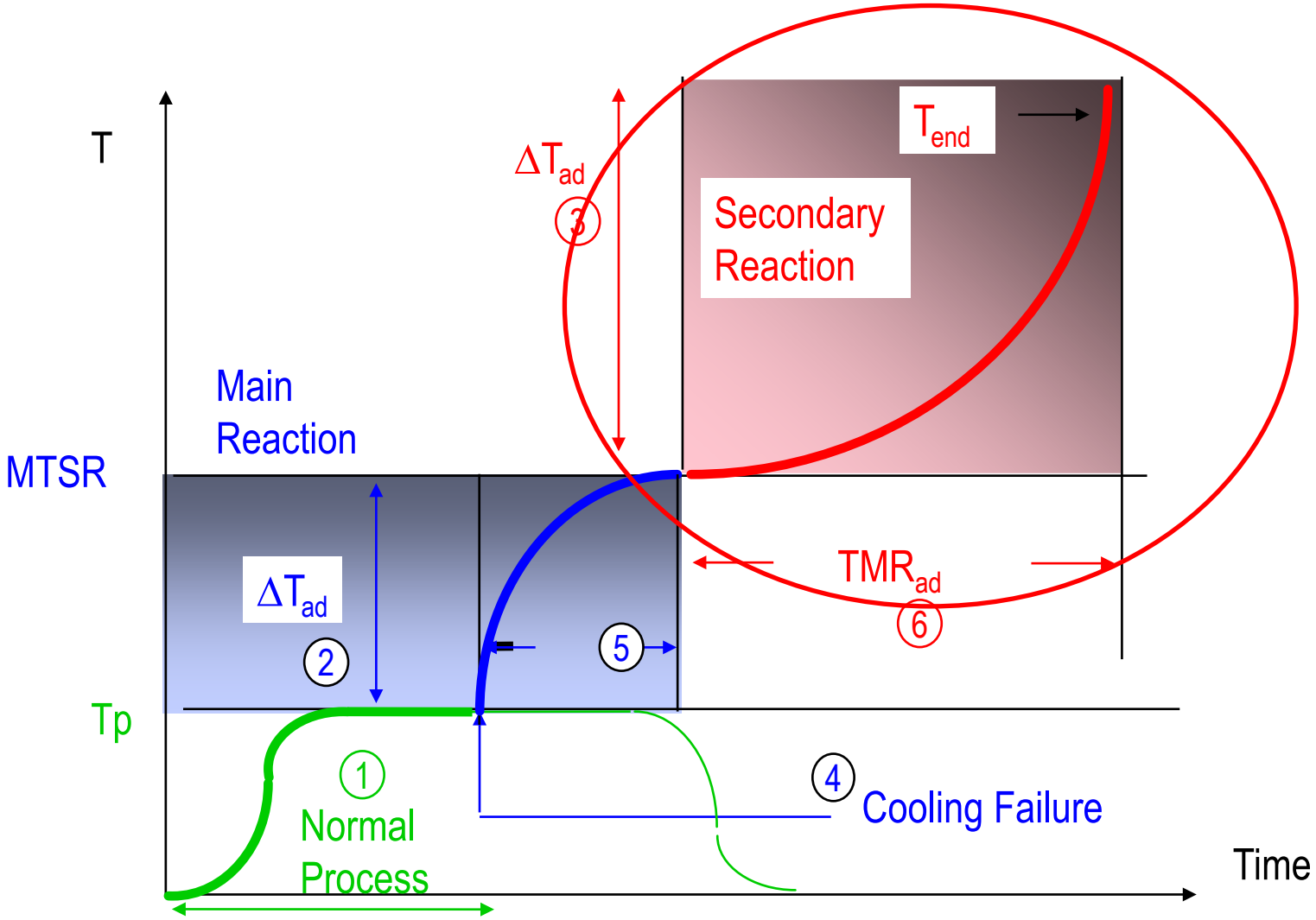
Thermal Stability
The TMRad concept

Module 4

ENG 431: Safety Cehcmical Processes

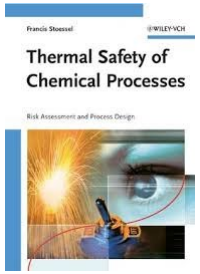
Annik Nanchen

Cooling Failure Scenario

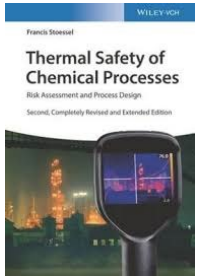


Decomposition Reactions

- What are decomposition reactions?
- Characterisation of secondary reaction
  - Energy of decomposition
  - Onset and Safety Margin
  - Determination of TMR_{ad}
- Examples
- Highly energetic molecules



Chapter 11

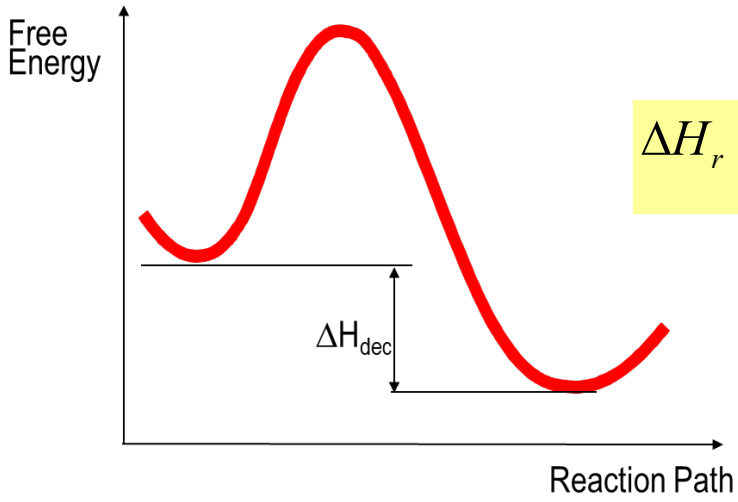


Chapter 10

Examples when the study of decomposition reaction is required

Decomposition Reactions

- Stoichiometry often unknown: cannot estimate the decomposition energy



$$\Delta H_r = \sum_{\text{Products}} \Delta H_f - \sum_{\text{Reactants}} \Delta H_f$$

ΔH_r: reaction enthalpy	J/mol
ΔH_f: enthalpy of formation	J/mol
ΔH_{dec}: decomposition enthalpy	J/mol

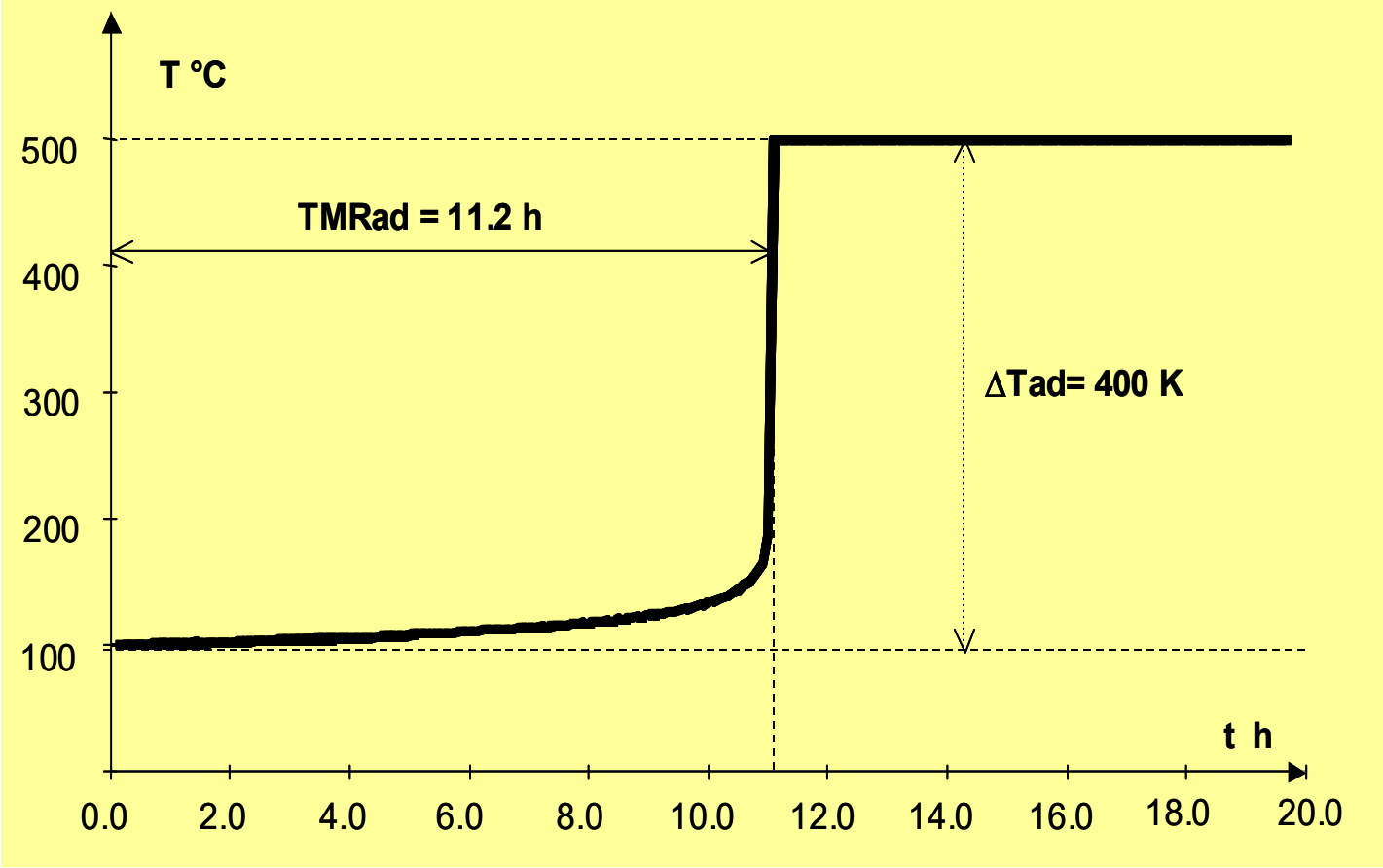
- High energies
- Gaseous products
- Difficult to predict triggering conditions
  - Sensitive towards catalytic effects
  - Sensitive to impurities

Decomposition Reactions

- What are decomposition reactions?
- Characterisation of secondary reaction
  - Energy of decomposition
  - Onset and Safety Margin
  - Determination of TMR_{ad}
- Examples

Characterisation of Decomposition Reactions

- Characterisation: Risk: probability x severity



Decomposition Energies

- Can be estimated based on structure and functional groups

Group	ΔU (kJ/mole)
Acetylene	120-170
Epoxide	70-100
Azo	100-180
Diazonium	160-180
Diazo	170-190
Azide	200-240
Triazene	250-270
Aldoxime	190-230
Ketoxime	140-170
N-hydroxide	180-240
N-oxide	100-130
Nitroso	150-290
Isocyanate	50-70
C-nitro	310-360

Compiled from literature sources (Hasegawa & Nuba, 1992; Grewer, 1994, Whitmore & Baker 1999)

Severity: ΔTad

$$\Delta T_{ad} = \frac{Q'_R \quad [kJ/kg]}{c_p' \quad [kJ/(kg.K)]}$$

ΔT_{ad}	adiabatic temperature rise (°C or K)
Q'_R	heat of reaction (kJ/kg)
c_p'	specific heat capacity (kJ/kg/K)

Typical values for c'_p:

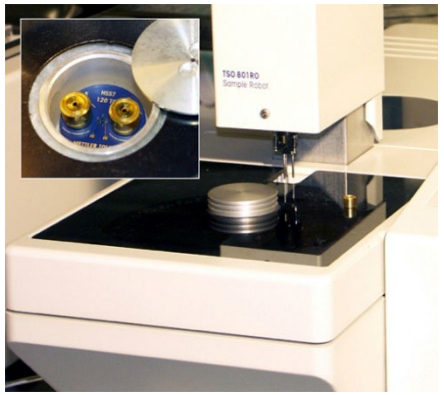
H_2SO_4	1.3 kJ/kg/K
H_2O	4.2 kJ/kg/K
Organic liquids	1.8 kJ/kg/K
Organic solids	1.3 kJ/kg/K

Decomposition Reactions

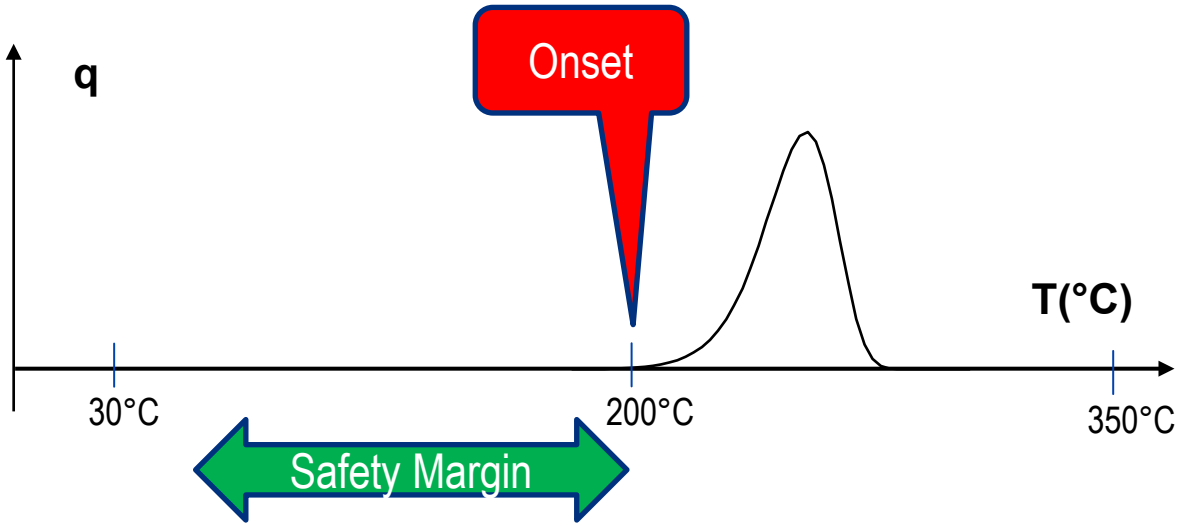
- What are decomposition reactions?
- Characterisation of secondary reaction
  - Energy of decomposition
  - Onset and Safety Margin
  - Determination of TMR_{ad}

Safety Margin

- What is a safe temperature?
  - Perform measurement and then?

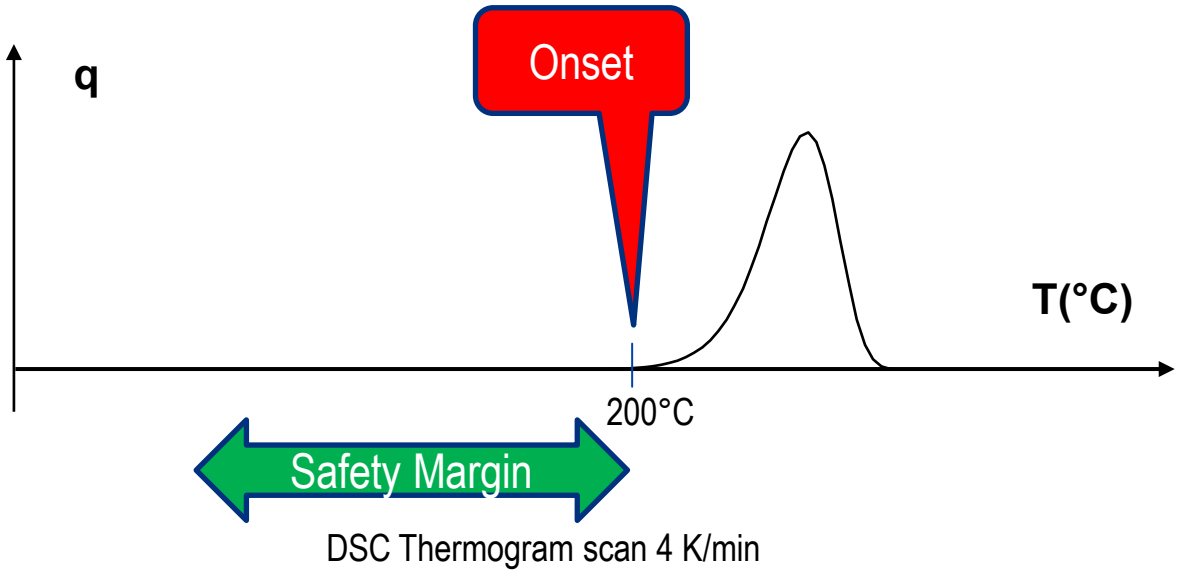


DSC Thermogram, measured in scan mode



DSC Thermogram scan 4 K/min

What temperature is safe?



DSC Thermogram scan 4 K/min

A. < 250°C
B. < 200°C
C. < 150°C
D. < 100°C
E. < 50°C

Onset: The starting of a reaction

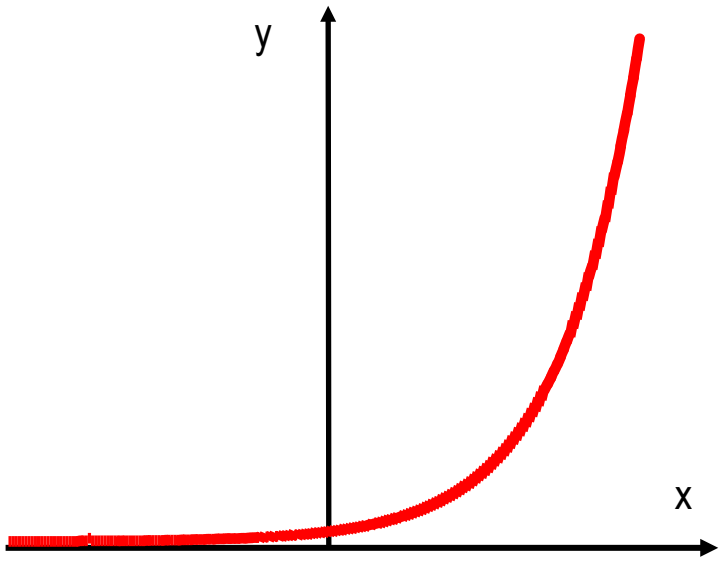
Onset: The starting of a reaction

- When does the reaction start = Onset Temperature ?

- Arrhenius equation to describe reaction rate

$$r = k_0 \cdot \exp\left[\frac{-Ea}{RT}\right] \cdot f(X)$$

r: reaction rate	mol/(l·s)
k_0: pre-exponential factor	units depend on reaction rate
E_A: activation energy	J/mol
R: gas constant	J/(mol·K)
X: conversion	-



$y = e^x$

$$x \to -\infty \Rightarrow y \to 0$$

$$T \to 0 \Rightarrow r \to 0$$

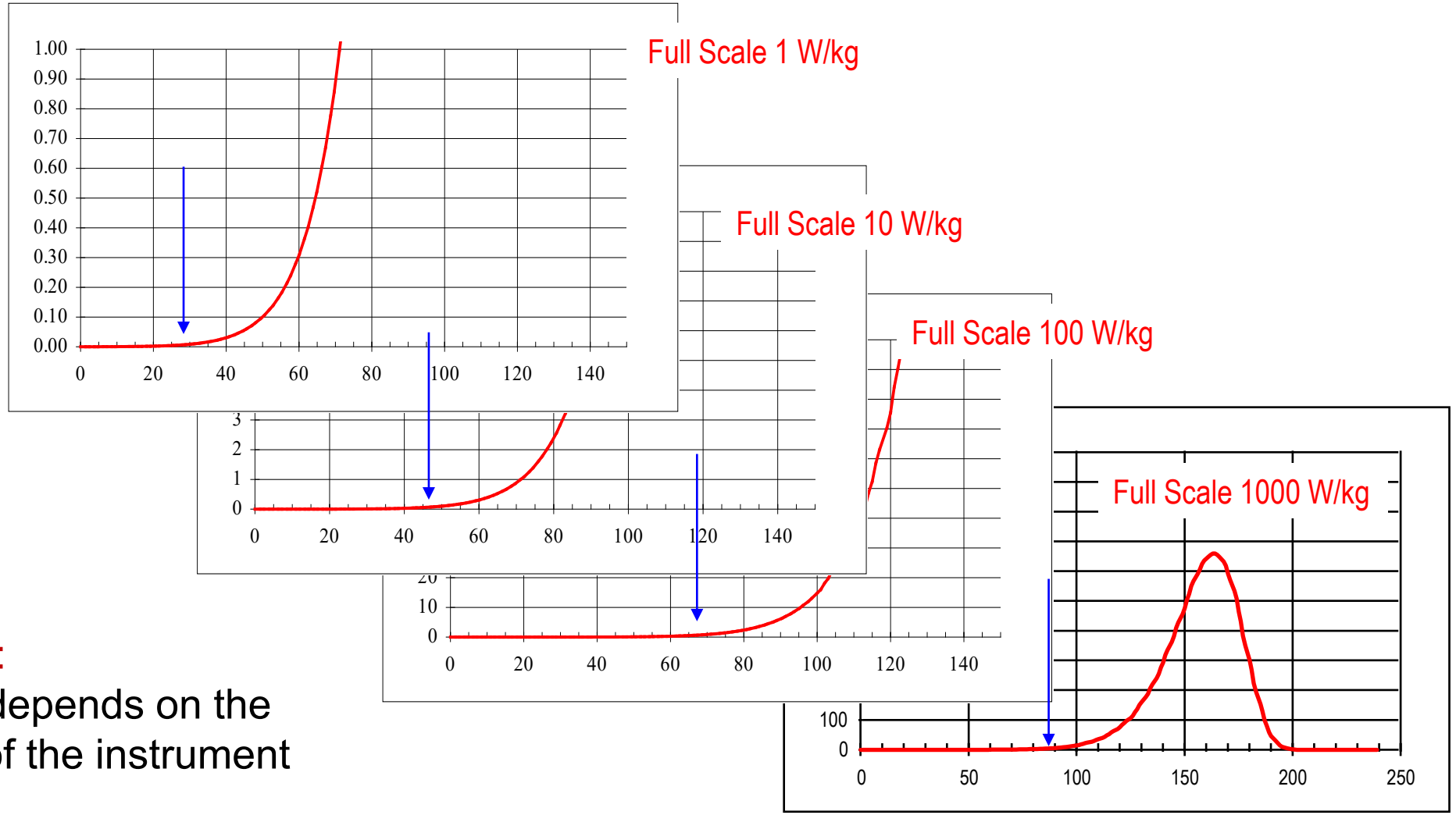
Conclusion:

The reaction rate is zero at 0K. The reaction is always active. Whether the reaction rate is relevant depends on time and scale

There is no «onset temperature for the decompositon».

Onset temperature defined as the measured detection of a decomposition peak

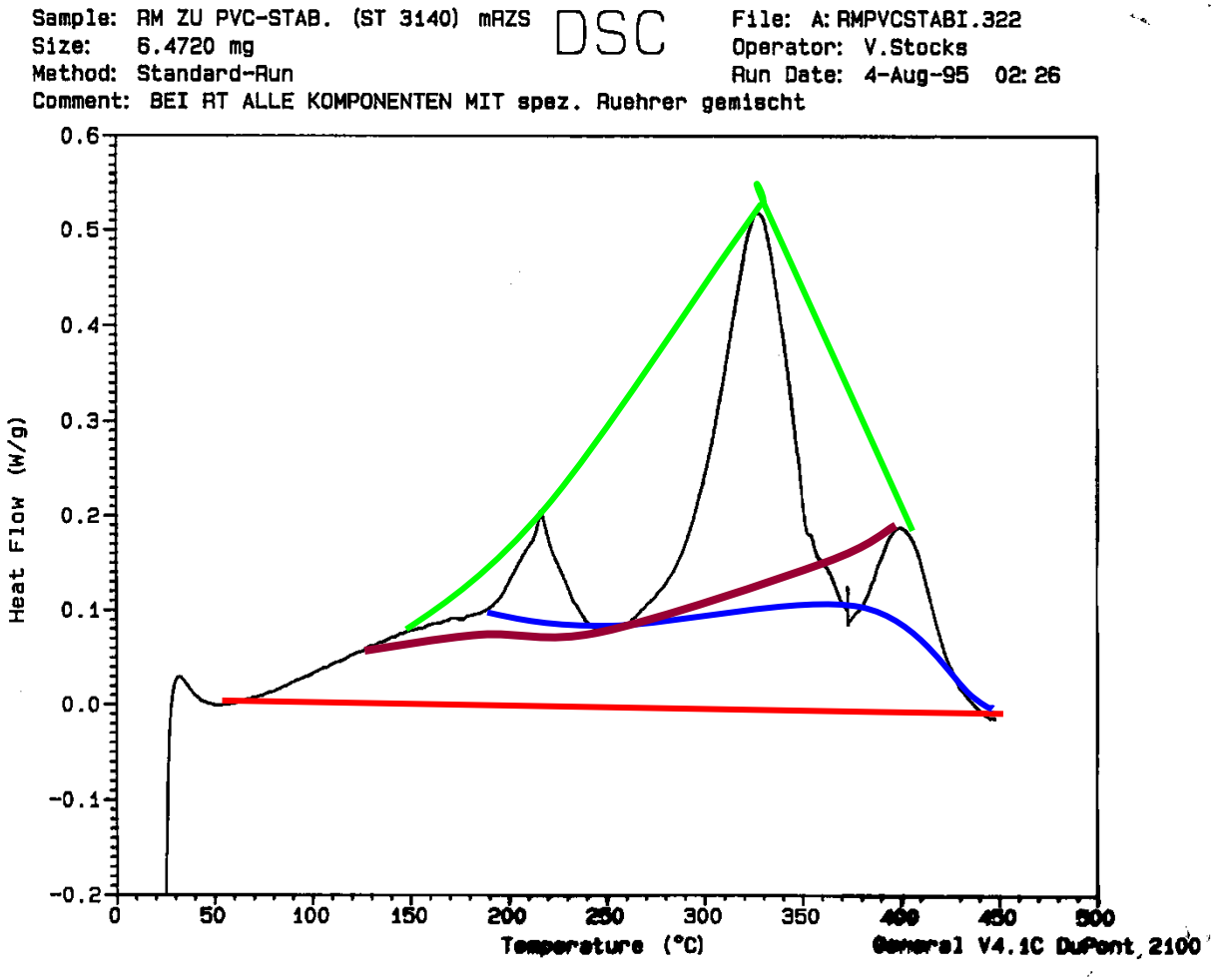
DSC: Sensitivity & Onset



Conclusion:

The onset depends on the sensitivity of the instrument

DSC: Baseline



Conclusion:

Setting a baseline requires experience and sometimes additional measurements.

The onset temperature depends strongly on the baseline.

Therefore, there is an uncertainity with respect to the onset temperature.

Conclusion on “on-set”

- There is no “on-set” temperature for a reaction
- The on-set temperature for a measurement depends on:
  - Sensitivity of the equipment → instrument and method dependent
  - Baseline

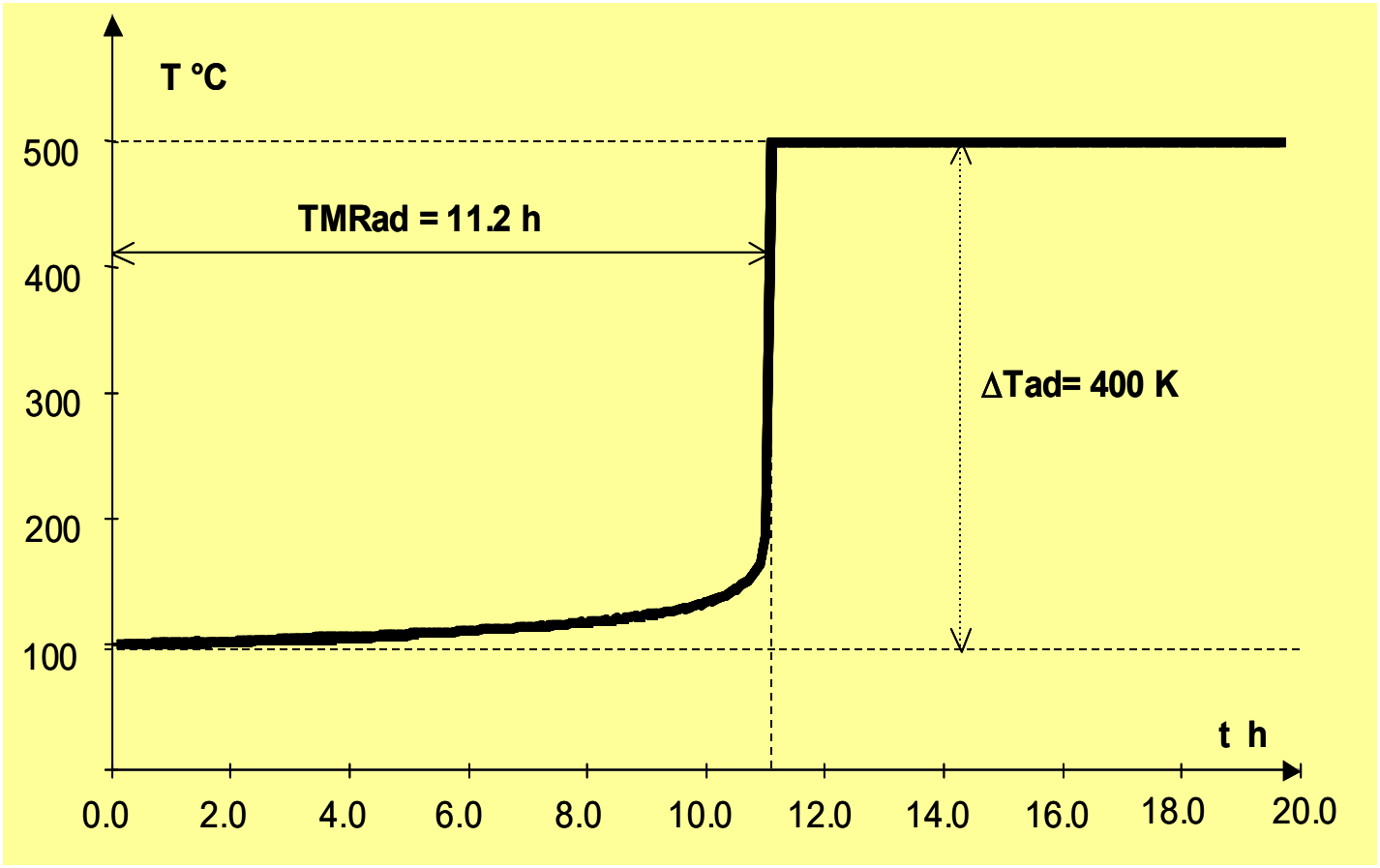
- Rules exist with safety margins (for example: 100°C below onset of DSC: safe situation). Those rules:
  - Are instrument and method dependent
  - Are not conservative: → there are exceptions to the rules
  - Depend on the situation/time to be assessed (storage of 100 m^3 is not the same than keeping a reaction mass in a reactor over a few hours)
  - Easy to have a first indication, but should not be used to exclude the risk of a decomposition

Decomposition Reactions

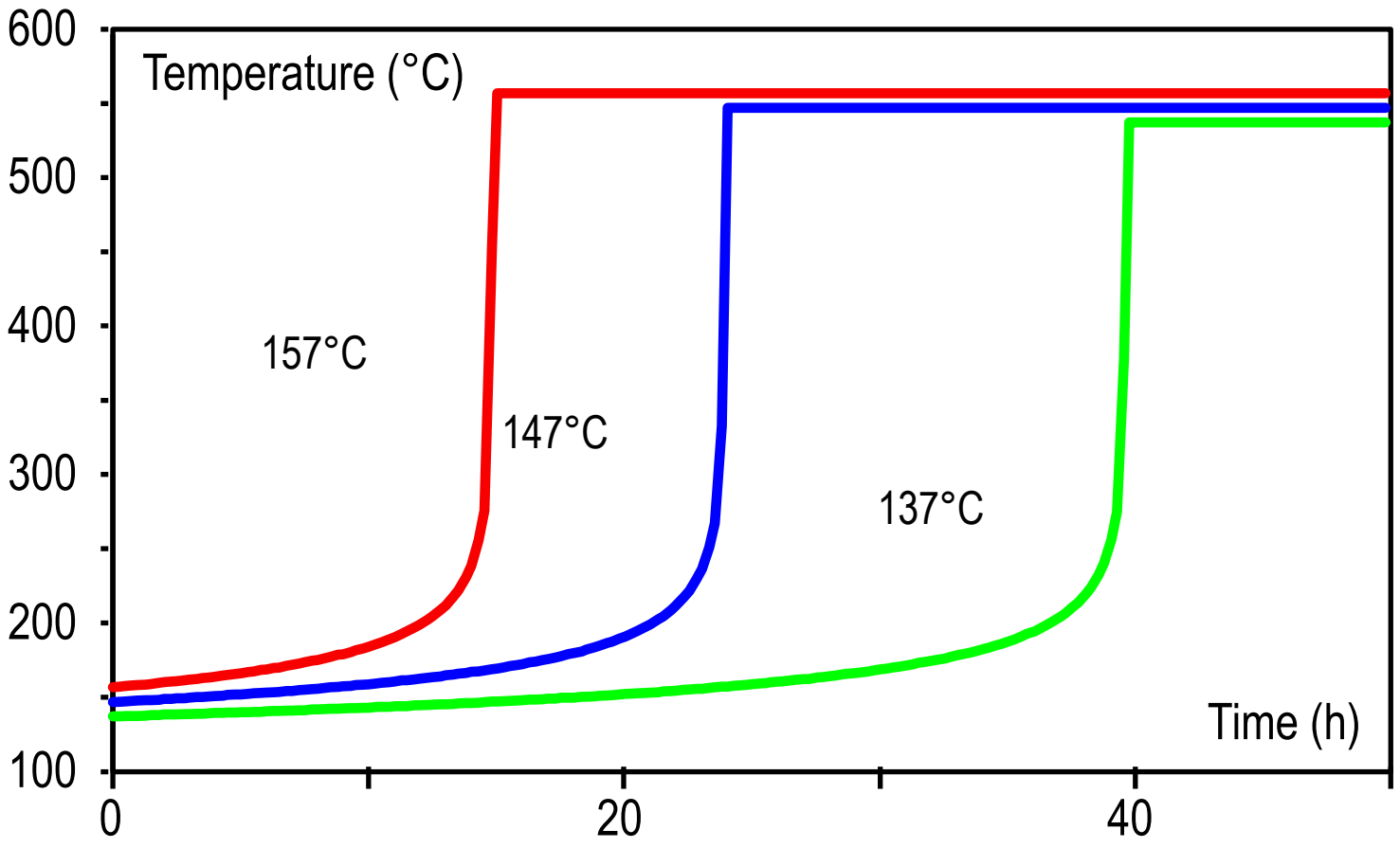
- What are decomposition reactions?
- Characterisation of secondary reaction
  - Energy of decomposition
  - Onset and Safety Margin
  - Determination of TMR_{ad}
    - Derivation of equation
    - Determination
- Examples
- Highly energetic molecules

Characterisation of Decomposition Reactions

- TMRad: Time to Maximum Rate under Adiabatic Conditions



Adiabatic Temperature Curves: Different Starting Temperatures



TMR_{ad}

$$\frac{dT}{dt} = \frac{q'}{c'_p} \quad \text{adiabatic conditions}$$

$$\frac{dT}{dt} = \frac{k_0 \cdot \exp\left(-\frac{E}{RT}\right) \cdot Q'_r}{c'_p} = \Delta T_{ad} \cdot k_0 \cdot \exp\left(-\frac{E}{RT}\right) \quad \text{Kinetic 0. Order}$$

$$q' = q'_0 \exp\left(-\frac{E}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right)$$

$$\frac{dT}{dt} = \left.\frac{dT}{dt}\right|_{T_0} \cdot \exp\left(\frac{E}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right) \approx \left.\frac{dT}{dt}\right|_{T_0} \cdot \exp\left(\frac{E}{R}\left(\frac{T - T_0}{T_0^2}\right)\right) \quad \text{conservativ approximation when } T > T_0$$

$$\Rightarrow \quad t_T \cdot \left.\frac{dT}{dt}\right|_{T_0} = \left[-\frac{RT_0^2}{E} \cdot \exp\left(-\frac{E}{R}\left(\frac{T - T_0}{T_0^2}\right)\right)\right]_{T_0}^{T} = \frac{RT_0^2}{E} \cdot \left\{1 - \exp\left(-\frac{E}{R}\left(\frac{T - T_0}{T_0^2}\right)\right)\right\}$$

TMR reached when $T = T_0 + \Delta T_{ad}$

$$TMR = \frac{RT_0^2}{E \cdot \left.\frac{dT}{dt}\right|_{T_o}} \cdot \left\{1 - \exp\left(-\frac{E}{R}\left(\frac{\Delta T_{ad}}{T_0^2}\right)\right)\right\} \approx \frac{RT_0^2}{E \cdot \left.\frac{dT}{dt}\right|_{T_o}}$$

for relevant, i.e. interesting exothermies

with $\left.\frac{dT}{dt}\right|_{T_o} = q'(T_0) / C_p$

$$TMR(T_0) = \frac{RT_0^2 C_P}{E \cdot q'(T_0)}$$

q' in W/kg

r: reaction rate	mol/(l·s)
k_0: pre-exponential factor	units depend on reaction rate
E_A: activation energy	J/mol
R: gas constant	J/(mol·K)
T: Temperature	K
T_0: Temperature of interest	K
t: time	s
Q': specific reaction energy	J/kg
q': specific heat release rate	W/kg
c'_p: specific heat capacity	kJ/(kg·K)

Conclusion:

TMRad based on heat balance

Hypothesis:

- 0 order reaction
- Adiabatic conditions

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

Approximate estimation in seconds

$$TMR_{ad} = \frac{c_{p'} \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E}$$

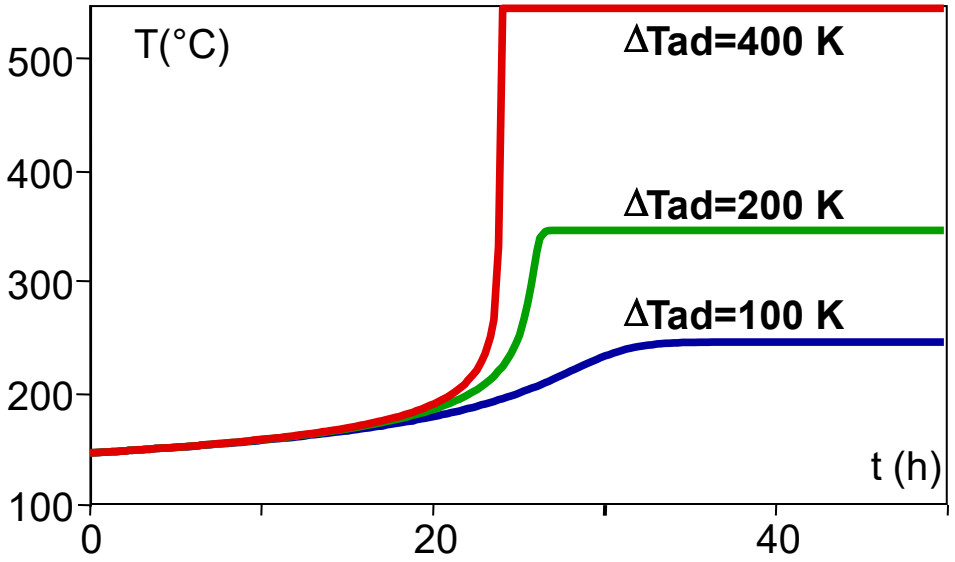
c_p'	specific heat capacity [J / kg / K]
R	universal gas constant 8.314 J /(mol. K)
T	temperature (K)
$q'_{(T0)}$	Heat release rate at T_0 [W / kg]
Ea	Activation energy [J / mol]

Decomposition reactions: 0 order approximation

$$r = k_0 \cdot \underbrace{\exp\left[-E/RT\right]}_{\text{Increases}} \cdot C_0 \quad \underbrace{\cdot(1-X)}_{\text{Decreases}}$$

r: reaction rate	mol/(l·s)
k_0: pre-exponential factor	1/s
E: activation energy	J/mol
R: gas constant	J/(mol·K)
T: Temperature	K
C_0: initial concentration	mol/l
X: conversion	-

Adiabatic conditions: 1st order exothermic reactions with different reaction energies (same activation energy and initial concentration)



Conclusion:

0 order approximation:

- Good estimation of TMRad for high decomposition energies
- Conservative for lower decomposition energies

Decomposition Reactions

- What are decomposition reactions?
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  - Determination of TMR_{ad}
    - Derivation of equation
    - Determination
- Examples

Determination: TMR_{ad}

- Required data:
  - q'(T)
  - Ea

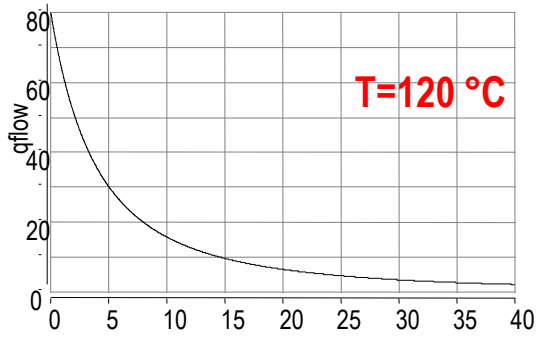
- Isothermal method 1
- Isoconversional method 2
- Simplified method (rule of thumb) 3

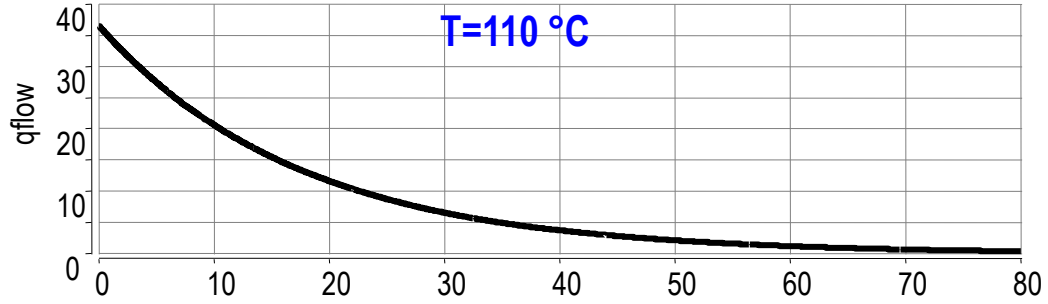
Approximate estimation in seconds

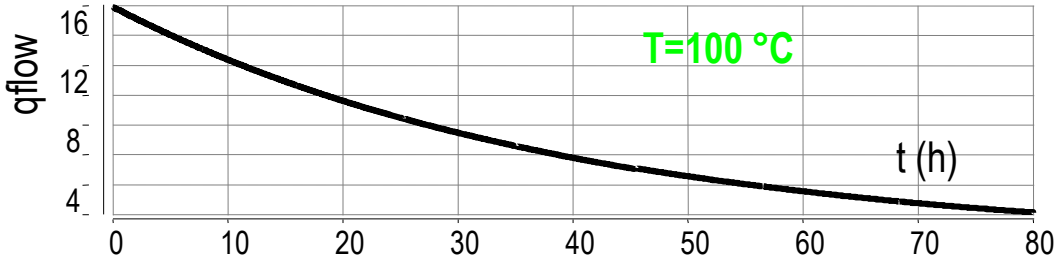
$$TMR_{ad} = \frac{c_{p'} \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E}$$

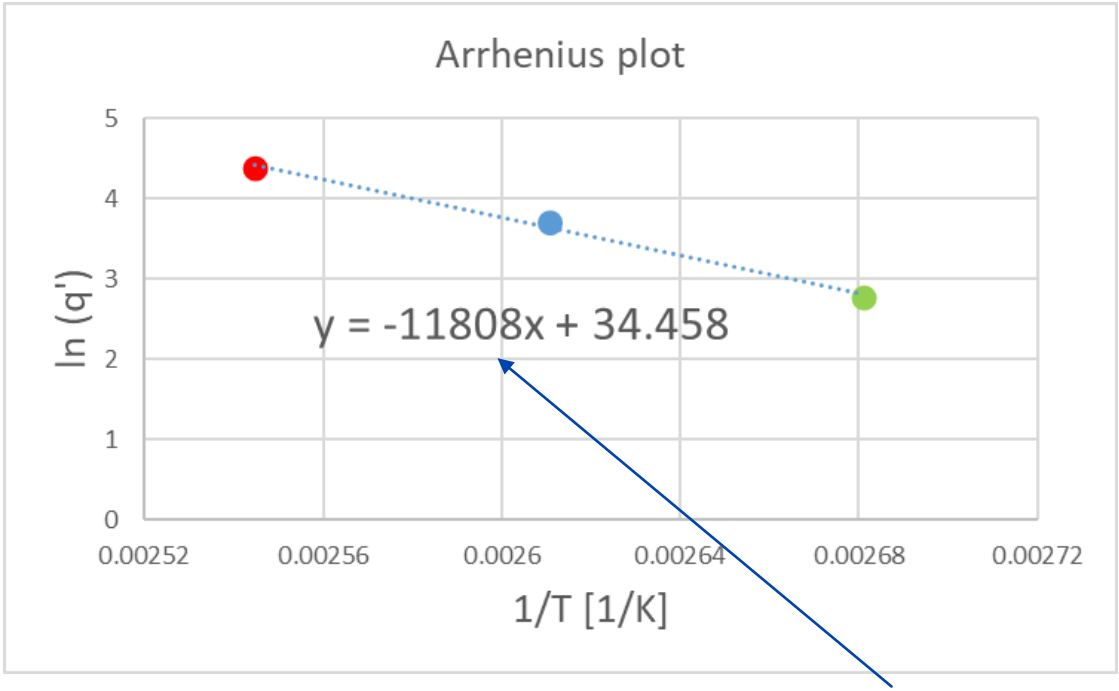
c_p'	specific heat capacity [J / kg / K]
R	universal gas constant 8.314 J /(mol. K)
T	temperature (K)
$q'_{(T0)}$	Heat release rate at T_0 [W / kg]
Ea	Activation energy [J / mol]

Isothermal DSC Experiments



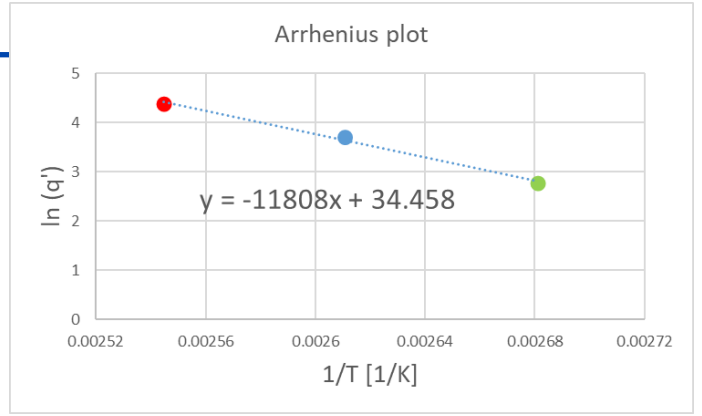






$$TMR_{ad} = \frac{c_{p'} \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E}$$

Isothermal DSC: calculation of TMRad



- TMRad at 100°C:
  - q': 16 W/kg
  - Ea: 11808 x 8.314 = 98'172 J/mol
  - c'p: estimation for an organic liquid: 1.8 kJ/(kg·K)

$$TMR_{ad} = \frac{c_{p'} \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E} = \frac{1800 \cdot 8.314 \cdot (373)^2}{16 \cdot 98172} = 1325s = 22\,\text{min}$$

- TMRad at 50°C?

Isothermal DSC: calculation of TMRad

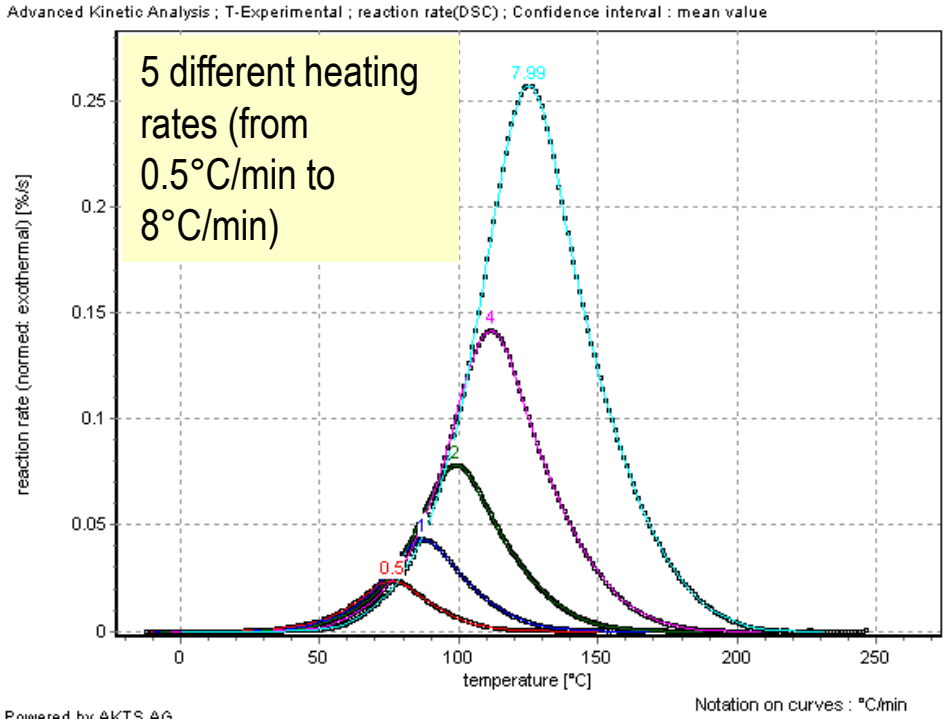
- TMRad at 100°C:
  - q': 16 W/kg
  - Ea: 11808 x 8.314 = 98'172 J/mol
  - c'p: estimation for an organic liquid: 1.8 kJ/(kg·K)

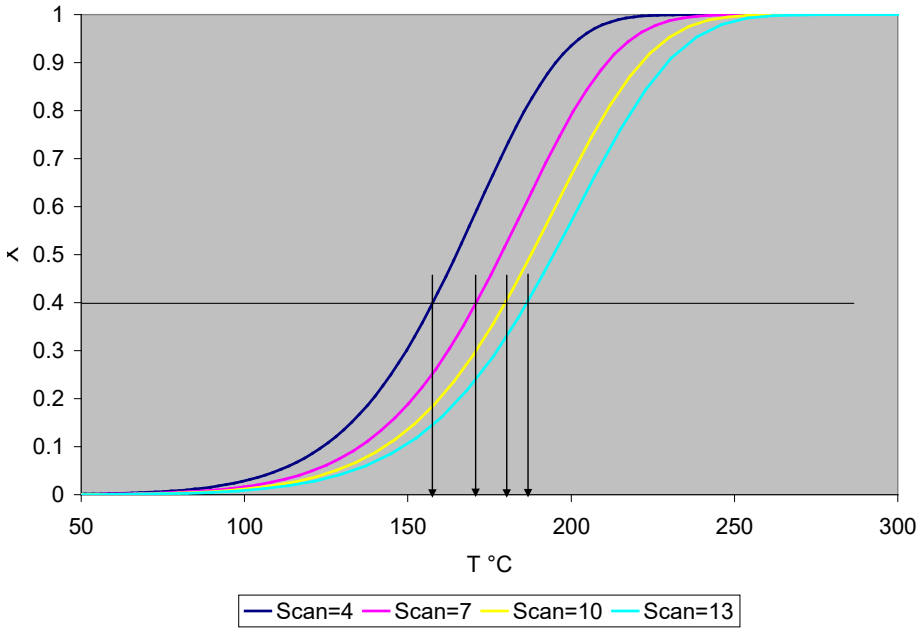
$$TMR_{ad} = \frac{c_{p'} \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E} = \frac{1800 \cdot 8.314 \cdot (373)^2}{16 \cdot 98172} = 1325 s = 22 \,\text{min}$$

- TMRad at 50°C
  - q':? Extrapolate from isothermal measurements → 0.12 W/kg or calculate from $q' = q'_0 \exp\left(-\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right)$
  - Ea: 11808 x 8.314 = 98'172 J/mol
  - c'p: estimation for an organic liquid: 1.8 kJ/(kg·K)
  - TMRad: 129'779 s → 36 hours

Isoconversional methods

Series of thermogrammes at different scan rates





$$q' = \frac{dX}{dt} \cdot Q' = k_0 \cdot e^{\frac{-E}{RT}} \cdot f(X) \cdot Q'$$

q': specific heat release rate	W/kg
X: conversion	-
t: time	s
Q': specific reaction energy	J/kg
k_0: pre-exponential factor	1/s
E: activation energy	J/mol
R: gas constant	J/(mol·K)
T: Temperature	K

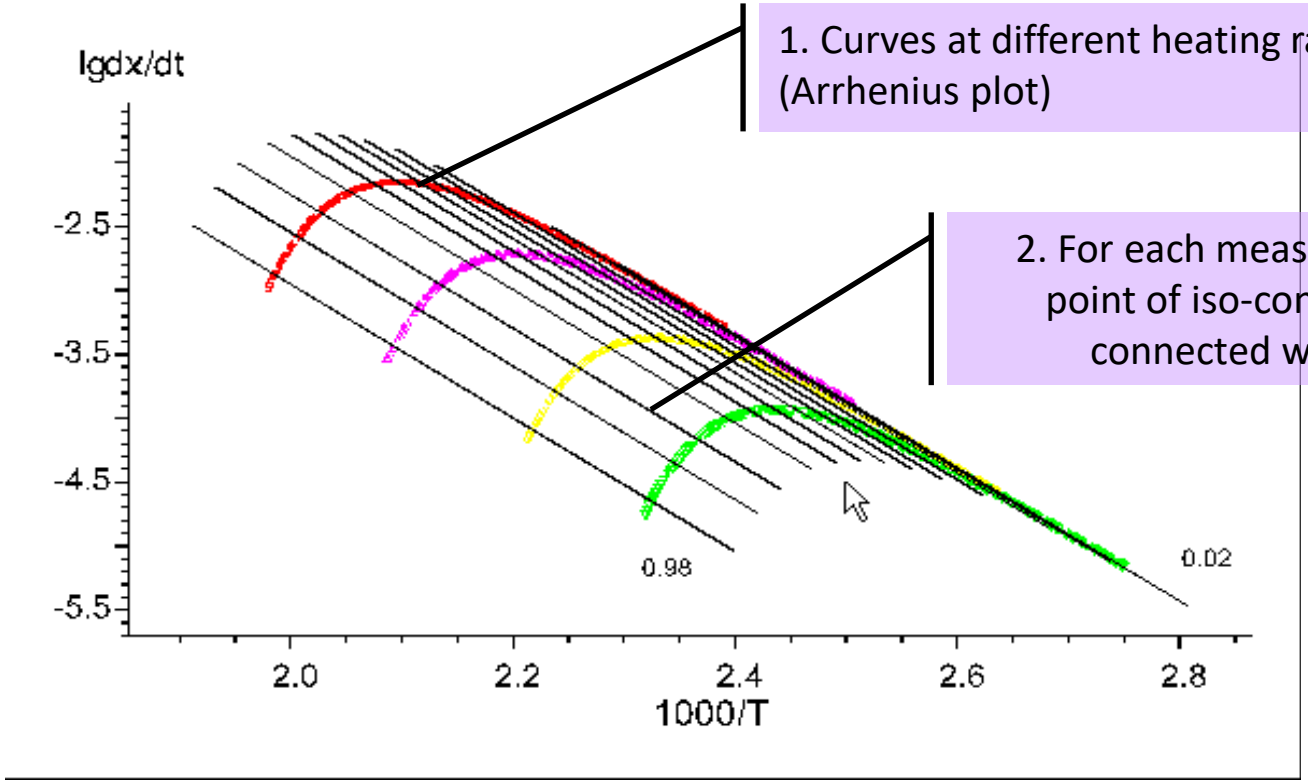
$$\frac{dX}{dt} = k_{0(X)} \cdot \exp\left\{\frac{-E_{a(X)}}{RT}\right\} \cdot f(X)$$

This part of the equation is a function of the concentrations

$$\ln\left(\frac{dX}{dt}\right) = \underbrace{\ln k_0 + \ln\left(f(X)\right)}_{\text{constant for constant X}} - \frac{E_{a(X)}}{R \cdot T}$$

X: conversion	-
t: time	s
$k_{0(X)}$: pre-exponential factor for a specific X	depends on rate law
$E_{a(X)}$: activation energy for a specific X	J/mol
R: gas constant	J/(mol·K)
T: Temperature	K

Friedmann plot



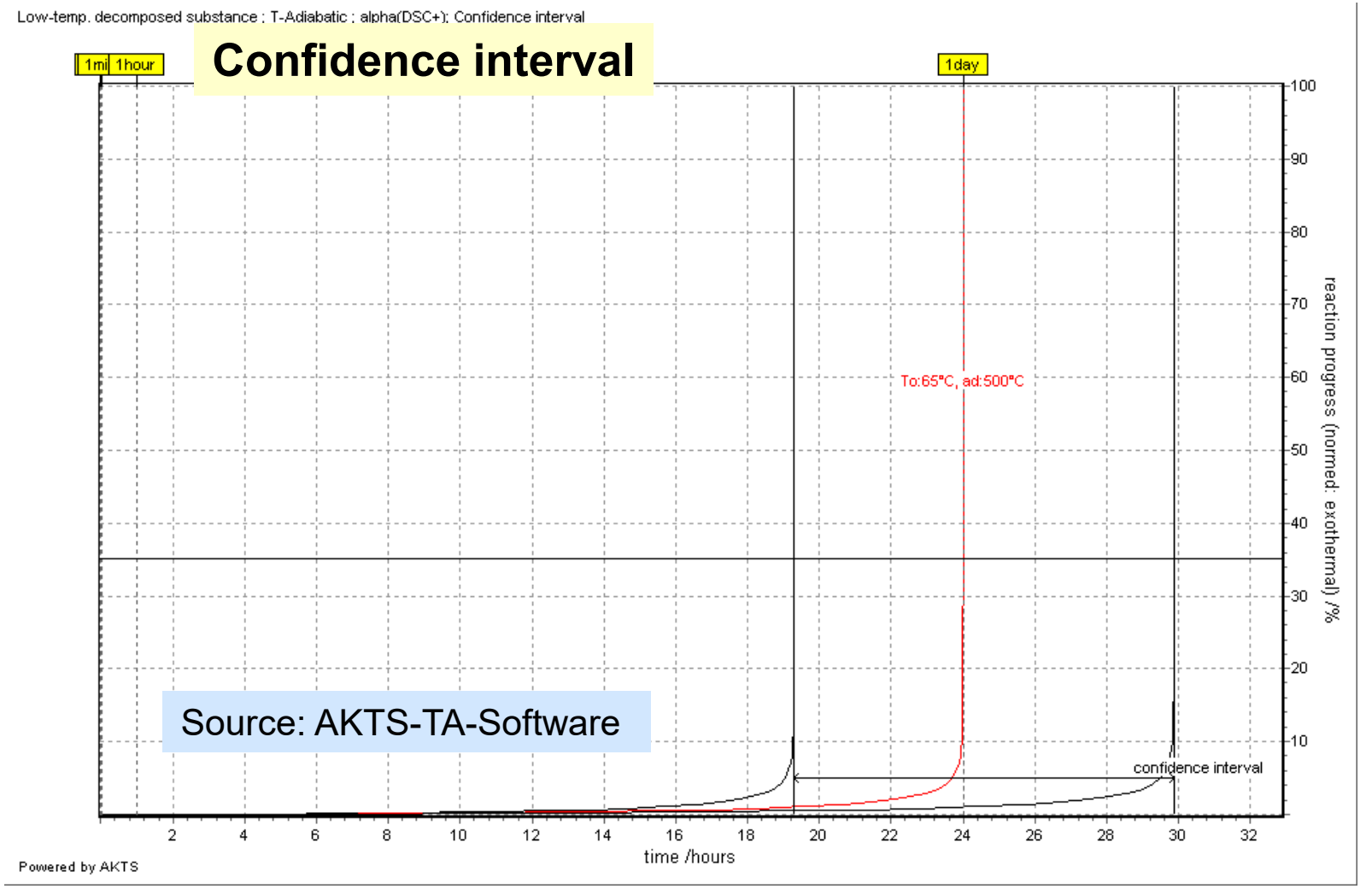
1. Curves at different heating rates (Arrhenius plot)

2. For each measurement, the point of iso-conversion are connected with a line

Every line has an activation energy (Ea) and an y-interception ($\ln k_{0(X)}$ + ln(f(X))

$$\ln\left(\frac{dX}{dt}\right) = \ln(k_{0(X)}) + \ln(f(X)) - \frac{E_{a(X)}}{R \cdot T}$$

Kinetics and safety margin



Source: AKTS-TA-Software

Advantages of TMRad concept

1, 2

On-Set (100K rule)

- Instrument specific
- No direct scale-up to plant situation
- Requires a strict guideline for scale-up

TMRad

- Independant of laboratory instrument (not when using rule of thumbs)
- Scale-up to plant situation possible
- Based on physical chemistry (kinetics)

Determination of TMRad with isothermal and isoconversional methods: summary

1, 2

- Isothermal method:
  - Several isothermal measurements
  - Arrhenius plot: determination of activation energy
  - Extrapolation of heat release rate

- Isoconversional method
  - Several measurements in scan rate
  - Model free kinetics
  - Modeling decomposition
  - Problem when several decompositions

- Both methods require some time to determine TMRad (~ one week) → Need a screening method (conservative): Rule of thumb

Estimation of T_{D24}

Rule of Thumb based on a DSC in scan mode (4°C/min)

- q_{ref} =20 W/kg at peak detection temperature (T_{ref})
- Assume low Activation energy: 50 kJ/mol
- Calculate q = f (T) (0 order kinetics)

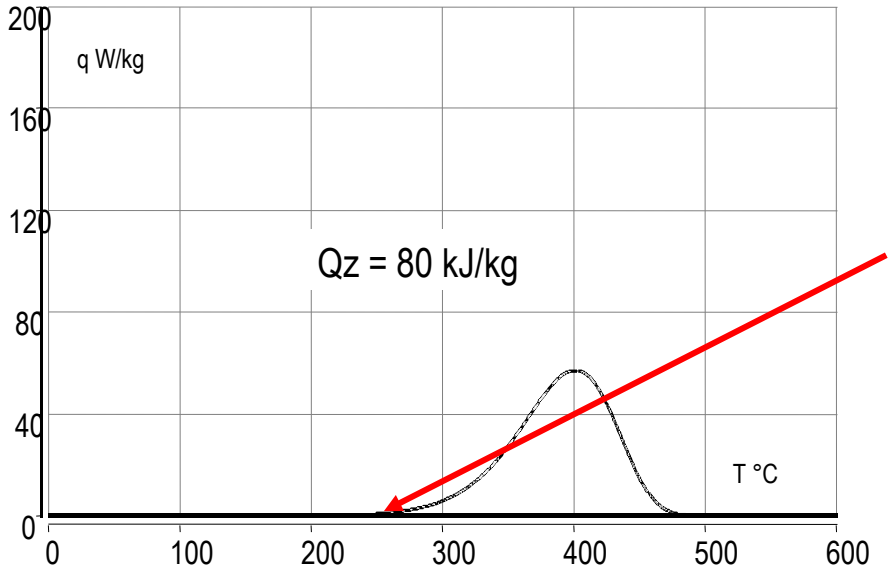
$$q'_{(T)} = q'_{(Tref)} \times \exp\left[\frac{-E_a}{R} \times \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$$

- Calculate TMRad = f (T) (cp for liquids 1.8, solids 1.3 kJ/kg.K)

$$TMR_{ad}(T) = \frac{c'_p \, R \, T^2}{q'_{(T)} \, E_a}$$

☹ Not valid for autocatalytic reactions (not necessarily conservative)

☹ Depends on instrument (on-set problematic)



Sample: 12.5 mg

Scan: 4°C / min
Gold plated high pressure crucible

Scan mode DSC: calculation of TMRad

- TMRad at 100°C:
  - q'_{ref}: 20 W/kg for a T_{ref} of 250°C
  - Ea: 50 kJ/mol
  - c'_p: estimation for an organic liquid: 1.8 kJ/(kg·K)

Scan mode DSC: calculation of TMRad

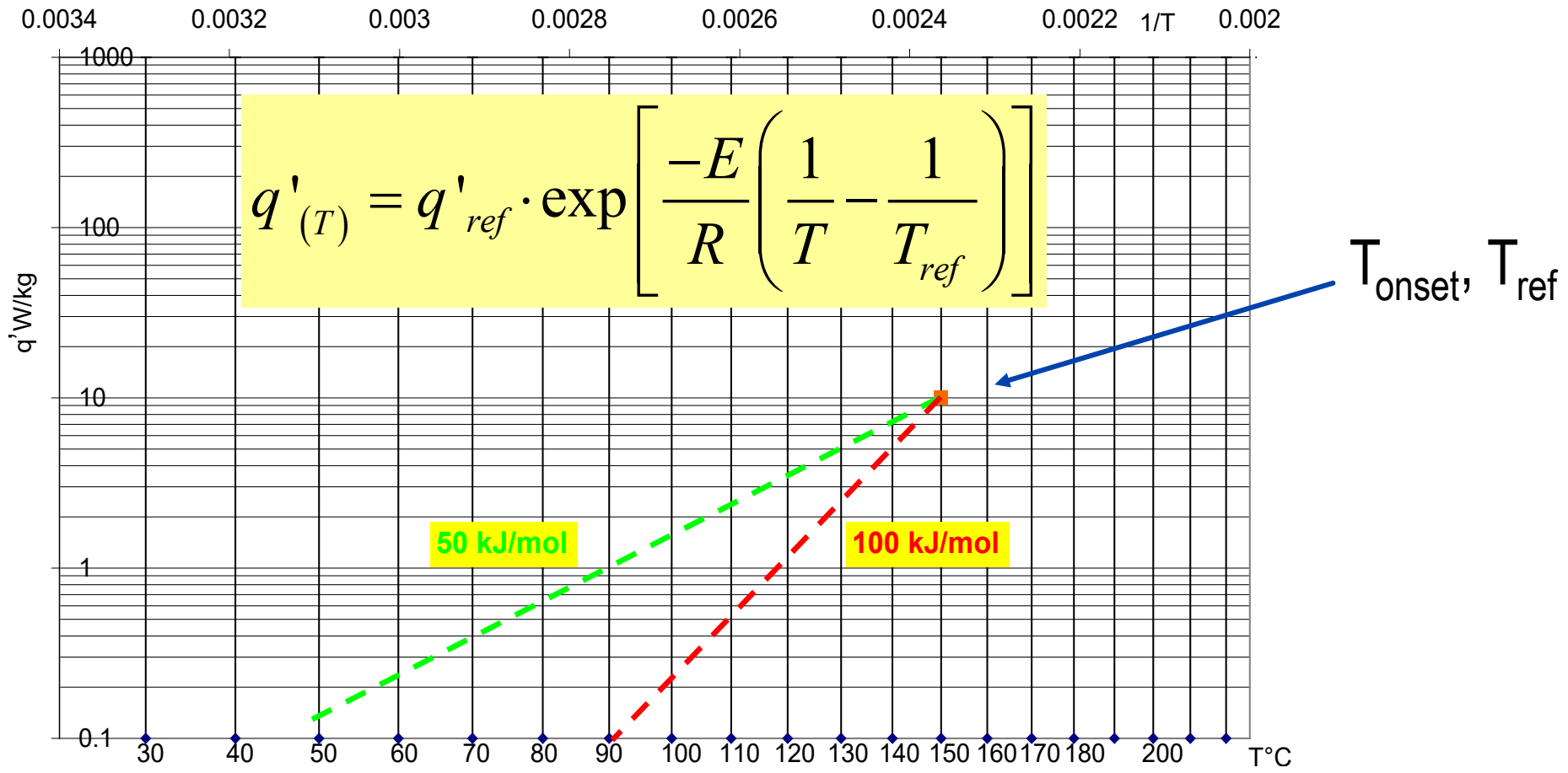
- TMRad at 100°C:
  - q'_{ref}: 20 W/kg for a T_{ref} of 250°C
  - Ea: 50 kJ/mol
  - c'_p: estimation for an organic liquid: 1.8 kJ/(kg·K)

$$q'_{(T)} = q'_{(Tref)} \times \exp\left[\frac{-E_a}{R} \times \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] = 20 \times \exp\left[\frac{-50'000}{8.314} \times \left(\frac{1}{373} - \frac{1}{523}\right)\right] = 0.2 W / kg$$

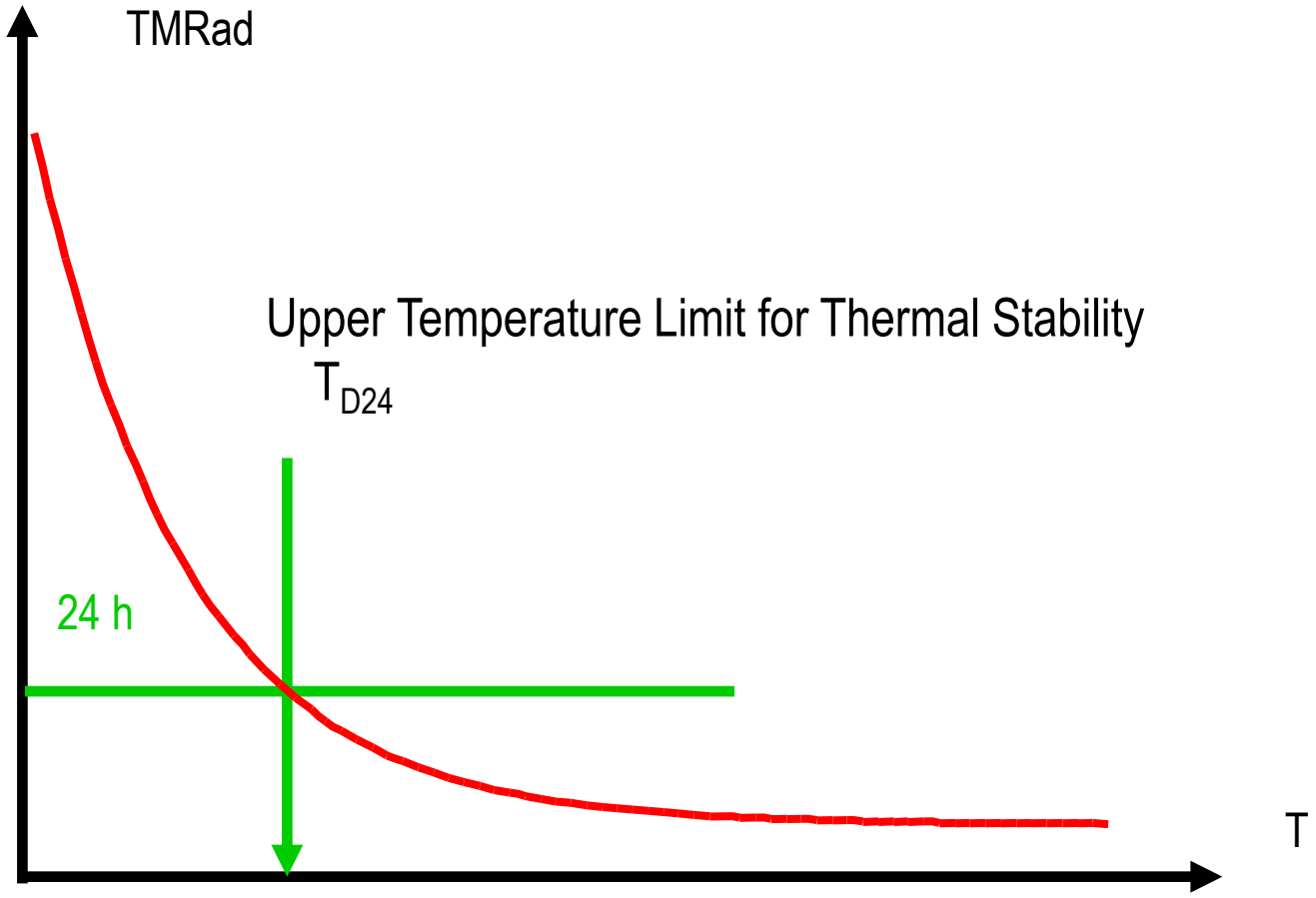
$$TMR_{ad} = \frac{c_{p'} \cdot R \cdot T_0^{\,2}}{q'_{(T_0)} \cdot E} = \frac{1800 \cdot 8.314 \cdot (373)^2}{0.2 \cdot 50'000} = 2 \cdot 10^5 = 58h$$

Arrhenius diagram

- Extrapolation from one reference point, why is 50 kJ/mol a conservative activation energy?



TMRad as a Function of Temperature



Definitions

- T_{D24}: Temperature at which TMRad = 24 h
- T_{D8} : Temperature at which TMRad = 8 h

Rule of thumb / Order of magnitude:

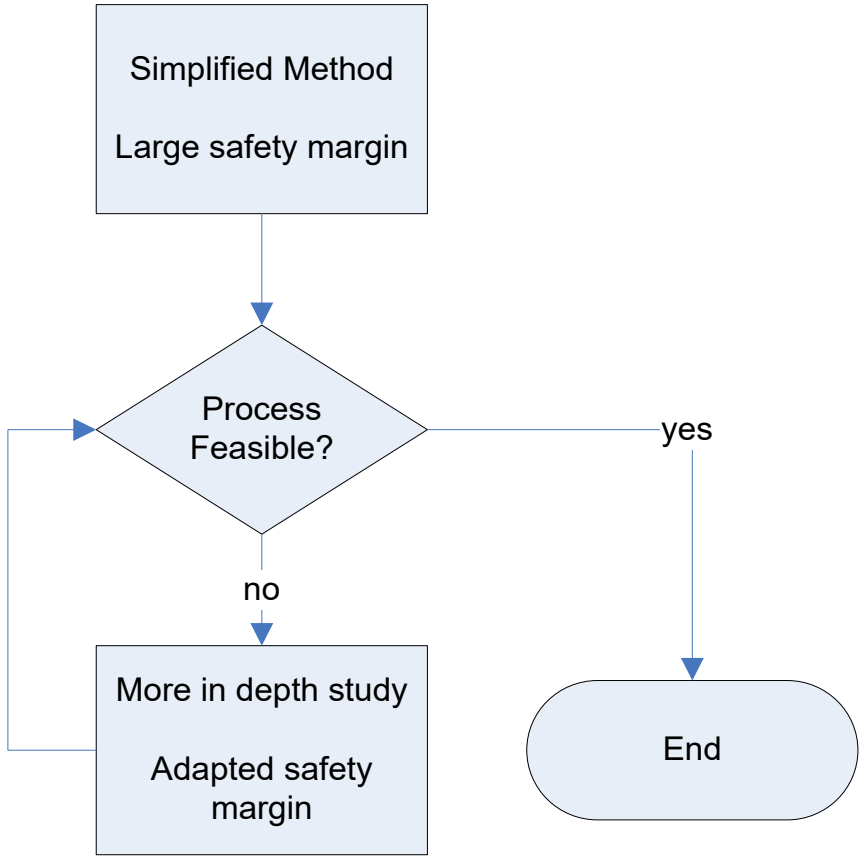
- Detection limit in DSC — TMRad = 1hr
- For 1 W/kg — TMRad = 8 hrs
- For 0.3 W/kg — TMRad = 24 hrs

TMR_{ad} and risk assessment

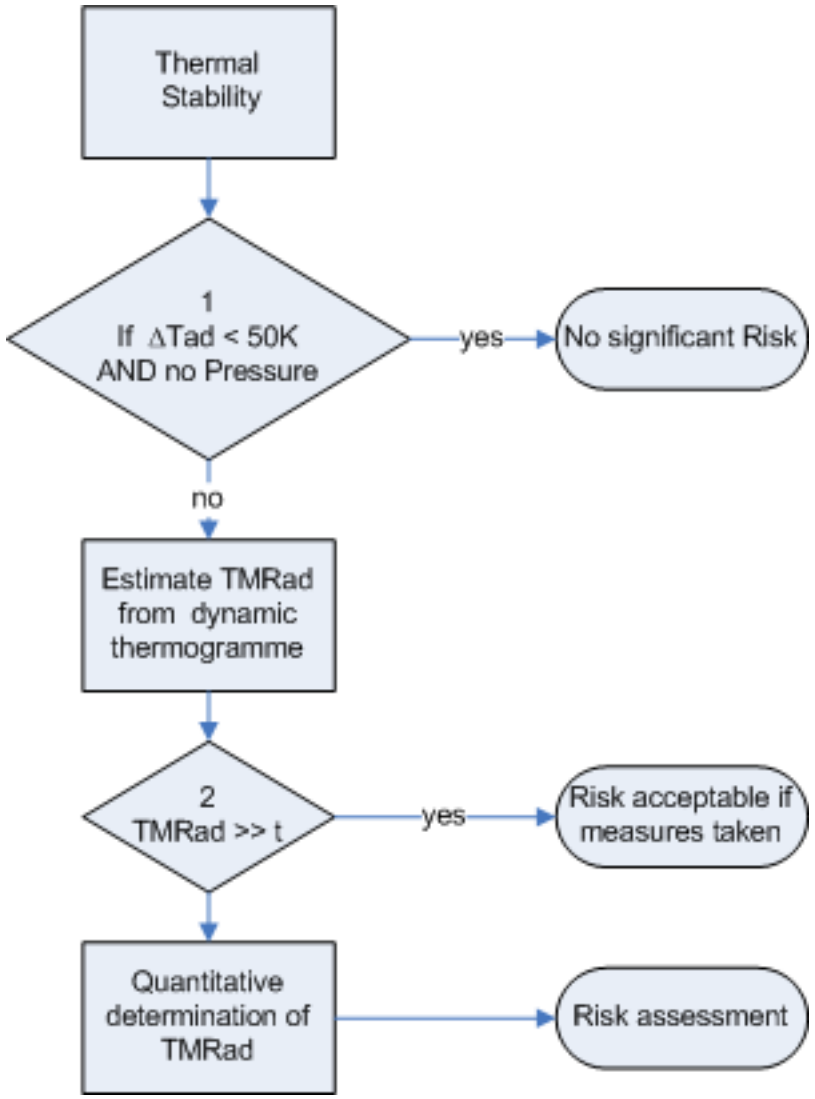
Which method should we use?

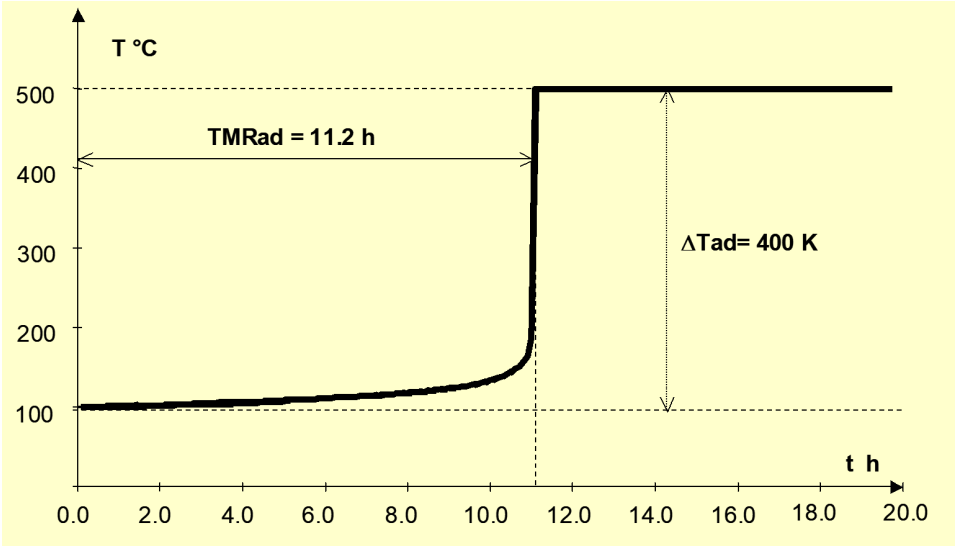
- KISS-Principle:

  Keep It Simple and Safe



TMR_{ad} and Risk Assessment
Characterisation of secondary reactions



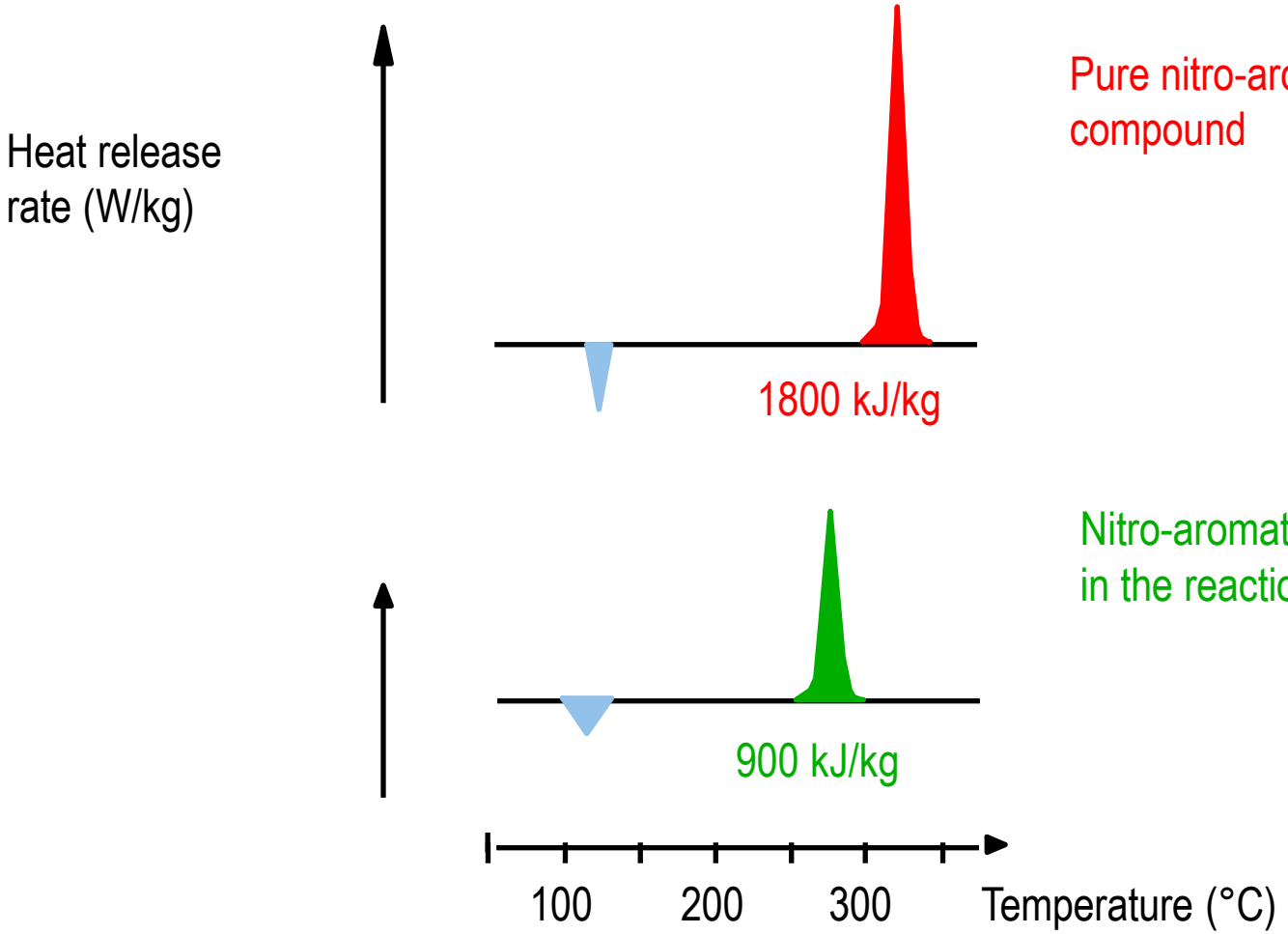


- Risk assessment
  - Severity:
    Energy, temperature, pressure
  - Probability of triggering TMR_{ad}, time for applying measures

Decomposition Reactions

- What are decomposition reactions?
- Characterisation of secondary reaction
  - Energy of decomposition
  - Onset and Safety Margin
  - Determination of TMR_{ad}
- Examples
- Highly energetic molecules

DSC: Hydrogenation of a Nitro-Aromatic Compound

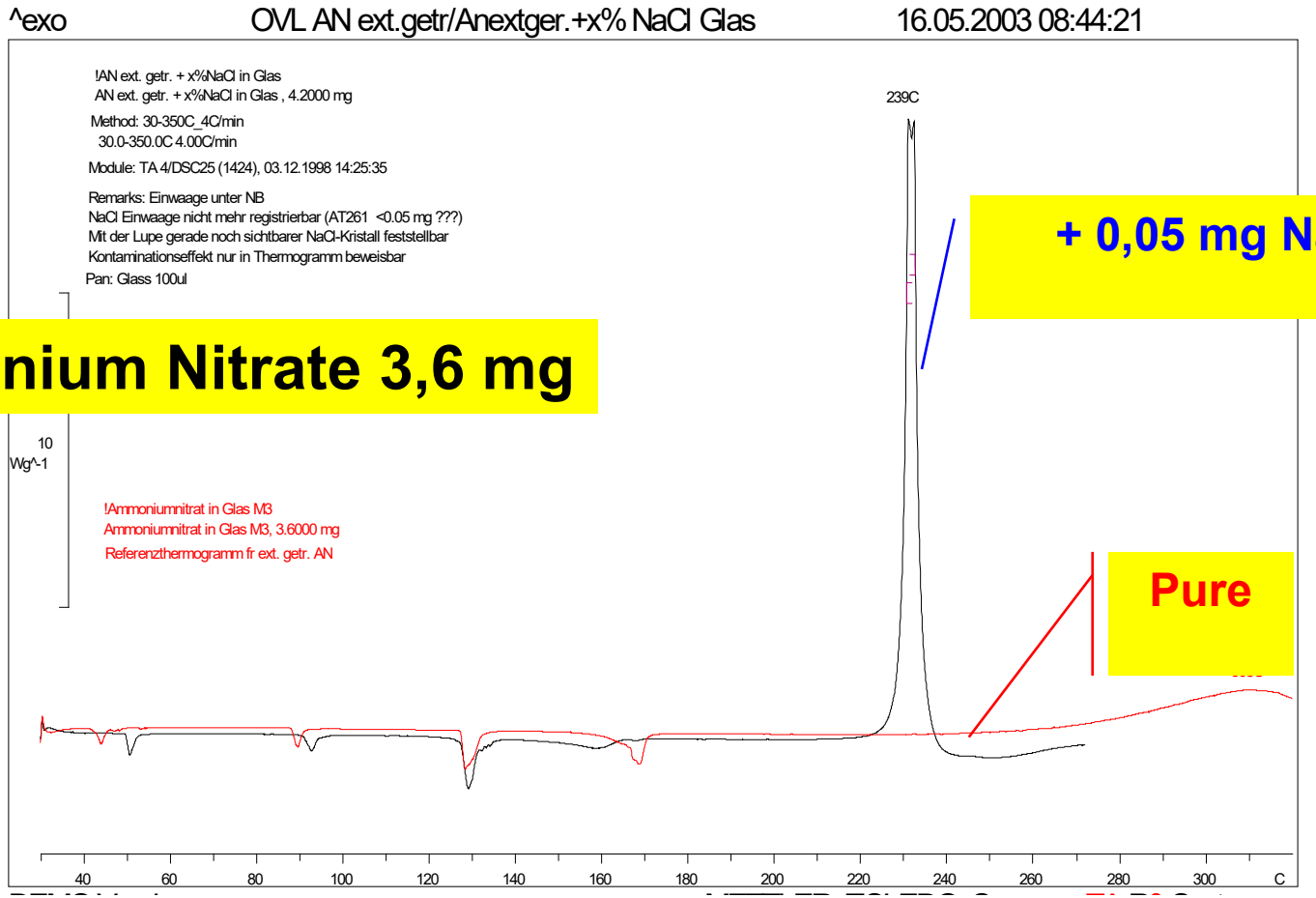


Pure nitro-aromatic compound

Nitro-aromatic compound in the reaction mass

Conclusion: measure the stability of a representative sample → as it will be present in the process

Contamination by impurities



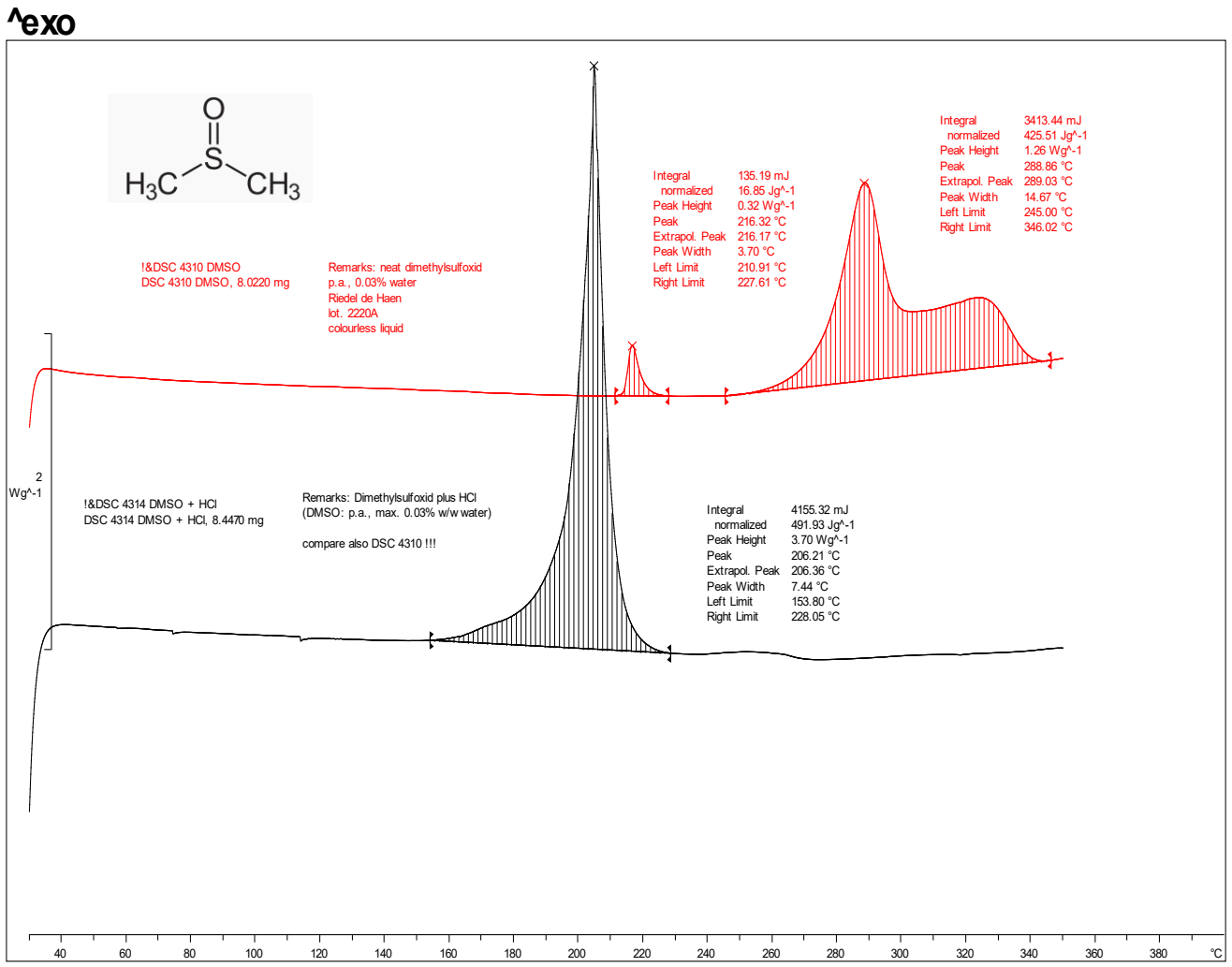
Ammonium Nitrate 3,6 mg

+ 0,05 mg NaCl

Pure

Conclusion: impurities can have a tremendous effect on the stability. Test foreseeable impurities

Effects of contaminants on DMSO

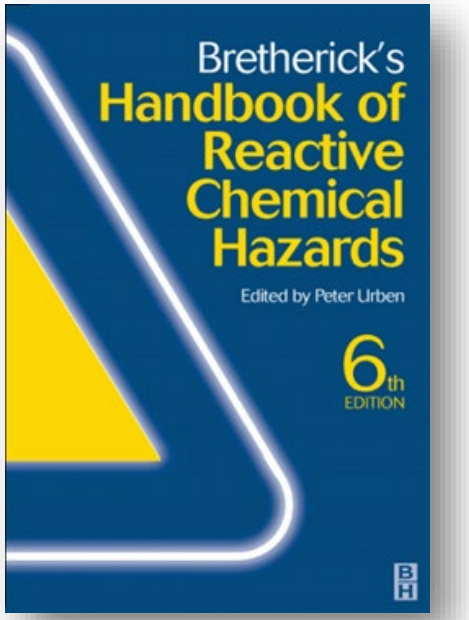


Conclusion: impurities can have a tremendous effect on the stability. Test foreseeable impurities

Literature on DMSO

Bretherick:

… Two instances of used DMSO decomposing exothermally while being kept at 150ºC prior to recovery by vacuum distillation were investigated. Traces of alkyl bromides lead to a delayed, vigorous and strongly exothermic reaction (Q = 850 J/gm) at 180ºC …

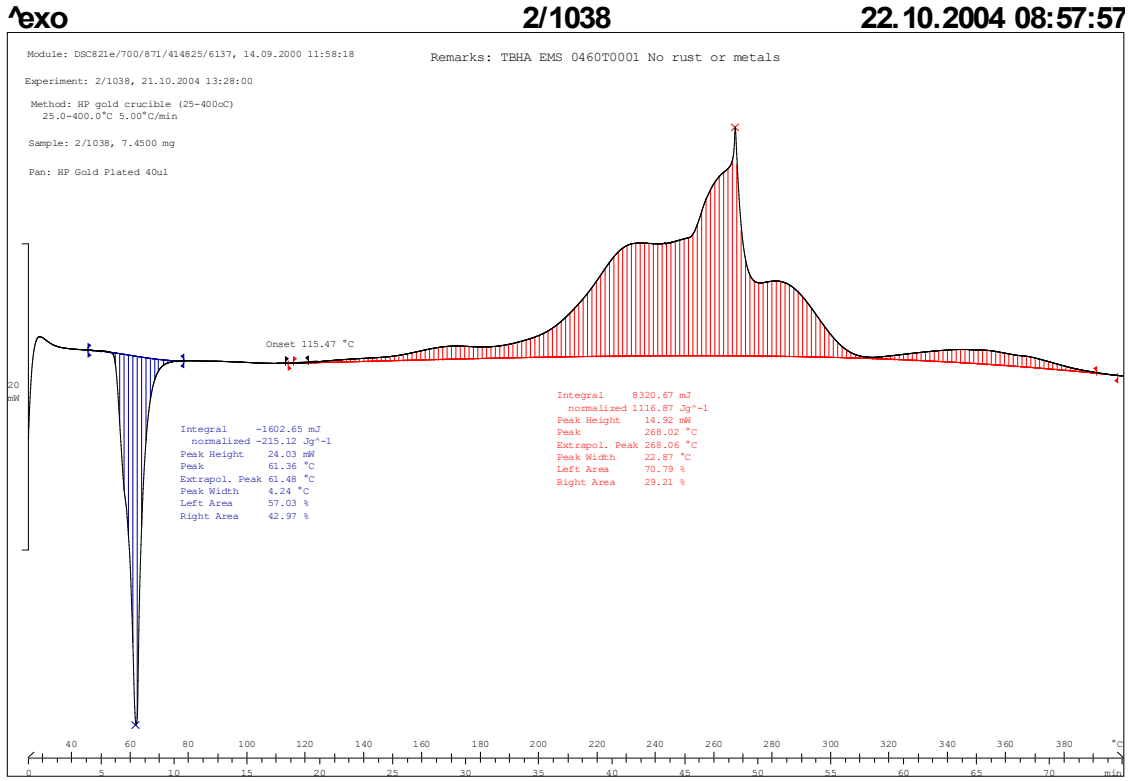


Named compatibility issues with 30 compounds or classes:

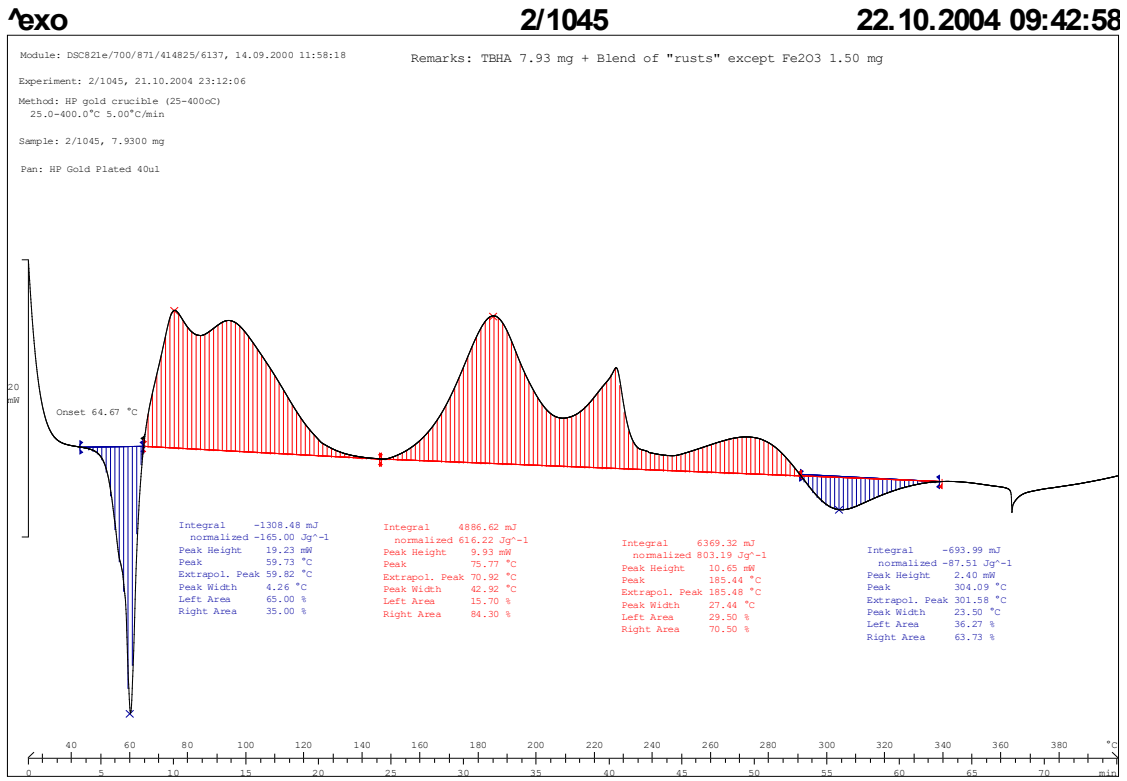
Acid anhydrides - Acids, or Bases - Acyl halides, or Non-metal halides - Allyl trifluoromethanesufonates - Boron compounds Bromides - 4(4'-Bromobenzoyl)acetanilide – Bromomethane - Carbonyl diisothiocyanate - per, Trichloroacetic acid - Dichloromethane, Perchloric acid - Dinitrogen tetraoxide – Hexachlorocyclotriphosphazine - Iodine pentafluoride Magnesium erchlorate - Metal alkoxides - Metal oxosalts - Nitric acid - Non-metal halides - Other reactants Perchloric acid - Periodic acid - Phosphorus(III) oxide – Potassium - Potassium permanganate Silver difluoride – Sodium - Sodium hydride - Sulfur trioxide - Trifluoroacetic anhydride

Effects of rust contaminants on a hydroxylamine

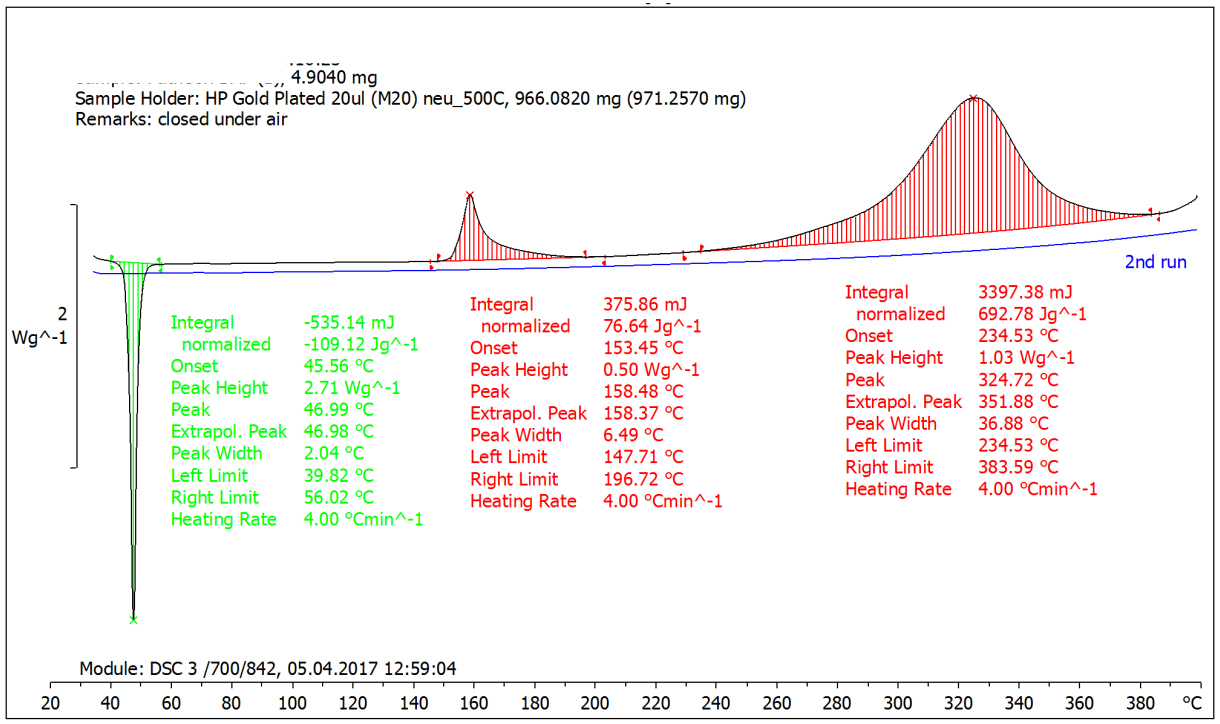
neat

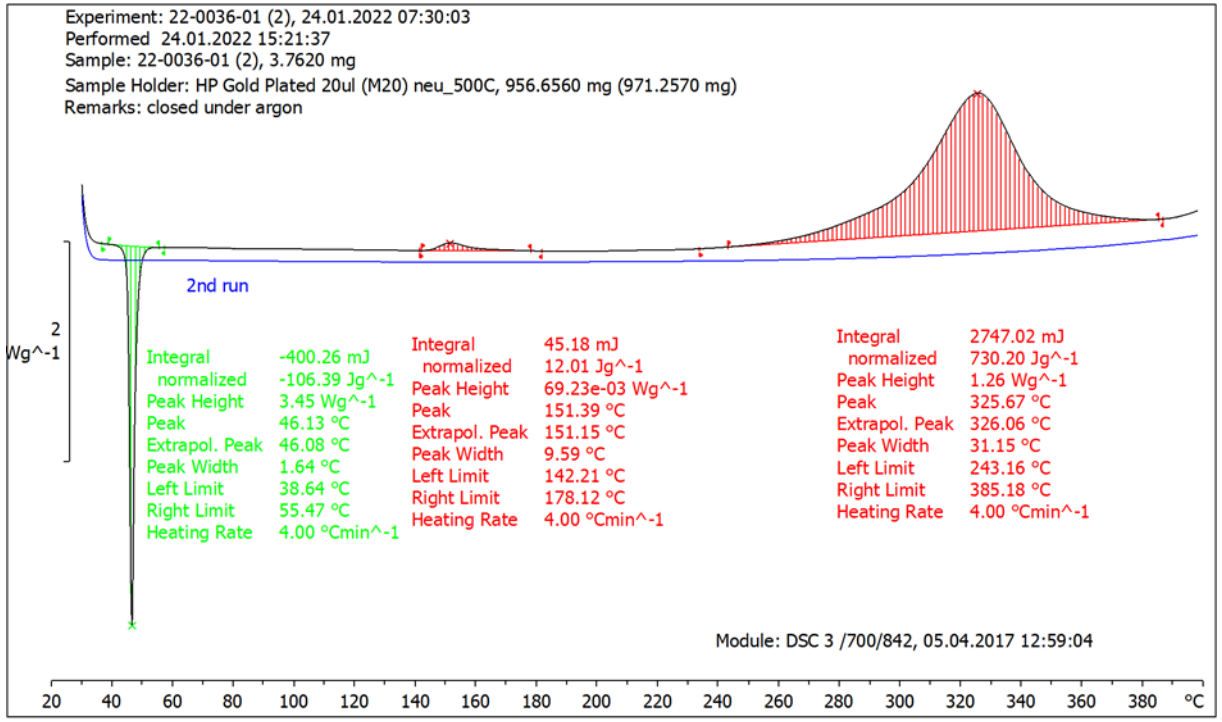


contaminated



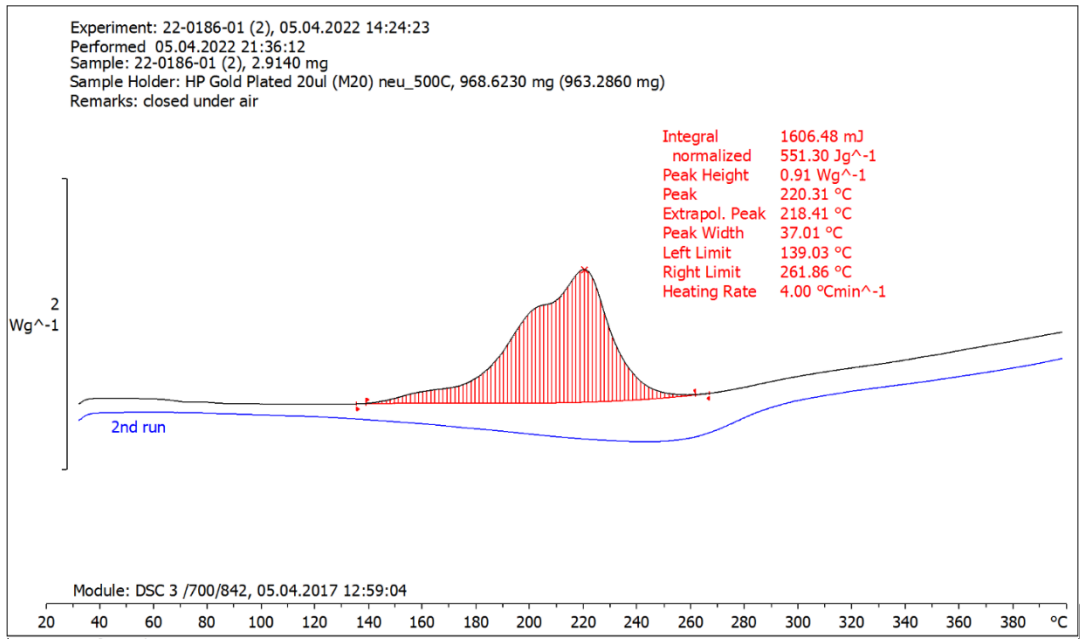
Oxidation

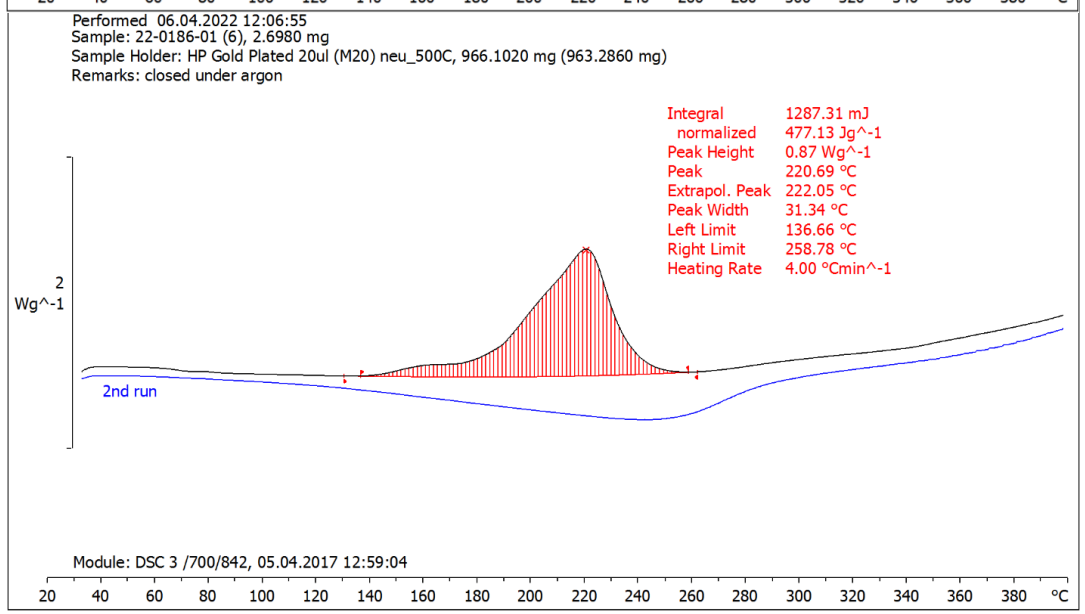


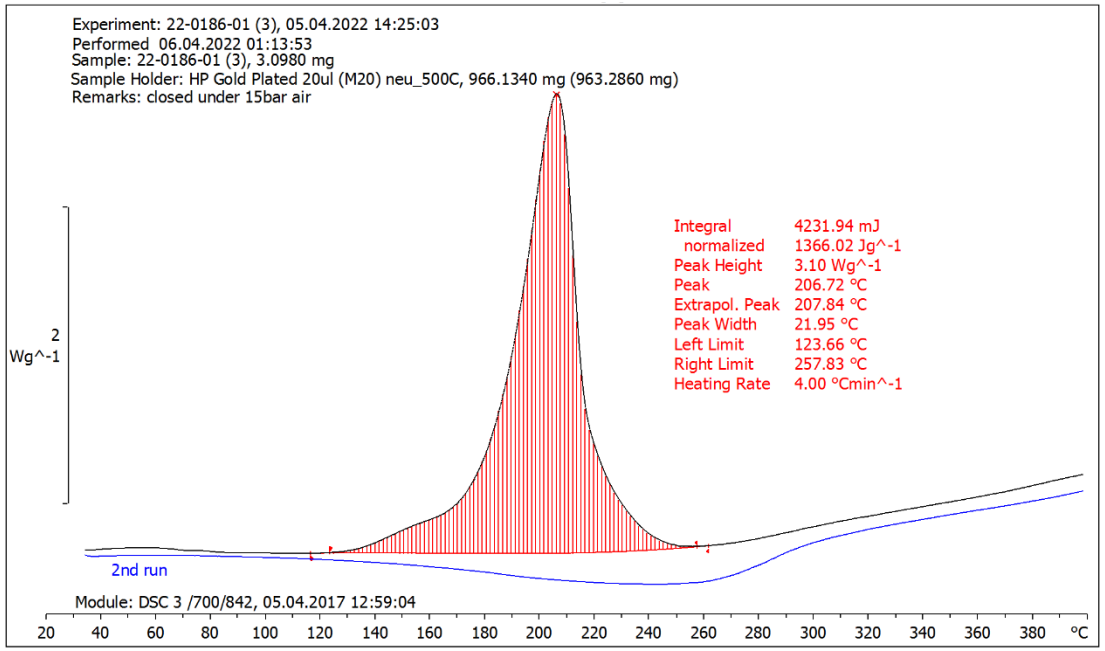


Conclusion: crucibles under air might show a little oxidation. However the amount of oxygen present in the crucible is low
→ if the decomposition is problematic, make a measurement under argon

Oxidation


Experiment: 22-0186-01 (2), 05.04.2022 14:24:23
Performed 05.04.2022 21:36:12
Sample: 22-0186-01 (2), 2.9140 mg
Sample Holder: HP Gold Plated 20ul (M20) neu_500C, 968.6230 mg (963.2860 mg)
Remarks: closed under air
Integral 1606.48 mJ
normalized 551.30 Jg^-1
Peak Height 0.91 Wg^-1
Peak 220.31 °C
Extrapol. Peak 218.41 °C
Peak Width 37.01 °C
Left Limit 139.03 °C
Right Limit 261.86 °C
Heating Rate 4.00 °Cmin^-1
2
Wg^-1
2nd run
Module: DSC 3 /700/842, 05.04.2017 12:59:04
20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 °C

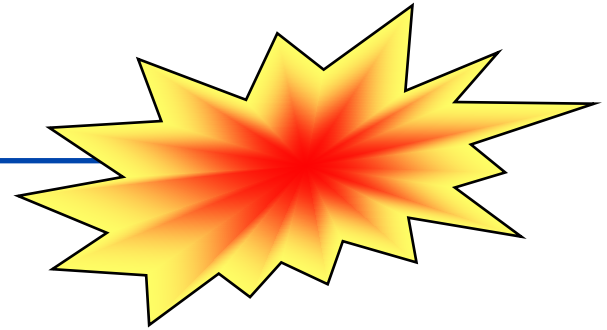

Performed 06.04.2022 12:06:55
Sample: 22-0186-01 (6), 2.6980 mg
Sample Holder: HP Gold Plated 20ul (M20) neu_500C, 966.1020 mg (963.2860 mg)
Remarks: closed under argon
Integral 1287.31 mJ
normalized 477.13 Jg^-1
Peak Height 0.87 Wg^-1
Peak 220.69 °C
Extrapol. Peak 222.05 °C
Peak Width 31.34 °C
Left Limit 136.66 °C
Right Limit 258.78 °C
Heating Rate 4.00 °Cmin^-1
2
Wg^-1
2nd run
Module: DSC 3 /700/842, 05.04.2017 12:59:04
20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 °C


Experiment: 22-0186-01 (3), 05.04.2022 14:25:03
Performed 06.04.2022 01:13:53
Sample: 22-0186-01 (3), 3.0980 mg
Sample Holder: HP Gold Plated 20ul (M20) neu_500C, 966.1340 mg (963.2860 mg)
Remarks: closed under 15bar air
Integral 4231.94 mJ
normalized 1366.02 Jg^-1
Peak Height 3.10 Wg^-1
Peak 206.72 °C
Extrapol. Peak 207.84 °C
Peak Width 21.95 °C
Left Limit 123.66 °C
Right Limit 257.83 °C
Heating Rate 4.00 °Cmin^-1
2
Wg^-1
2nd run
Module: DSC 3 /700/842, 05.04.2017 12:59:04
20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 °C

Decomposition Reactions

- What are decomposition reactions?
- Characterisation of secondary reaction
  - Energy of decomposition
  - Onset and Safety Margin
  - Determination of TMR_{ad}
- Examples
- Highly energetic molecules

Explosives



- Substances that undergo decomposition or combustion with great rapidity, evolving much heat and producing a large volume of gas.

- … are
  - Impact sensitive
  - Friction sensitive
  - Heat sensitive

Consequences of a detonation

- 1 gram:
  - Serious injury to a person holding the explosive
- 10 gram:
  - Very serious injury to a person close to the explosive
- 100 gram:
  - Almost certain death of persons in very close proximity (e.g. holding the material)

Hazardous Chemicals Handbook by P. Carson & C. Mumford (pub.: Butterworth-Heinemann)

Explosion in condensed phase (liquid/solid)

- Oppau - September 21st, 1921

- Ammonium nitrate
- Mass: 4500 t

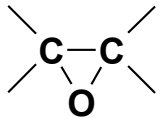
- Damages:
  - 561 fatalities
  - 1997 injured
  - structural damages within a radius of 6 km

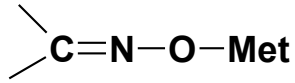
VUE AÉRIENNE DE L'USINE DE LA « BADISCHE ANILIN UND SODA FABRIK », A OPPAU, APRÈS LA FORMIDABLE EXPLOSION DU 21 SEPTEMBRE

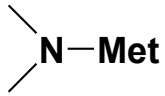
Au premier plan, le cratère formé par la mystérieuse déflagration et à demi rempli d'eau par les canalisations rompues et par les infiltrations souterraines; au delà, les bâtiments rasés ou défoncés; à l'arrière-plan, le Rhin

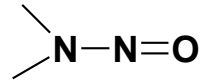
Photographie prise d'un avion spécialement envoyé sur les lieux, pour L'Illustration, par la Compagnie Aérienne Française — Tous droits réservés

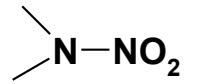
Structures known to be hazardous

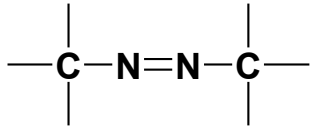


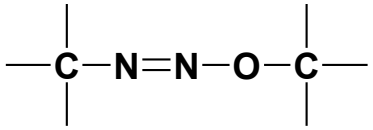


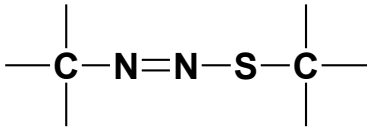


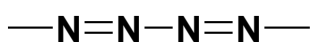


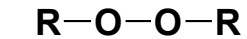




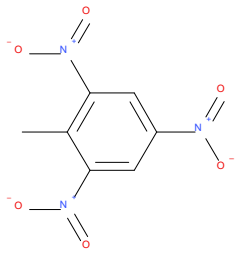


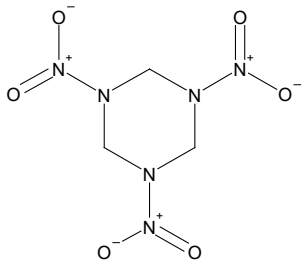


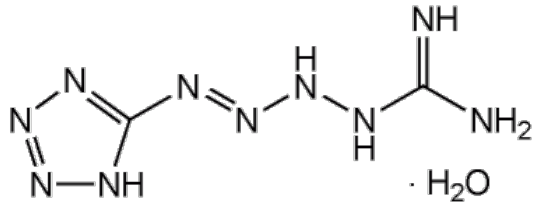




Military Explosives:





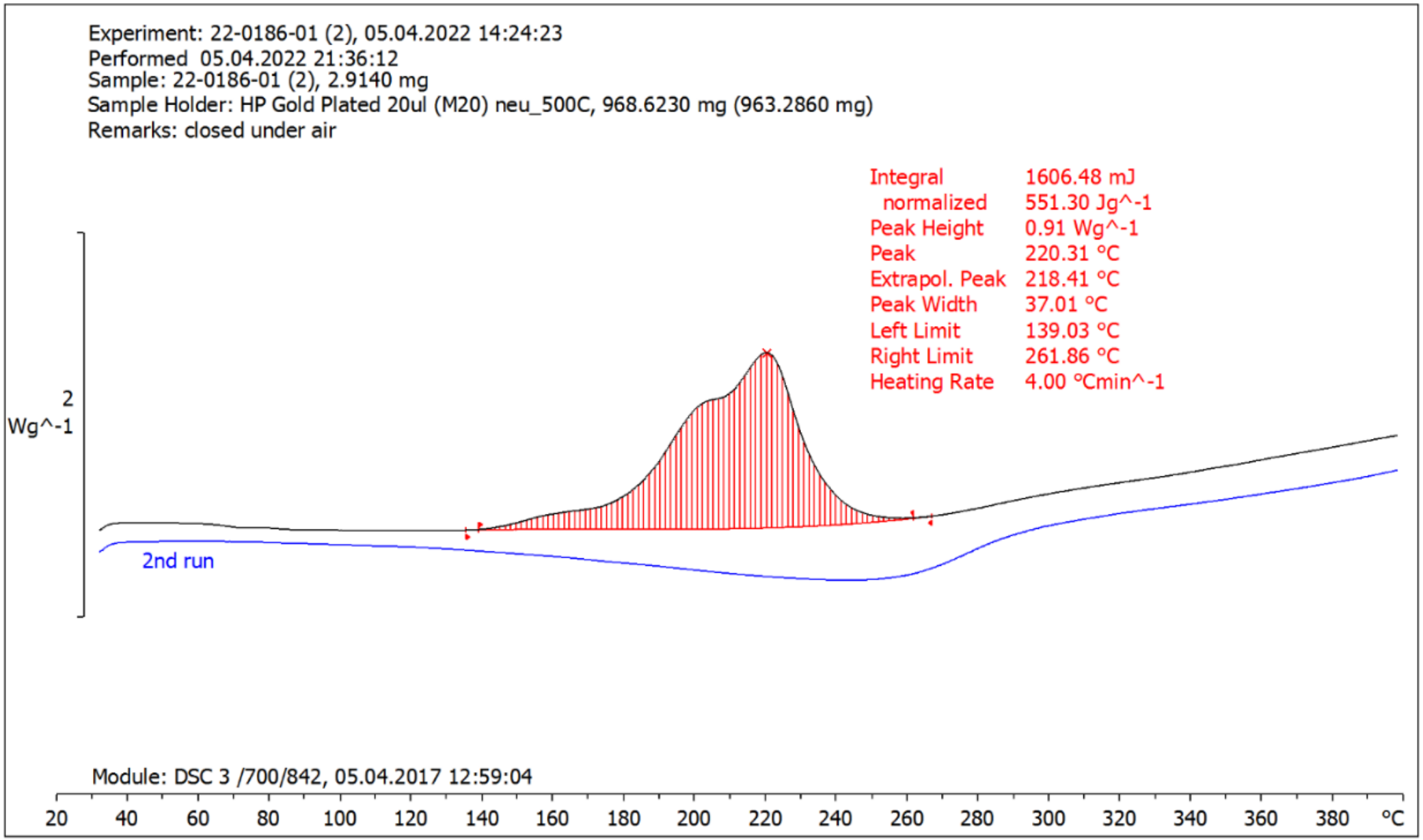


Questions

- What equipment are used to assess thermal stability?

- New substance and you need to assess whether you can handel it safely
  - What do you do

Question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2nd run
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20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 °C

Question

Question

- Isothermal measurements in DSC

Temperature	Heat release rate (W/kg)
150°C	15
160°C	28
170°C	51
180°C	90

Summary

- Take a few minutes to write the main points concerning thermal stability and TMRad