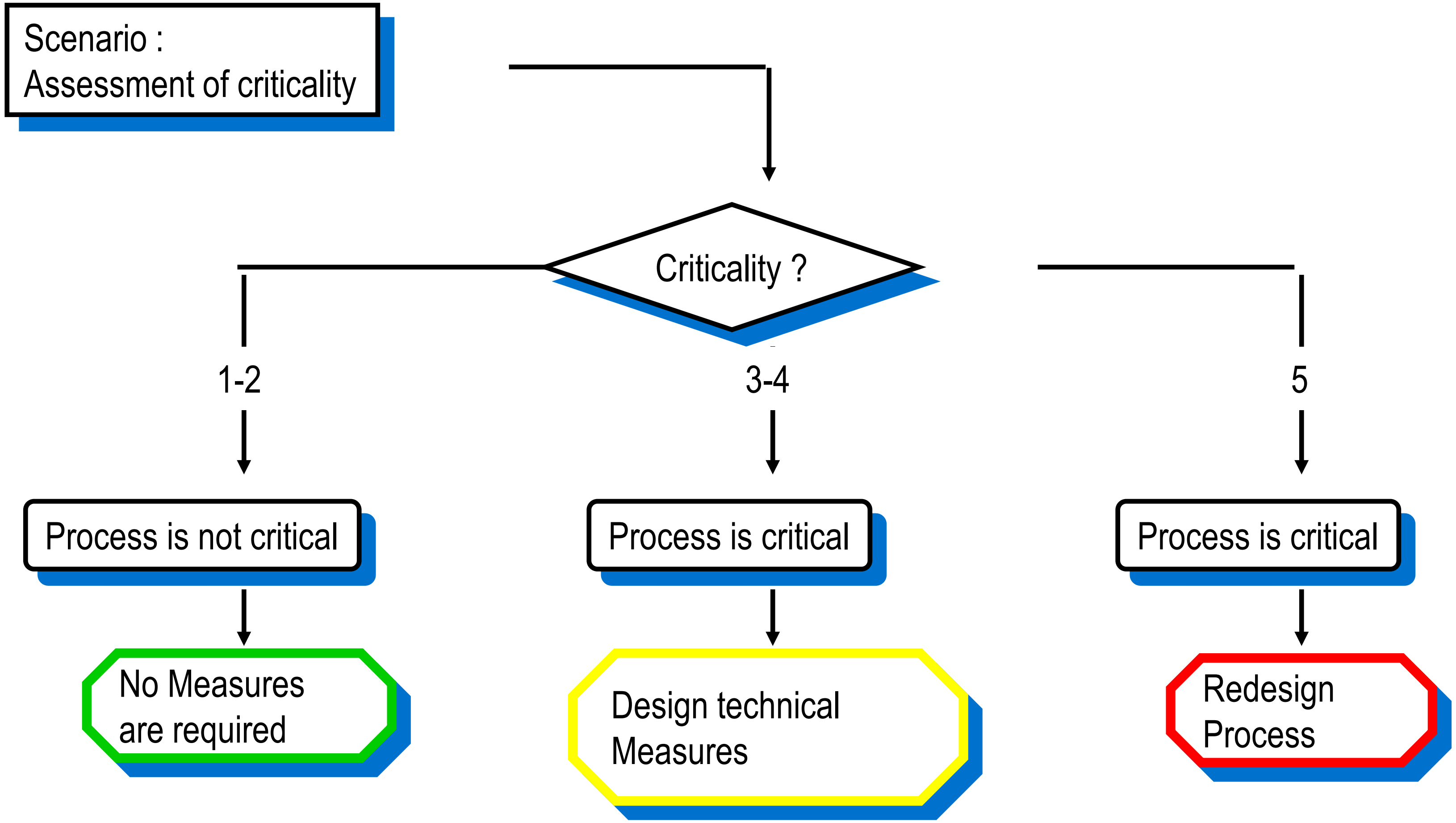


Chapters 2 and 3

Thermal Risks: Required Data



Thermal Risks: Assessment



Scenario :
Assessment of criticality

Criticality ?

1-2

Process is not critical

No Measures are required

3-4

Process is critical

Design technical Measures

5

Process is critical

Redesign Process

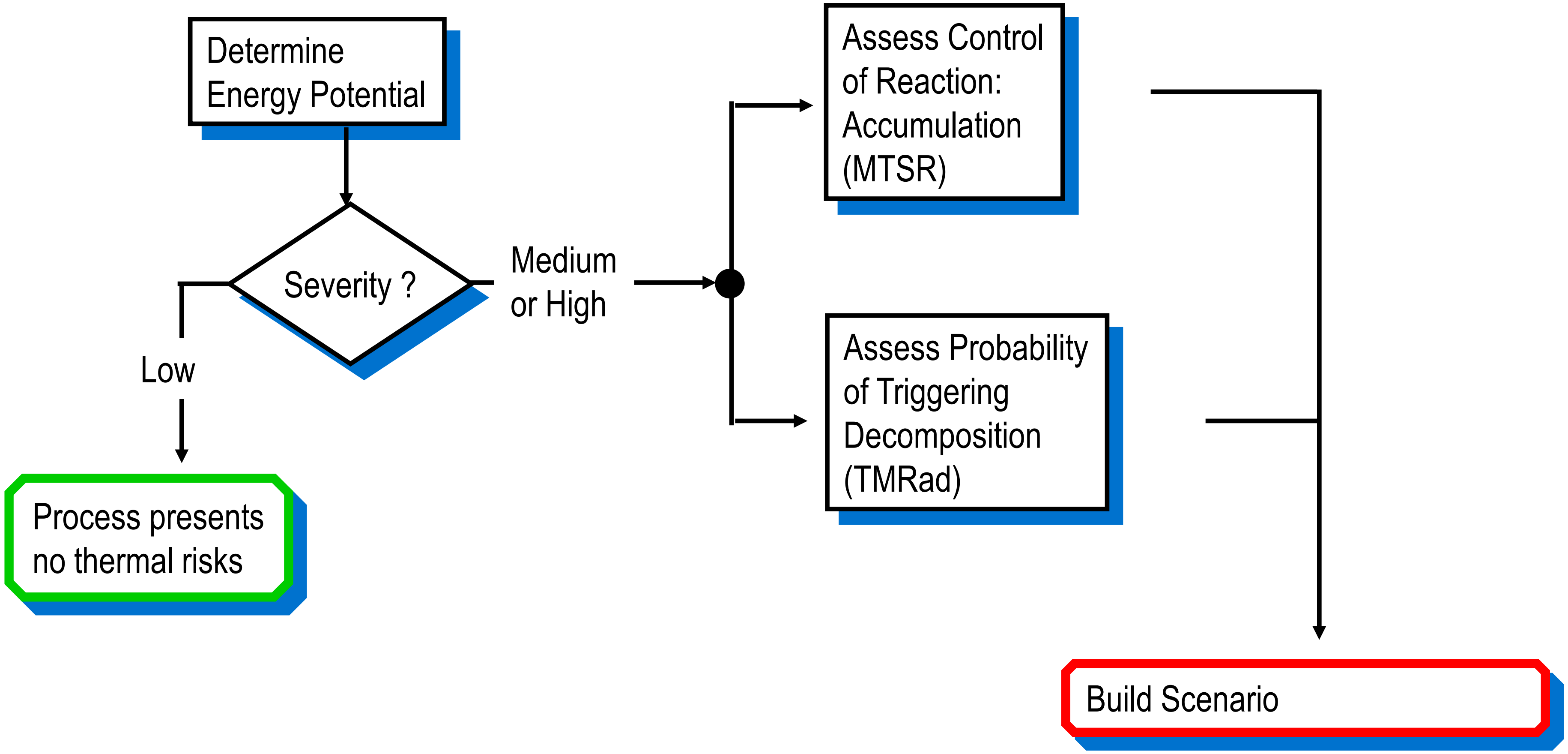
Example

- A diazotization is performed by adding sodium nitrite to an aqueous solution of the amine (2.5 mol kg^{-1}). The industrial scale charge is 4000 kg of final reaction mass in a stirred tank reactor with a nominal volume of 4 m^3. The reaction temperature is 5 °C and the reaction is very fast. For the safety study an accumulation of 10 % is considered realistic.

- Thermal data :
  - Reaction : $-\Delta H_r = 65$ kJ/mol cp' = 3,5 kJ/(kg·K)
  - Decomposition: $-\Delta H_{dc} = 150$ kJ/mol $T_{D24} = 30$ °C

- What is the thermal risk of this reaction?

Thermal Risks: Required Data



Determine Energy Potential

Severity ?

Low

Process presents no thermal risks

Medium or High

Assess Control of Reaction: Accumulation (MTSR)

Assess Probability of Triggering Decomposition (TMRad)

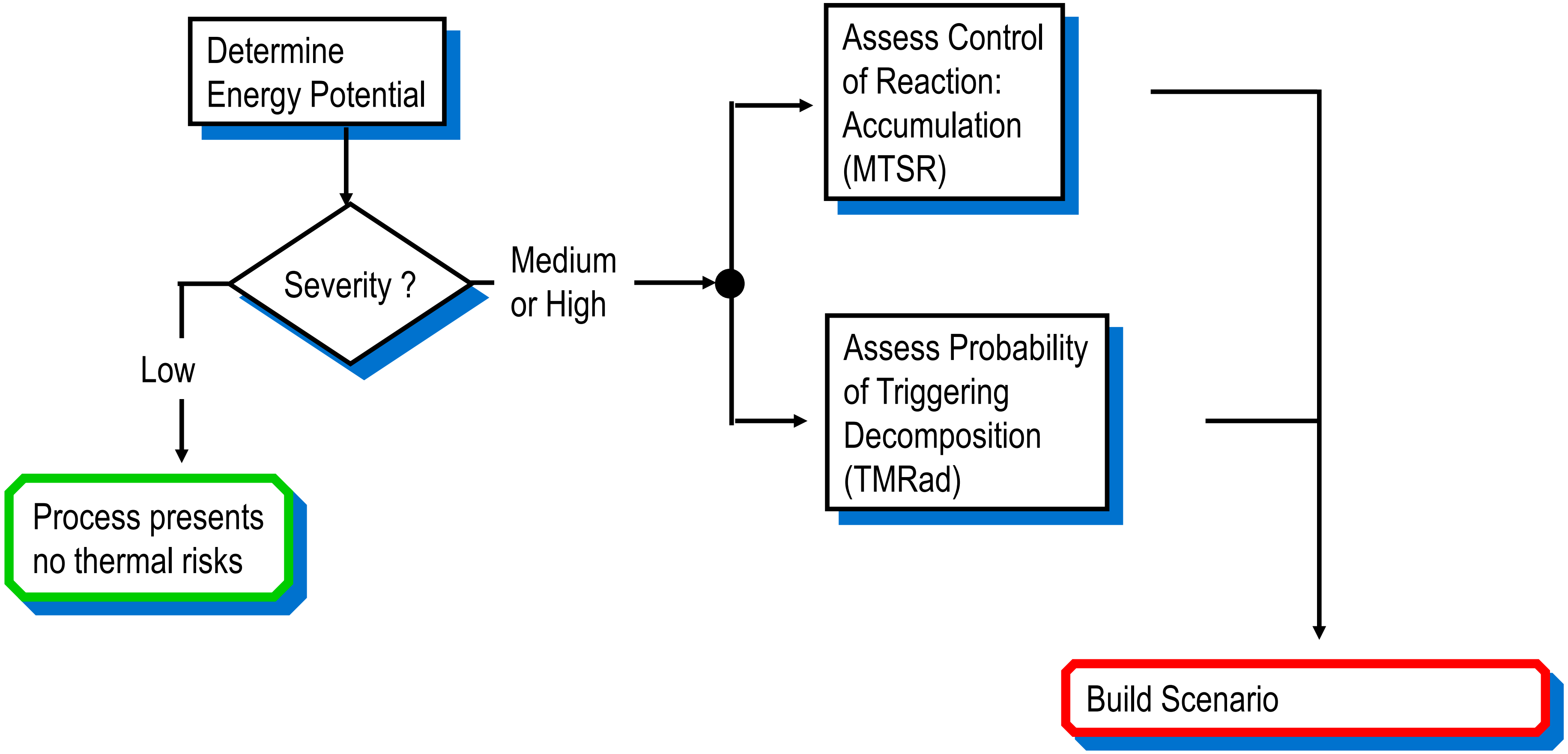
Build Scenario

Example

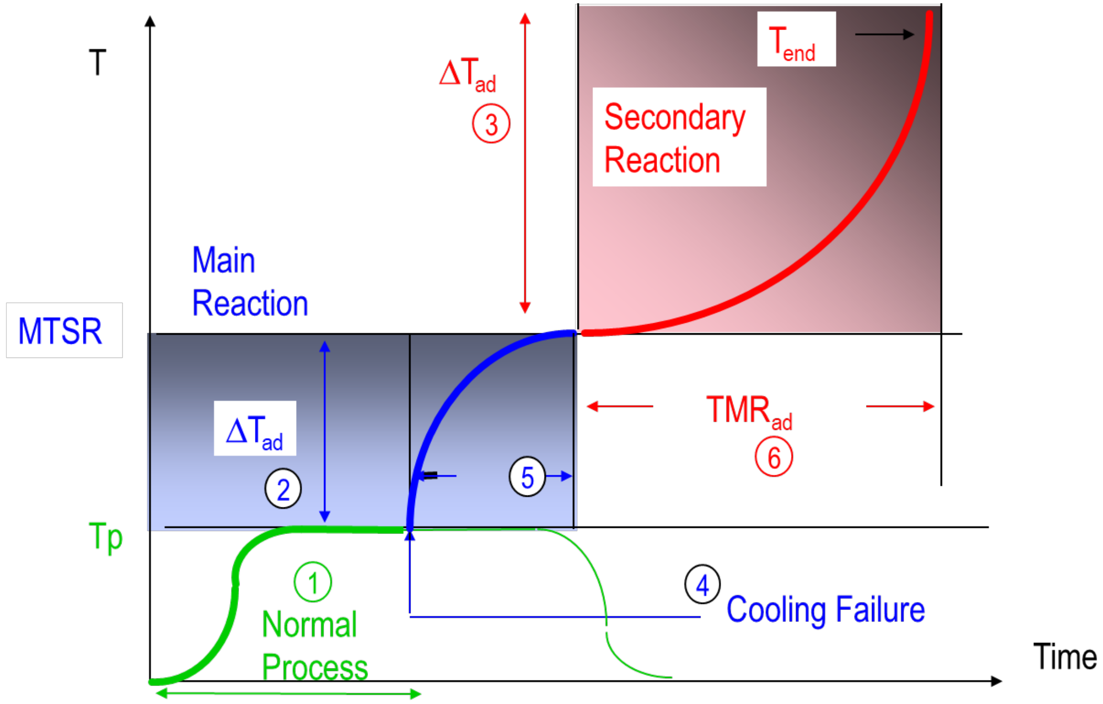
- Determine energy potential
  - Reaction energy: 2.5 mol/kg is the concentration and the reaction enthalpy is -ΔHr = 65 kJ/mol
  - Specific **reaction** energy: $Q'_{rx} = 2.5\,\frac{mol}{kg} \cdot 65\,\frac{kJ}{mol} = 162.5\,\frac{kJ}{kg}$
  - Adiabatic temperature rise reaction $\Delta T_{ad,rxn} = \frac{Q'_{rx}}{c'_p} = \frac{162.5\frac{kJ}{kg}}{3.5\frac{kJ}{kg \cdot K}} = 46K$
  - Specific **decomposition** energy: $Q'_{dec} = 2.5\,\frac{mol}{kg} \cdot 150\,\frac{kJ}{mol} = 375\,\frac{kJ}{kg}$
  - Adiabatic temperature rise decomposition $\Delta T_{ad,dec} = \frac{Q'_{rx}}{c'_p} = \frac{375\frac{kJ}{kg}}{3.5\frac{kJ}{kg \cdot K}} = 107K$
- Overall ΔTad 151°C: medium consequences

Criteria	Consequences	Probability
High	ΔTad > 200°C	TMRad < 8 h
Medium	50°C < ΔTad < 200°C	8 h < TMRad < 24 h
Low	ΔTad < 50°C and no pressure	TMRad > 24 h

Thermal Risks: Required Data



Example



1	Is the **cooling capacity** sufficient to remove the heat released by the reaction under normal operating conditions?	4	**When** does the cooling failure have the worset consequences?
2	What **temperature** may be reached after runaway of the **main reaction**?	5	**How long** does the runaway of the main reaction take?
3	What **temperature** may be reached after runaway of **secondary reaction**	6	**How long** does the runaway of the secondary reaction take?

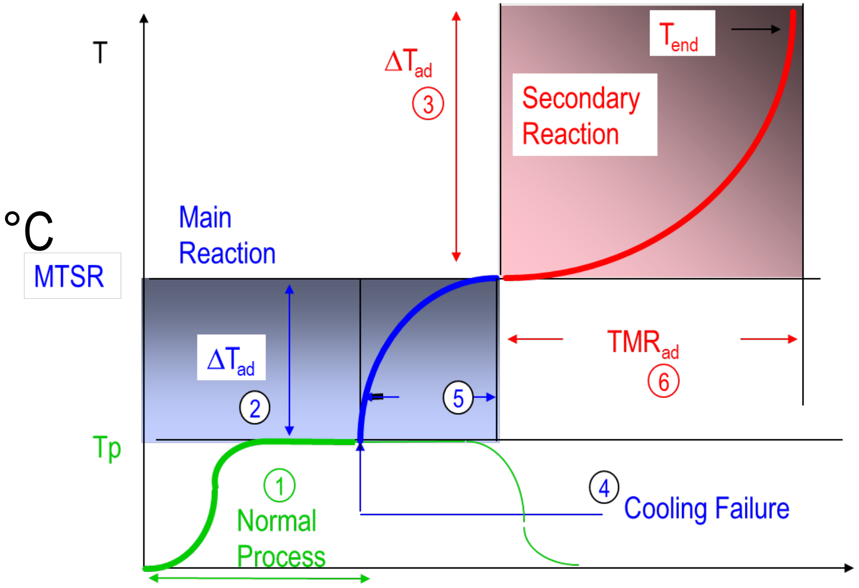
Example

1. Is the **cooling capacity** sufficient to remove the heat released by the reaction under normal operating conditions?

- No information on cooling capacity of the installation q_{ex}
- No information on heat release rate of the reaction q_{rx}
- Not possible to assess this question with the available data → remains an open question

2. What temperature may be reached after runaway of the main reaction?

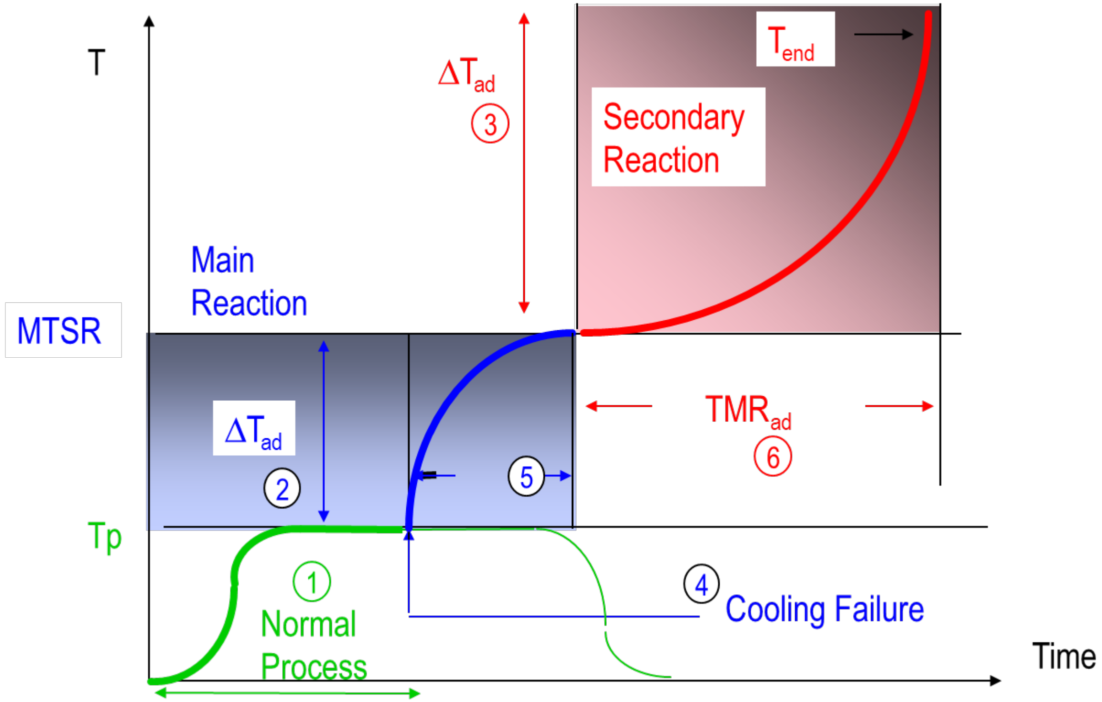
- Calculate adiabatic temperature rise:
  - Batch: $\Delta T_{ad,rxn} = \frac{Q'_{rx}}{c'_p} = \frac{162.5\frac{kJ}{kg}}{3.5\frac{kJ}{kg\cdot K}} = 46K$ MTSR=Tp+ΔTad_{rxn}=5+46=51°C
  - Semi-batch 10% accumulation: MTSR=Tp+ $Xacc\Delta Tad_{rxn}$= 5 +0.1*46=9.6°C



Example

3. What temperature may be reached after runaway of the secondary reaction?

- Calculate adiabatic temperature rise:
  - $\Delta T_{ad,dec} = \frac{Q'_{rx}}{c'_p} = \frac{375\frac{kJ}{kg}}{3.5\frac{kJ}{kg\cdot K}} = 107K$
  - T_f=MTSR+ ΔTad_{dec}
  - Batch: Tf=51+107=158°C
  - Semi-batch: Tf=10+107=117°C



Example

4. When does the cooling failure have the worst consequences?

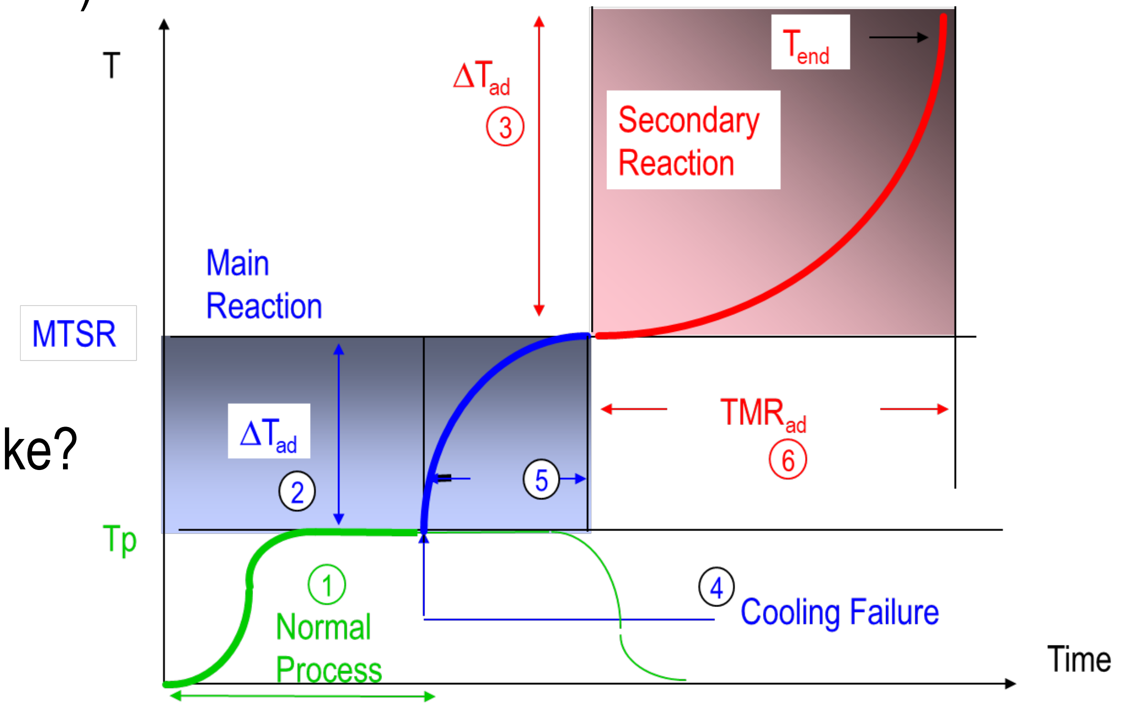
- For batch: at the beginning of the process (full accumulation)
- For semi-batch: at the maximum accumulation

5. How long does the runaway of the main reaction take?

- No information → conservative to neglect

6. How long does the runaway of the secondary reaction take?

- TMRad from the MTSR
  - MTSR Batch 51°C
  - MTSR Semi-batch 10°C
  - TD_{24}=30°C
  - Batch: MTSR > TD_{24} → TMRad < 24h for Batch
  - Semi-batch: MTSR<TD_{24} → TMRad > 24h for Semi-batch



Example

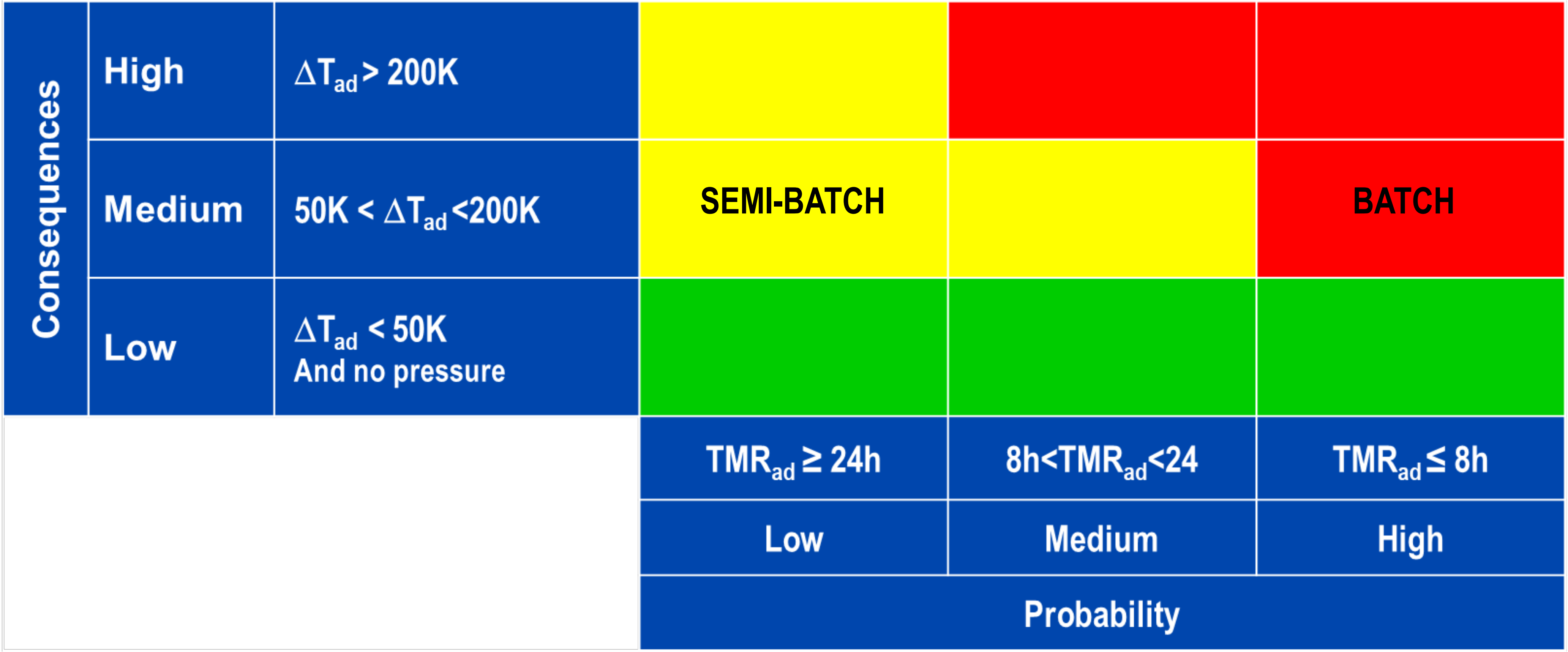
- Probability of runaway TD_{24}=30°C
  - Estimation by extrapolating with van't Hoff rule
  - Batch: TMRad at 51°C: ~6h → High probability of runaway
  - Semi-batch: TMRad at 10°C: ~100h → Low probability of runaway

T	TMRad
0	~200h
10	~96h
20	~48h
30	**~24h**
40	~12h
50	~6h

Criteria	Consequences	Probability
High	ΔTad > 200°C	TMRad < 8 h
Medium	50°C < ΔTad < 200°C	8 h < TMRad < 24 h
Low	ΔTad < 50°C and no pressure	TMRad > 24 h

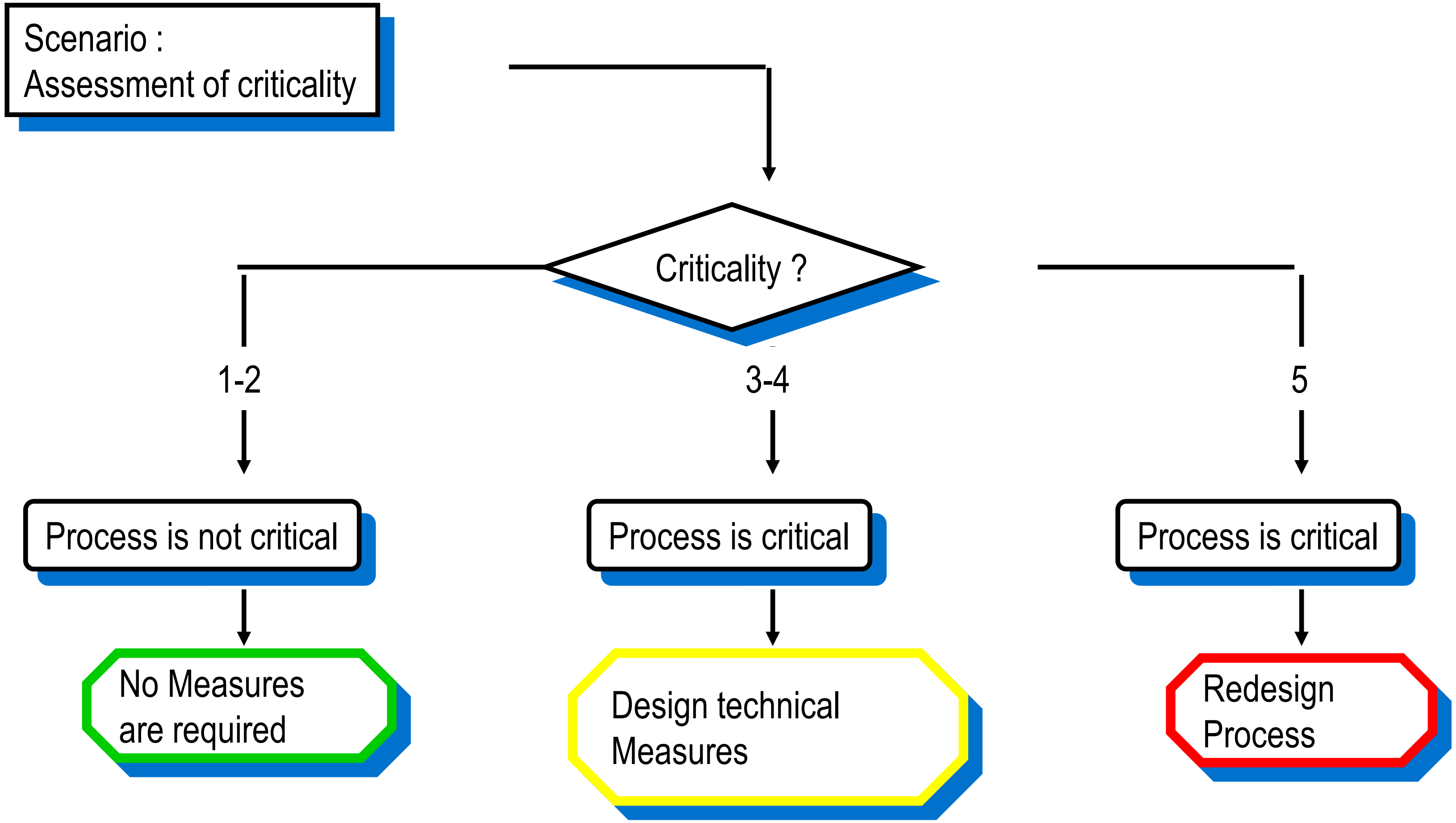
Example

- Thermal risk



Consequences	High	$\Delta T_{ad} > 200K$	🟨	🟥	🟥
	Medium	$50K < \Delta T_{ad} < 200K$	🟨 SEMI-BATCH	🟨	🟥 BATCH
	Low	$\Delta T_{ad} < 50K$ And no pressure	🟩	🟩	🟩
			$TMR_{ad} \geq 24h$	$8h < TMR_{ad} < 24$	$TMR_{ad} \leq 8h$
			Low	Medium	High
			Probability		

Thermal Risks: Assessment



Scenario :
Assessment of criticality

Criticality ?

1-2

3-4

5

Process is not critical

Process is critical

Process is critical

No Measures
are required

Design technical
Measures

Redesign
Process

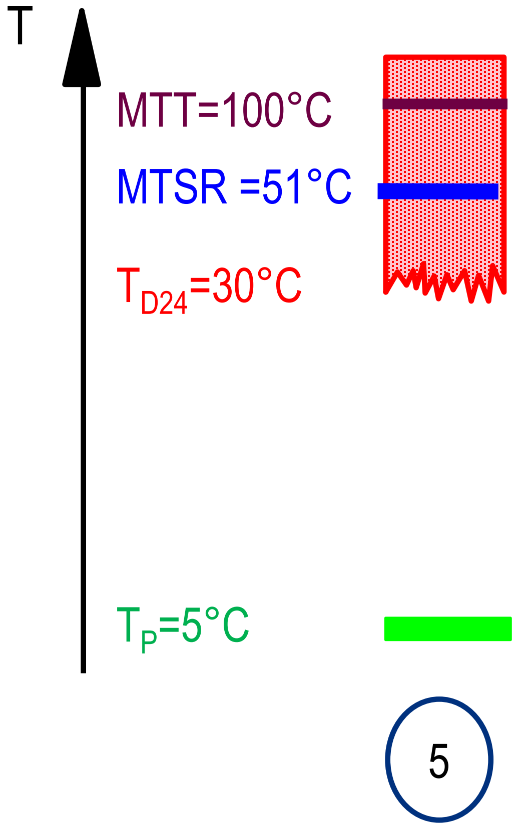
Characteristic Temperatures

- Tp : Process Temperature
  Defined by the mode of operation
- MTSR: Maximum Temperature of Synthesis Reaction
  Defined by the accumulation of reactants and Tp
- T_{D24}: Temperature at which the Decomposition becomes critical TMRad = 24 hrs
  Defined by the thermal stability of reaction mass
- MTT: Maximum Temperature for Technical Reasons
  Defined by the equipment

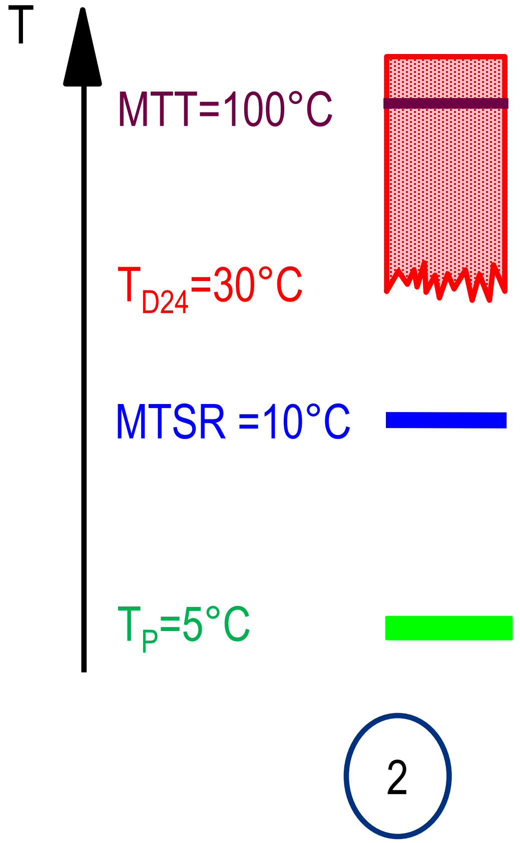
Tp: 5°C $MTSR_B$=51°C $MTSR_{SB}$=10°C T_{D24}=30°C MTT=~100°C (aqueous system, boiling T)

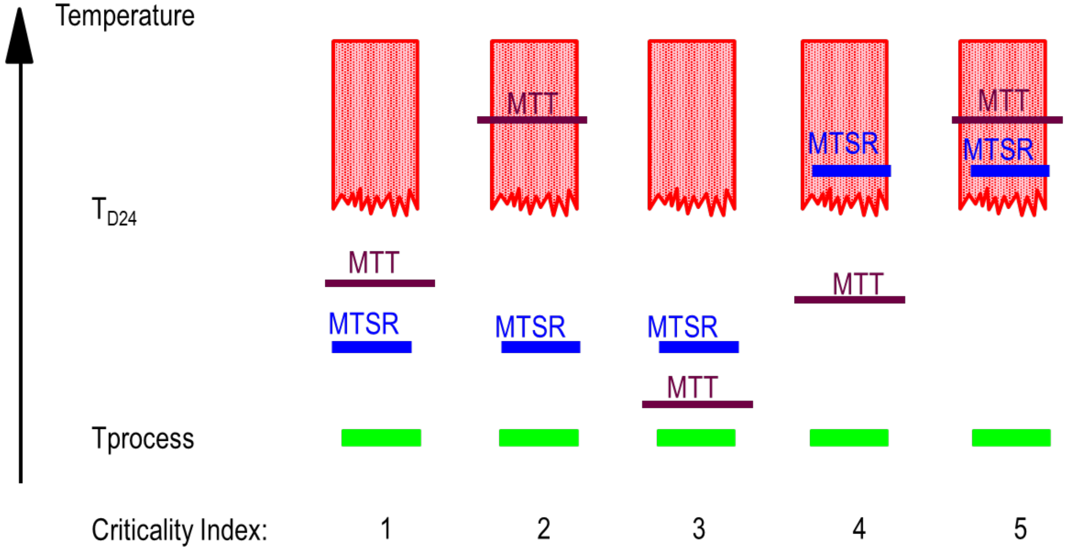
Classification of Scenarios

Batch



Semi-Batch



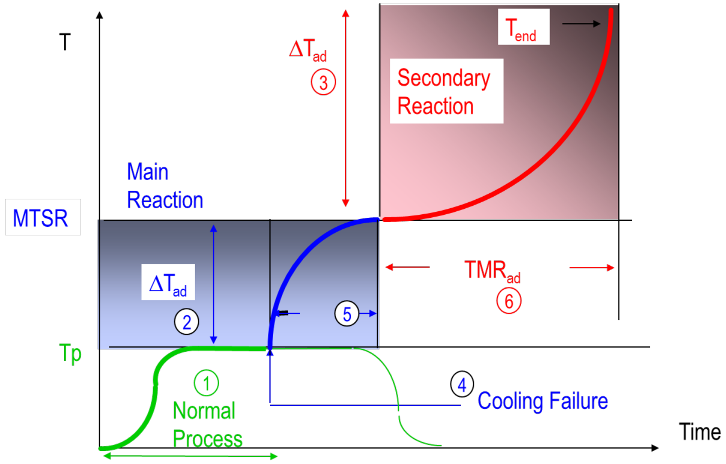


Example

- Conclusions

Key points Cooling failure and Criticality Class

- Cooling Failure Scenario is the scenario used to assess the thermal hazard of a process
  - Graph (normal conditions, main reaction, secondary reaction)
  - Six questions and Nomenclature
    - MTSR: maximum temperature of the synthesis reaction
    - Tf or Tend: final temperature
    - TMR_{ad} or tmr_{ad}: time to maximum rate under adiabatic conditions



- Criteria for severity and probability assessment for thermal hazard
  - Consequences: adiabatic temperature increase

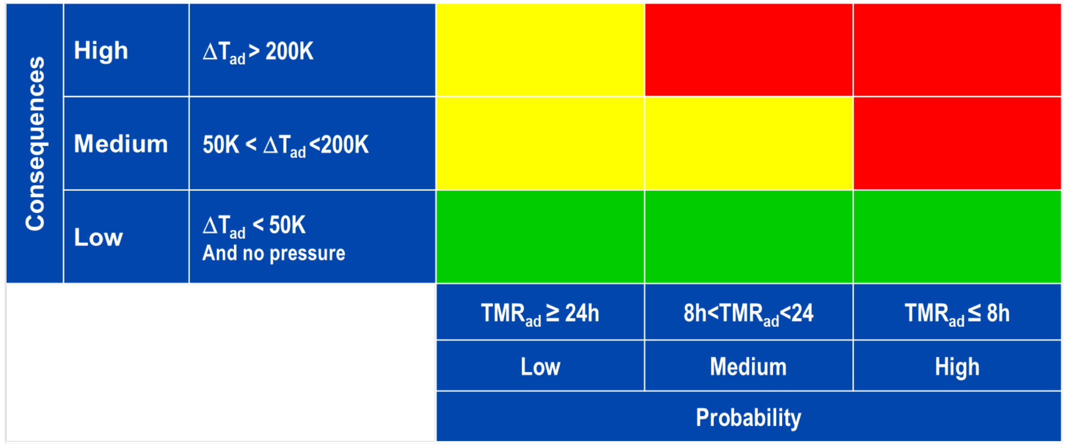
$$\Delta T_{ad} = \frac{Q'}{c_p'}$$

  - Probability: TMRad or tmrad

Criteria	Consequences	Probability
High	ΔTad > 200°C	TMRad < 8 h
Medium	50°C < ΔTad < 200°C	8 h < TMRad < 24 h
Low	ΔTad < 50°C and no pressure	TMRad > 24 h

Key points Cooling failure and Criticality Class

- Thermal Risk



Consequences	**High**	$\Delta T_{ad} > 200K$	🟨	🟥	🟥
	Medium	$50K < \Delta T_{ad} < 200K$	🟨	🟨	🟥
	Low	$\Delta T_{ad} < 50K$ And no pressure	🟩	🟩	🟩
			$TMR_{ad} \geq 24h$	$8h < TMR_{ad} < 24$	$TMR_{ad} \leq 8h$
			Low	Medium	High
			Probability		

- Convert probability (TMRad) into a temperature (T_{D24})
- Use 4 Temperatures to build-up criticality classes: (Tp, MTSR, MTT (boiling T for an open system), T_{D24})