Copenhagen Biomass Safety Workshop

TECHNICAL DEEP DIVE: CAUSES, CONTRIBUTING FACTORS, AND DETECTION METHODS FOR SELF-HEATING

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“Disclaimer: The following recommendations are provided for guidance only. They are based on industry experiences, controlled experiments, and peer-reviewed research publications, and should not be interpreted as legal or regulatory requirements.”

WHY THIS MATTERS

WHAT IS SELF-HEATING

- Self-heating is an internally driven process of heat buildup from biological, chemical or reactions that, if unchecked, can lead to combustion.
- Any material that can decompose or be oxidized by air can exothermically reach spontaneous combustion.
- Similar to coal, wood pellets self-heat when stored as a bulk.
- The self-heating can increase the bulk temperature to the point of self-ignition.
- Silo fires require a different approach than conventional fires.

SELF HEATING AND THERMAL RUNAWAY

Thermal runaway
Smoldering combustion

Heat of water adsorption

Chemical Reactions

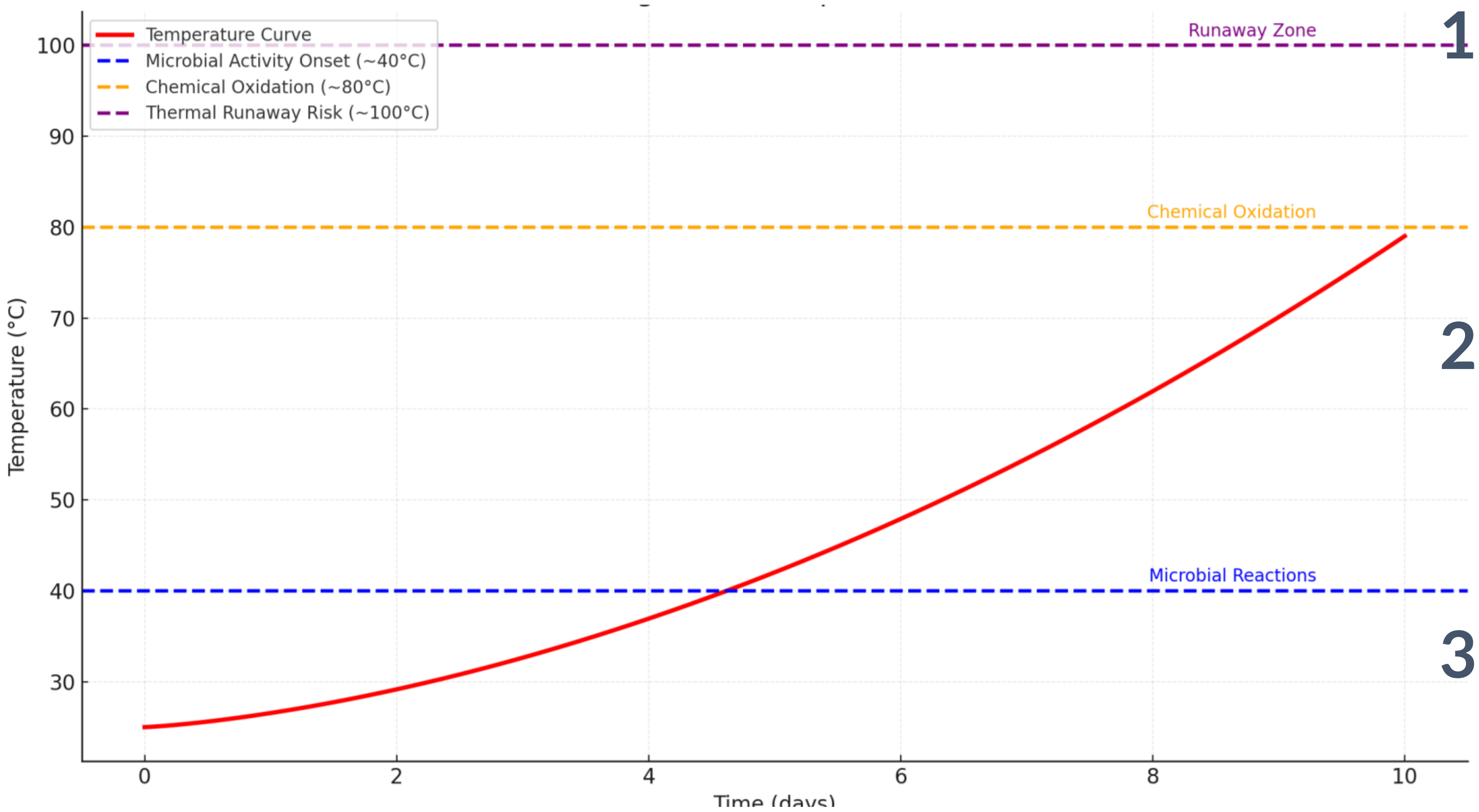
Chemical oxidation
Pyrolysis
Hydrolysis

Biological degradation

Metabolism and biological oxidation

Self-heating is an exothermic process that starts small. It may begin with microbial or oxidative reactions that slowly generate heat. If the heat can't dissipate, temperature rises further, eventually crossing into thermal runaway and combustion.

SELF HEATING AND THERMAL RUNAWAY



1. **Self-heating:** an increase in temperature due to exothermal reactions in the fuel.
2. **Thermal runaway:** self-heating which rapidly accelerates to high temperatures.
3. **Spontaneous combustion:** visible smoldering or flaming by thermal runaway.

SELF HEATING: CAUSES AND DETECTION

Causes

- Microbial degradation (early phase, damp storage)
- Chemical oxidation (extractives, fatty acids)
- Heat of moisture adsorption
- Heat accumulation in bulk (poor ventilation, insulation effect)

Detection

- CO off-gassing (early indicator)
- Odor (e.g., sour or irritating smell)
- Temperature gradient monitoring
- Color or texture changes in pellets

SELF HEATING: CAUSES AND DETECTION

- The most important prevention measure to take is **temperature monitoring of the storage** at several different locations in the bulk.
- For detection of any activity of the bulk, **CO concentration** should be measured in the air above the pellet surface.
- One of the first signs of an on-going self-heating process is often a **sticky and irritating smell**.
- If such smell is sensed, **pyrolysis is already taking place** in fuel bulk and fire fighting operation has to start.
- Color or texture changes in pellets

SELF-HEATING VS EXTERNAL IGNITION

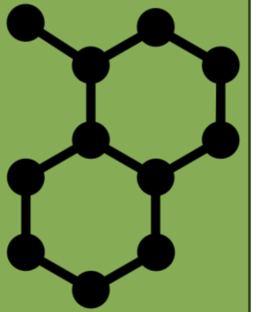
Category	Self-Heating	External Ignition
Trigger	Internal biological/chemical reactions	External heat/flame/spark source
Common Causes	Moisture reabsorption, microbial activity, oxidation	Welding, static discharge, hot surfaces
Development	Slow and often hidden (hours to days)	Sudden and visible
Detection	Requires sensors (CO, temperature, IR)	Typically visual or smoke/fire alarms
Prevention Focus	Monitoring, cooling, moisture control	Hot work permits, spark arrestors, housekeeping
Response Strategy	Careful suppression (venting, inerting, no water flooding)	Standard fire extinguishing methods (water/foam/suppression)
Risk Zones	Inside silos, bulk piles, confined storage	Conveyors, mechanical rooms, open areas

FACTORS THAT DRIVE SELF-HEATING

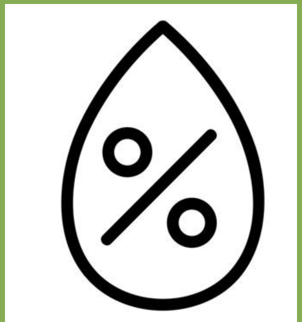
Intrinsic Factors	Operational Factors
Feedstock age	Storage temperature & humidity
Extractive content (fatty acids, resins)	Oxygen availability
Moisture content	Drying temperature/method
Particle size distribution	Residence time in dryer
Density & porosity	Residence time in storage
Internal surface area	

INTRINSIC FACTORS

Extractives &
Fatty Acid Content



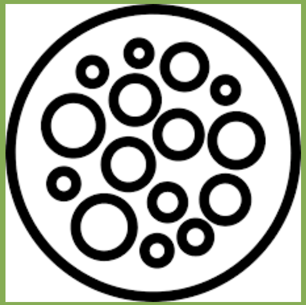
Moisture
Content



Particle Size
Distribution

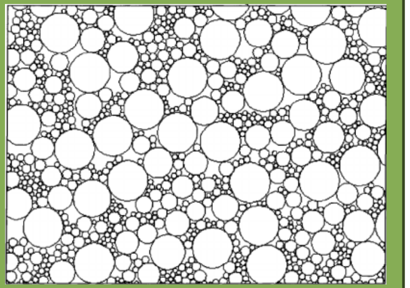
Pellet Density

Porosity



Internal

surface area



Feedstock age

INTRINSIC FACTORS - EXTRACTIVES & FATTY ACID CONTENT

- Species with high fatty acid and resin content → more reactive, higher heat release potential.
- Recent Studies (2023–2024) confirm that species extractive content and feedstock age are an important intrinsic factors influencing self-heating risk.
- Monitoring species mix and feedstock history is just as important as controlling moisture and temperature.

INTRINSIC FACTORS – MOISTURE CONTENT

Critical Threshold

- Self-heating risk rises sharply once moisture exceeds 6–8%.
- Below this level, microbial activity and oxidation remain limited.

Mechanisms

- Microbial Growth → generates biological heat in early storage phases.
- Moisture Adsorption → highly exothermic, releasing significant heat as pellets absorb water.
- Accelerated Oxidation → higher water content facilitates oxidative reactions of fatty acids and resins.

Moisture is the **single most critical intrinsic driver** of self-heating.
Secondary heat release from moisture rewetting can be **15–18× greater** than the initial oxidation heat.

INTRINSIC FACTORS – PARTICLE SIZE DISTRIBUTION

Surface Area Effect

- Fine particles dramatically increase surface area available for oxygen contact.
- This accelerates oxidative reactions, increasing the rate of heat release.

Hot Spot Formation

- Fines accumulate in localized zones within piles.
- These pockets restrict airflow, causing insulation effects → concentrated heating and localized hot spots.

Controlling fines during production, handling, and storage is essential to reducing self-heating risk.

INTRINSIC FACTORS – PELLET DENSITY POROSITY

- **High porosity** → increases internal oxygen diffusion → supports oxidation and self-heating.
- **High density** → traps heat inside → reduces dissipation and amplifies localized warming.
- Both **extremes of porosity and density** can elevate risk — but through different mechanisms.

INTRINSIC FACTORS – FEEDSTOCK AGE

- Fresh feedstock: More reactive → higher risk of self-heating.
- Aged feedstock: May undergo some oxidative degradation before pelletization → can generate early CO off-gassing in storage, but generally shows lower total reactivity
- Aging leads to partial oxidation of extractives (resins, fatty acids).
- This primes the material with degradation products but reduces the overall pool of reactive compounds.

Fresh feedstock is most reactive → requires tighter controls (cooling, monitoring).
Aged feedstock still carries risk (early CO and mild heating) but generally less prone to severe runaway.

OPERATIONAL FACTORS

Storage Temperature

Relative Humidity /wetting

Oxygen Availability

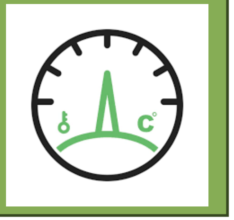
Drying

Temperature and

Residence Time

Pelletizer Pressure

and Temperature



Cooling

Efficiency

OPERATIONAL FACTORS –STORAGE TEMPERATURE

- Reduced Temperature Gradient
- Thermal Insulation Effect of Biomass
- Moisture & Exothermic Feedback
- Crossing the “Critical Zone”

OPERATIONAL FACTORS –COOLING EFFICIENCY

PELLETS EXIT THE PRESS HOT

(~70–90°C)

LATENT HEAT IS TRAPPED

MOISTURE + CONDENSATION CYCLES

POSITIVE FEEDBACK LOOP

Residual heat + moisture + limited airflow = perfect conditions for **oxidation reactions**.

OPERATIONAL FACTORS –DRYING

Overdrying Risks

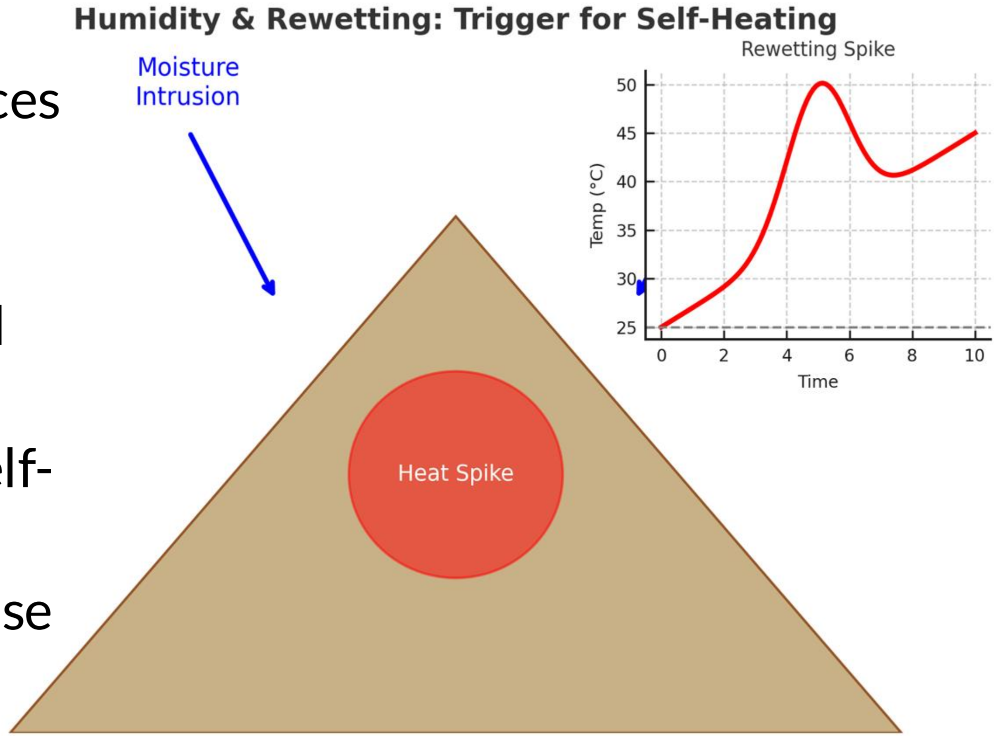
- Produces brittle pellets that generate **excess fines and dust**.
- Fines have a much **higher surface area-to-volume ratio**, which accelerates **oxidation reactions**.
- Leads to faster self-heating, off-gassing, and even higher explosion risk during handling.

Underdrying Risks

- Leaves excess **residual moisture** in the pellets.
- Promotes **microbial activity** in early storage, releasing biological heat.
- Excess water supports **moisture adsorption heat release**, which can trigger secondary chemical oxidation.

OPERATIONAL FACTORS –HUMIDITY AND REWETTING

- **Moisture intrusion sources:** humid ambient air, water leaks, condensation on cooler pellet surfaces, or reabsorption of steam.
- **Immediate effect:** adsorption of water onto dry pellet surfaces is highly exothermic, creating sudden localized **heat spikes**.
- **Secondary effects:**
  - Creates **hot spots** that accelerate oxidation and microbial activity.
  - Increases **relative humidity** inside the pile, leading to a self-reinforcing cycle.
  - Weakens pellet structure, producing fines that further raise oxidation risk.
- Even **short-term rewetting events** (e.g., rain, condensation during cooling, or moist air infiltration) can be enough to trigger **runaway self-heating**.



OPERATIONAL FACTORS – PELLETIZER TEMPERATURE AND PRESSURE

- High die temperature and pressure during pelletization change pellet structure and chemistry.
- Can cause thermal degradation of fatty acids, resins, and lignin → creates reactive compounds.
- Alters pellet porosity and internal stresses → increasing susceptibility to oxidation.
- Pelletizer operating conditions directly influence long-term storage stability.
- Overheating or over-pressurization may produce pellets that oxidize faster and are more prone to self-heating.

OPERATIONAL FACTORS – OXYGEN AVAILABILITY

- Low-temperature oxidation of extractives/fatty acids → heat + CO/CO_2 off-gas.
- **Creates gradients inside piles**: surface zones stay oxygen-rich while cores become O_2-depleted; heating localizes where O_2 and moisture meet.
- **Correlates with off-gassing**: methods studies show strong correlation between self-heating and CO off-gas (a practical early signal of O_2-driven oxidation).
- **Inerting/purging suppresses reactions**: N_2 purging or reduced O_2 markedly lowers off-gas and halts escalation in test reactors/containers.

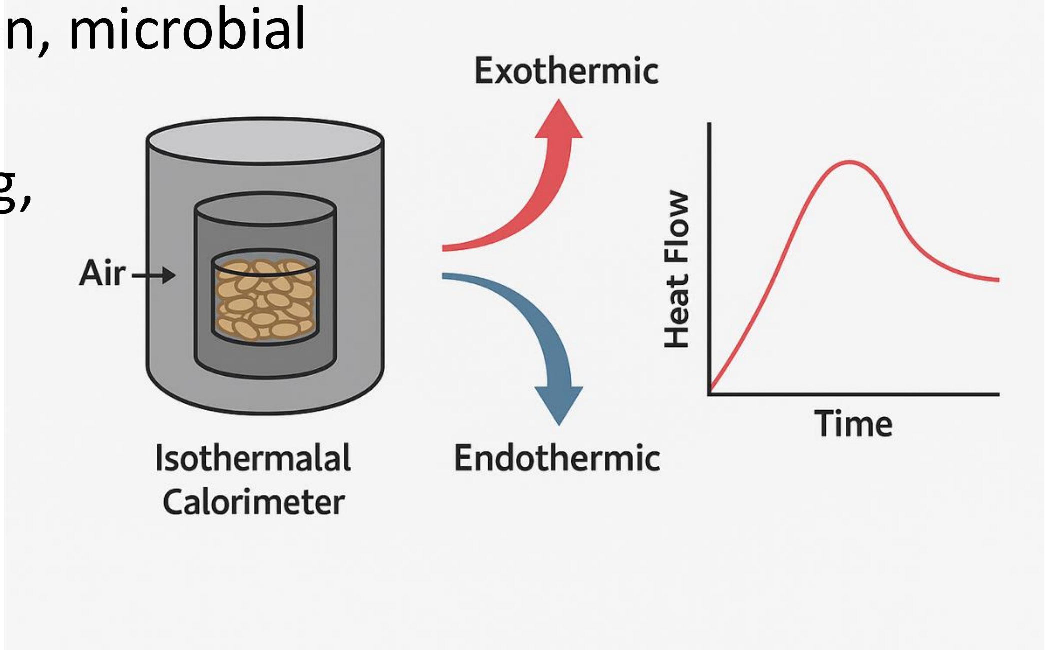
Moisture × Oxygen = high risk

- Elevated moisture increases O_2 consumption and heat production; the O_2–moisture interaction is a major driver of runaway heating.

Limit O_2 ingress where feasible (blanketing/inerting in enclosed systems).
Control moisture to avoid O_2-amplified auto-oxidation.
Track CO/CO_2 and O_2 in headspaces as early-warning indicators.

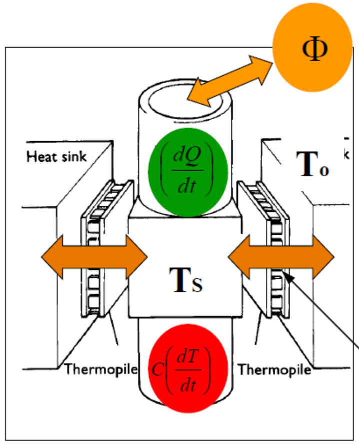
DETECTION METHODS (ISOTHERMAL CALORIMETRY (ISO 20049-1)

- Wood pellets are placed in an **isothermal chamber** with controlled airflow.
- The system measures the **rate of heat release** over time:
  - **Exothermic** = positive heat flow (e.g., oxidation, microbial activity)
  - **Endothermic** = negative heat flow (e.g., drying, decomposition)
- **Onset timing** of biological or chemical oxidation.
- **Rate of heat release** and how it changes with:
  - **Moisture content**
  - **Oxygen availability**
  - **Storage temperature**
- Helps predict conditions that could lead to **thermal runaway**.



DETECTION METHODS (TAM)

TAM III, TA Instument



General Heat Balance Equation

$$\frac{dQ}{dt} = \Phi + C\left(\frac{dT}{dt}\right)$$

Rate of Heat Production = $\underbrace{\text{Rate of Heat Exchange}}_{\text{The measured property}}$ + Rate of Heat Accumulation

After calibration the following holds:

Rate of Heat Production (dQ/dt) = **Heat flow Monitored by TAM**

Pellets + $O_2 \rightarrow CO_2 + CO + CH_4$ + q mW

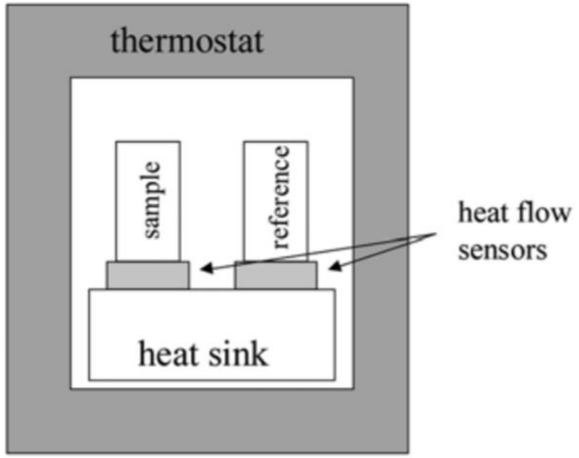
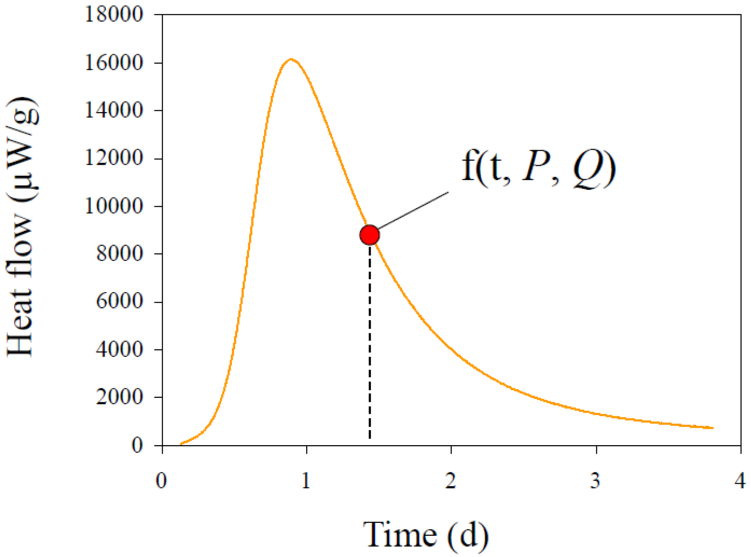


Figure 1 - Schematic drawing of an isothermal calorimeter

Calorimetry is sensitive to all physical and chemical processes associated with a heat flow.
Monitored heat flow may contain contributions from several processes.
The measured heat flow is proportional to the rate of the exothermic reaction.

ISOTHERMAL CALORIMETRY

Rate equations in terms of heat flow:



Shows how the reaction rate varies with time.

$$\frac{dC}{dt} = k.f\,(c) \qquad [\frac{mol}{m^3 s}]$$

$$\frac{dQ}{dt} = \frac{dC}{dt}\Delta H \qquad \left[\frac{J}{m^3 s}\right] = \left[\frac{mol}{m^3 s}\frac{J}{mol}\right]$$

$$\frac{dQ}{dt} = \Delta H.k.f\,(c) = Heat\ flow\ signal\ from\ calorimeter$$

Enthalpy , Thermodynamic Information

Reaction rate , Kinetic Information

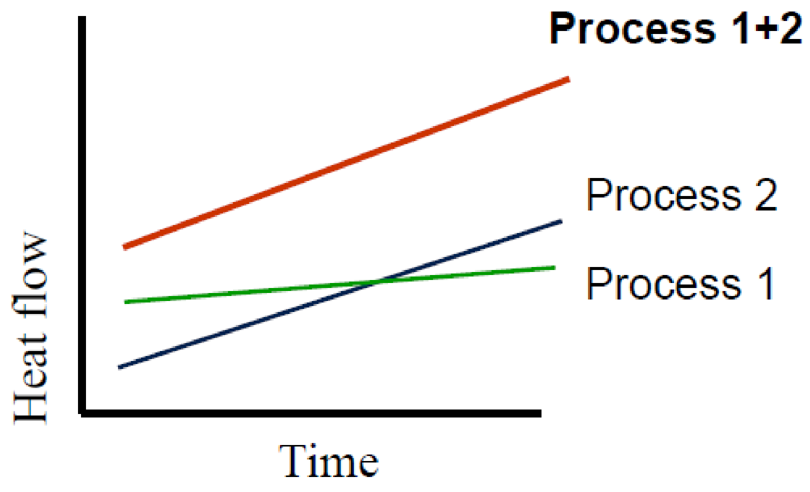
Concentration , Analytical Information

Exothermic reactions → Positive Heat flow signal

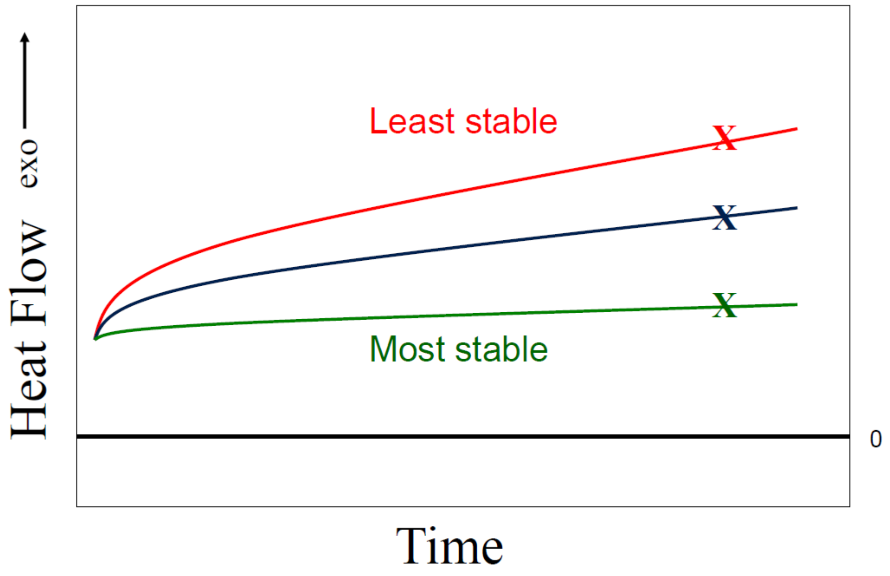
Endothermic reactions → Negative Heat flow signal

ISOTHERMAL CALORIMETRY

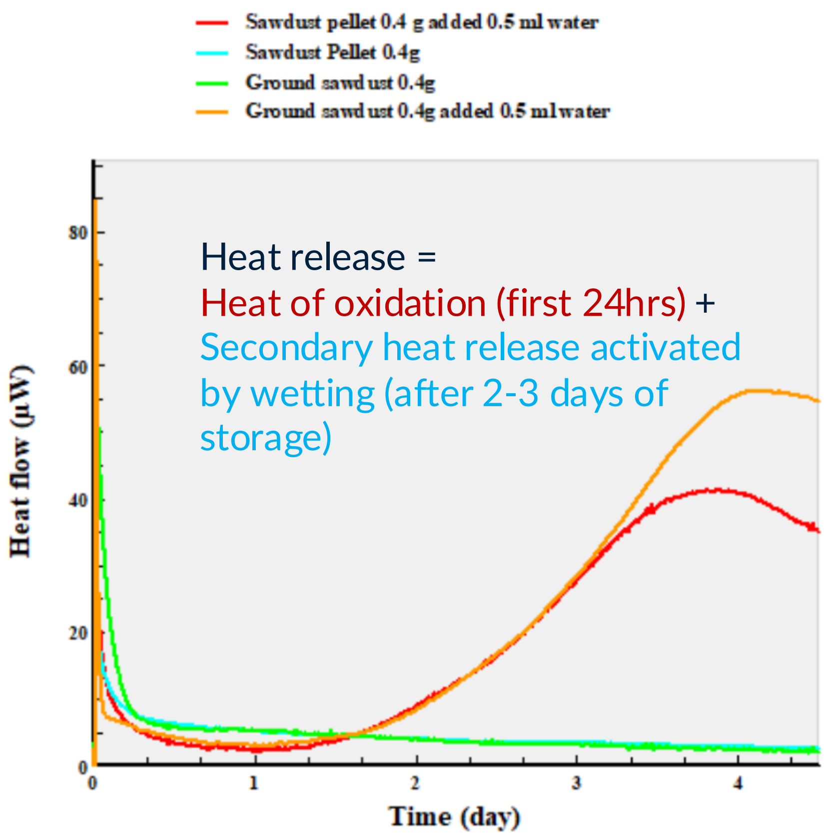
- Calorimetry is sensitive to all physical and chemical processes associated with a heat flow. Thus, the monitored heat flow may contain contributions from several processes.
- Individual contributions may be distinguished by varying the experimental conditions.

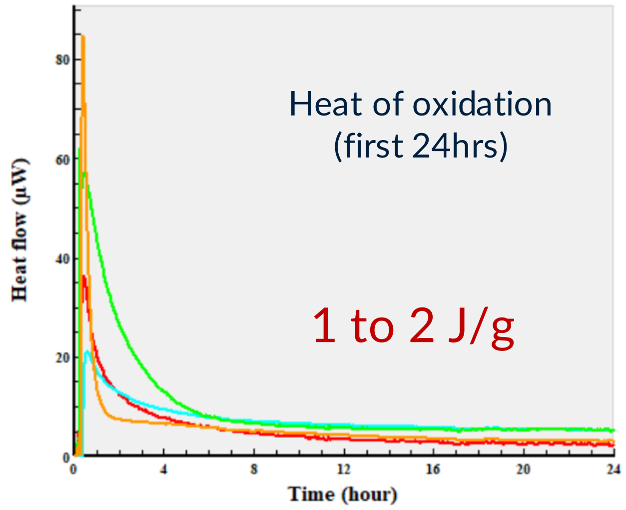


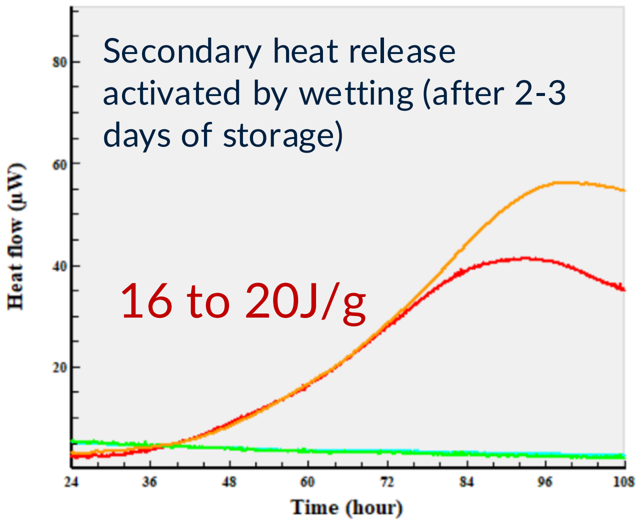
TAM Stability Testing



ISOTHERMAL CALORIMETRY- EFFECT OF MOISTURE



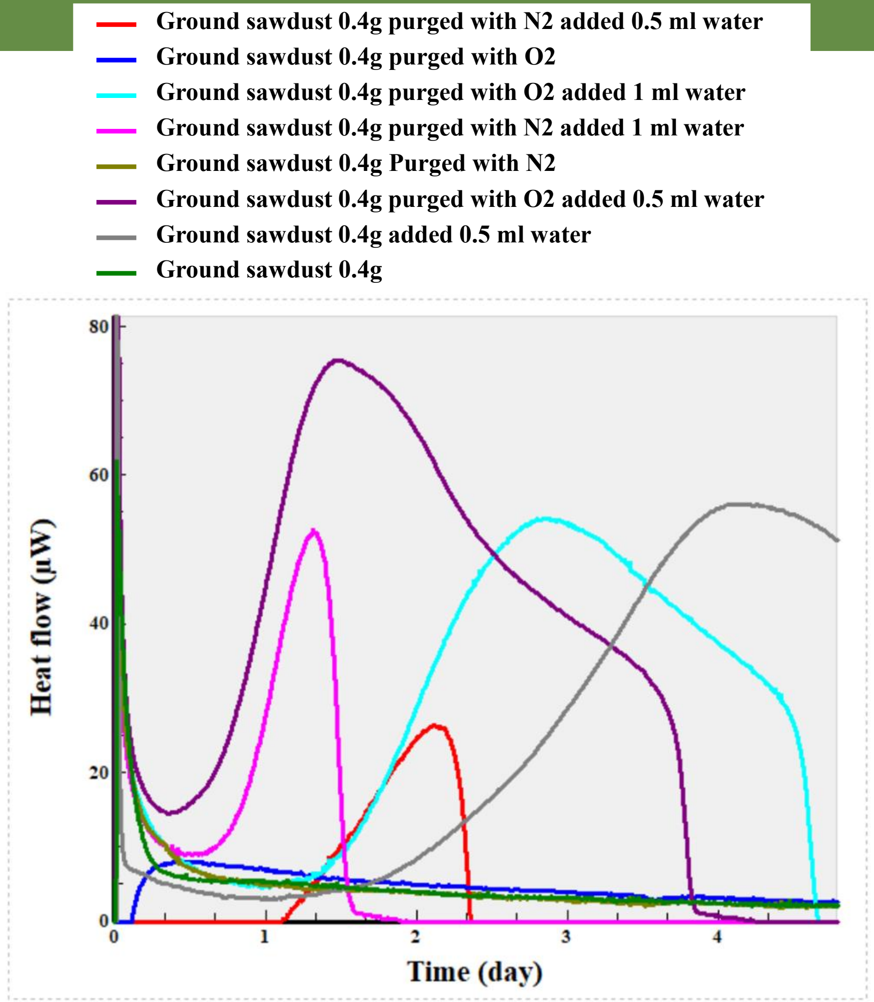




Heat released from ground sawdust over 5 day of storage in air with and without addition of moisture

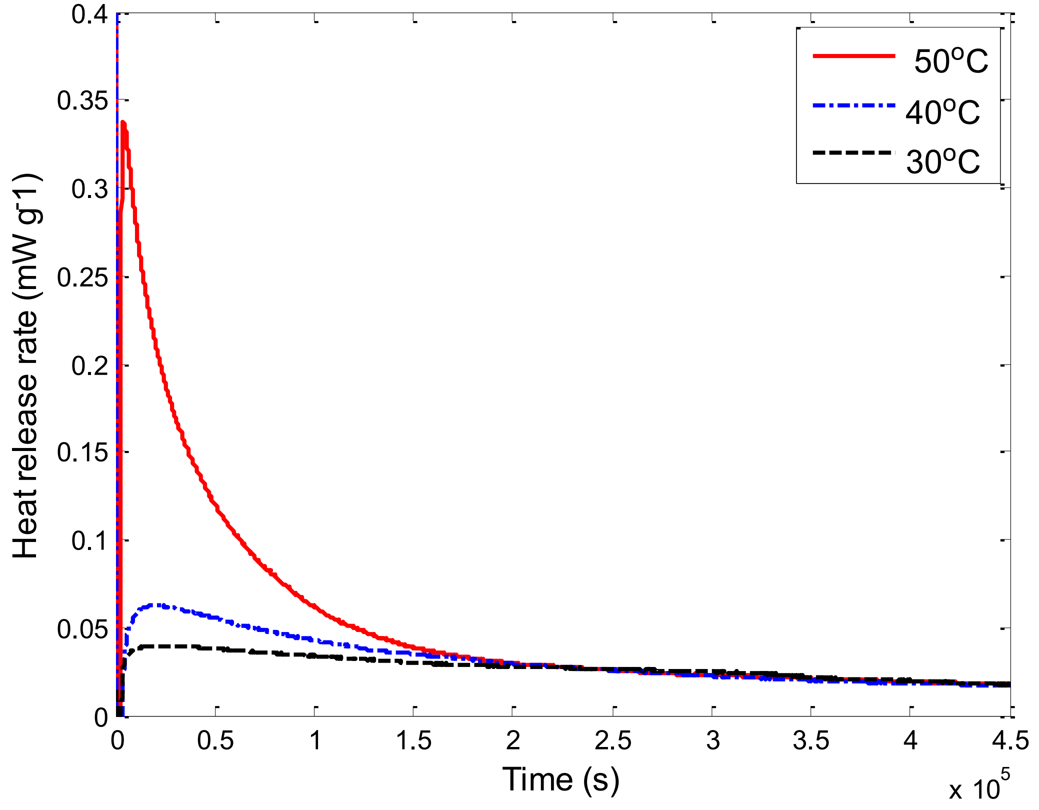
ISOTHERMAL CALORIMETRY- EFFECT OF OXYGEN AND WETTING

- Significant effect of O_2 when accompanied by moisture is shown→ auto-oxidation and thus significant heat release
- In oxygen poor environment the reaction is not self-sustained → no auto oxidation
- The effect of wetting in heat release is significantly higher than oxygen. e.g. the heat release in air & moist environment is as big as oxygen rich moist environment.



Heat released from ground sawdust over 5 day of storage in air, oxygen rich and nitrogen rich environment accompanied by wetting

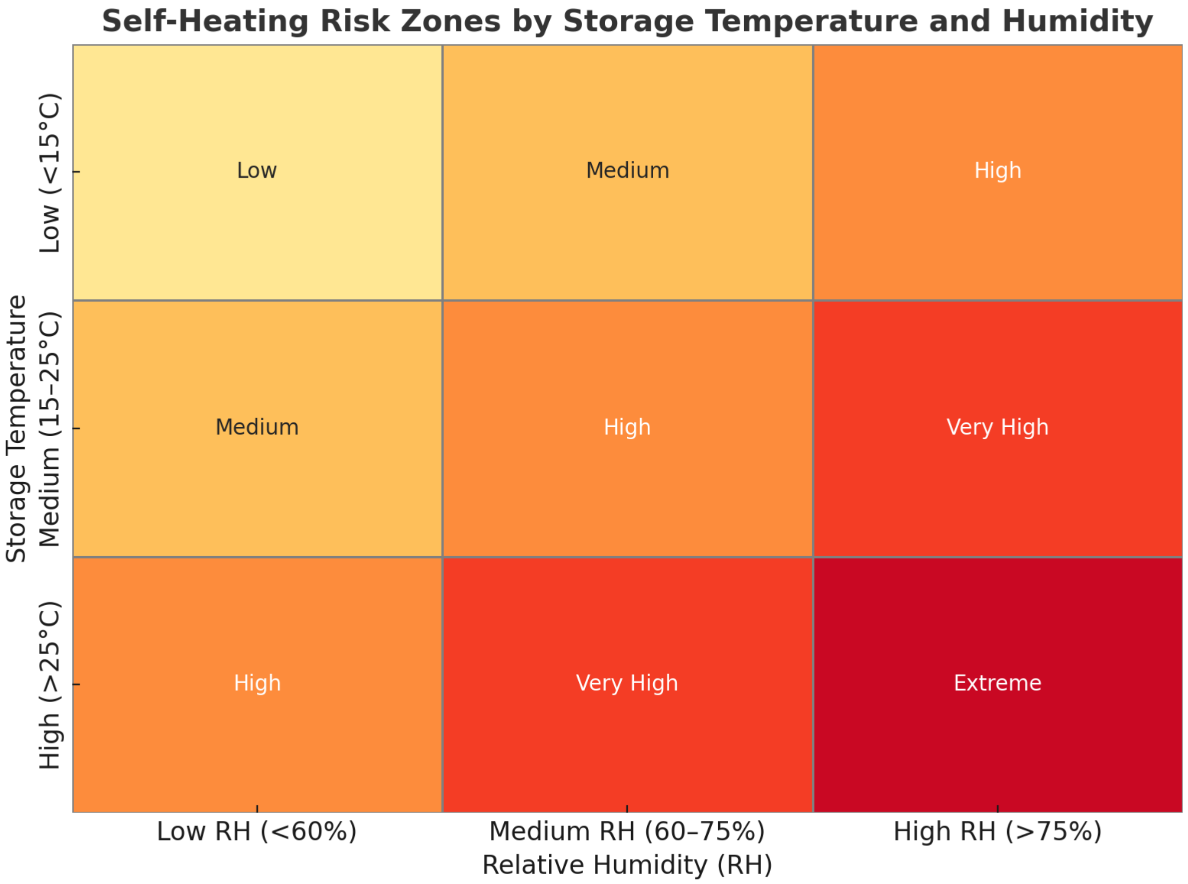
ISOTHERMAL CALORIMETRY- EFFECT OF TEMPERATURE



Temperature significantly effects the heat release rate

Heat released from sawdust over 10 days of storage in air stored at 30, 40 and 50C

EXAMPLE: MULTI-FACTOR RISK ZONES



1.Guo et al. (2019)
Spontaneous combustion characteristics of biomass pellets during storage
1. Studied heat generation in pine pellets at varying moisture and storage temperatures.
2. Found RH and temperature both influence CO off-gassing and self-heating risk.

2.Blomqvist et al. (2017)
Isothermal calorimetry and off-gassing from wood pellets
1. Demonstrated that higher RH and elevated storage temperatures accelerate exothermic oxidation.

3.Wang et al. (2002)
Biomass Storage and Self-Heating in Wood Chips and Pellets
1. Recorded internal pile temperature profiles at different ambient conditions.
2. Emphasized moisture’s key role in enabling runaway heating at high temperature.

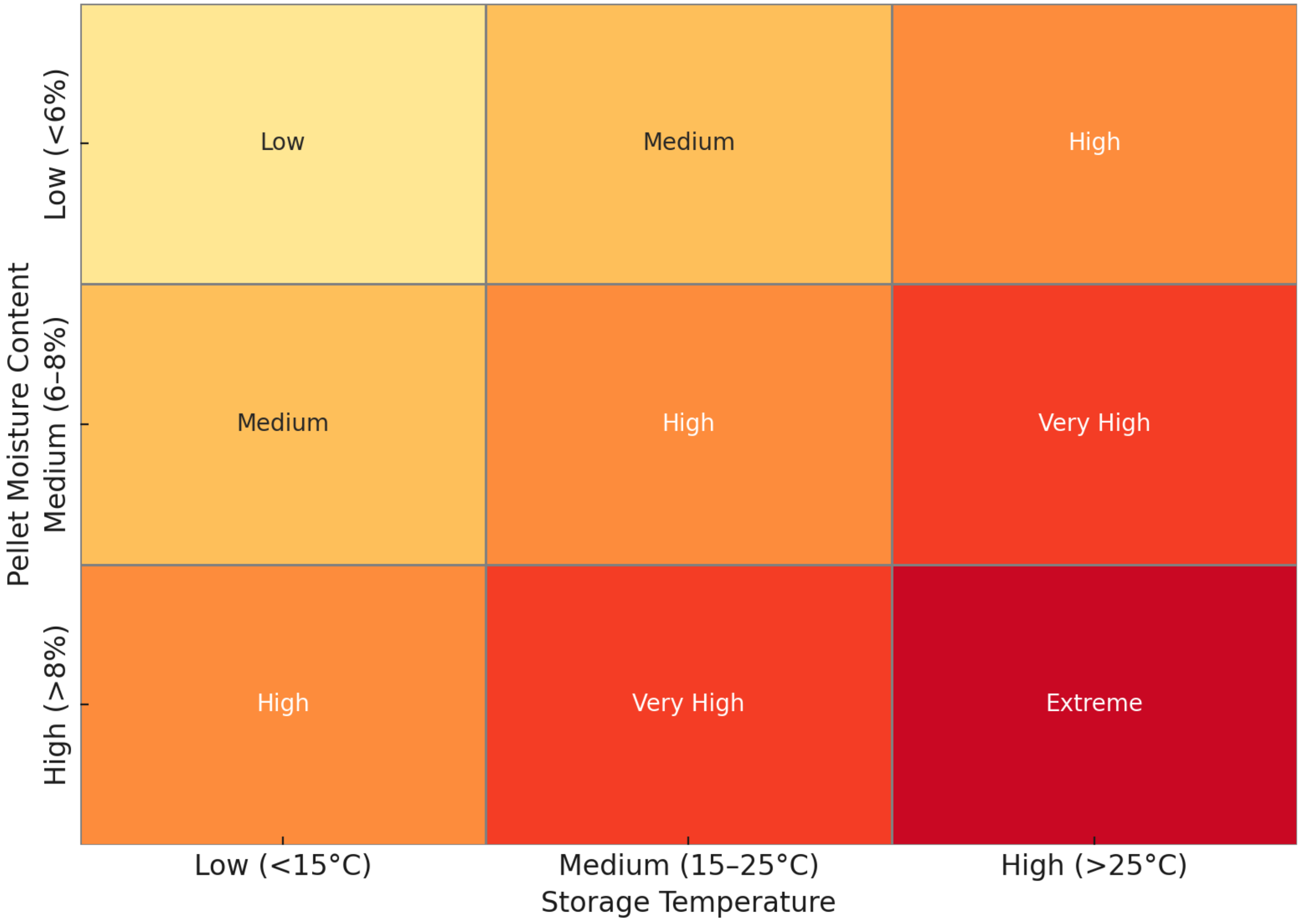
4.Siwale et al. (2024)
Thermal reactivity of juvenile vs mature wood pellets under storage
1. Showed 10–25°C ambient conditions led to significant heating in high-MC samples.
2. Confirmed synergistic effects of RH and temp.

5.Bartknecht, W. (1981)
Explosion Protection
1. Described thresholds at which heat accumulation outpaces dissipation in enclosed biomass storage (i.e., >25°C with moisture).

6.Statheropoulos & Kyriakou (2000)
Thermogravimetric analysis of biomass fuels
1. Discussed oxygen and RH impacts on early-phase oxidation and drying heat release.

EXAMPLE: MULTI-FACTOR RISK ZONES

Self-Heating Risk Zones by Moisture Content and Storage Temperature



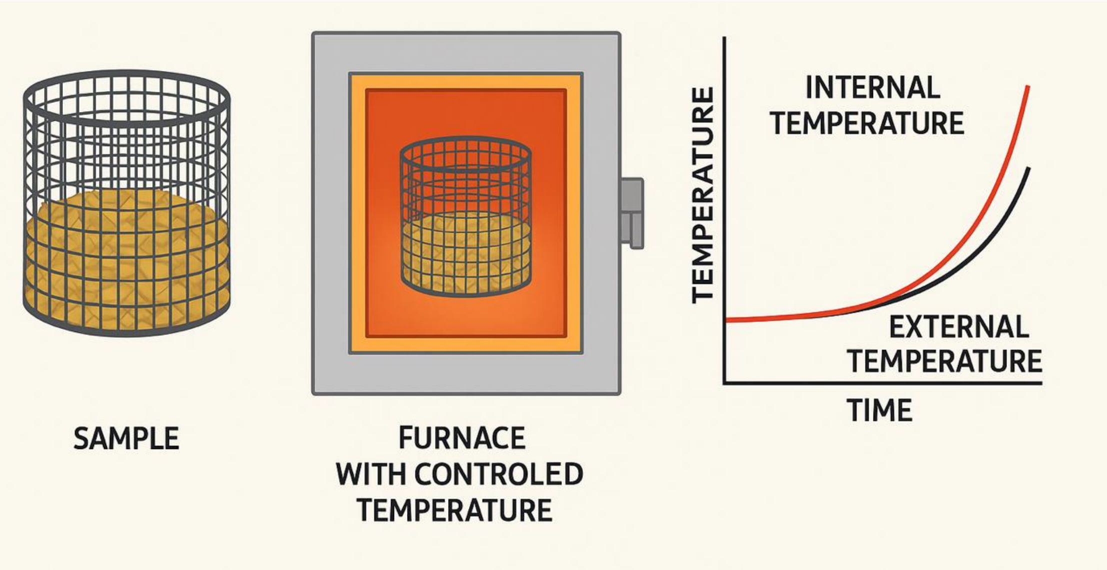
1. **Guo et al. (2019)** – *"Spontaneous combustion characteristics of biomass pellets during storage"*
   Found that **higher moisture content (>8%) combined with elevated temperatures** led to significantly increased CO and heat generation.
   Demonstrated strong **temperature–moisture interaction** effects on self-heating thresholds.
2. **Siwale et al. (2024)** – *Experimental work on juvenile vs mature wood pellets*
   Storage trials showed **higher temperature rise in pellets with higher MC**, especially from juvenile pine sawdust.
   Confirmed elevated heat release in the 6–10% MC range during storage at ~25°C.
3. **Wang et al. (2002)** – *Temperature profiles in stored biomass piles*
   Showed **non-linear escalation of internal temperature** when ambient and internal storage temps exceeded 25°C with moisture present.
4. **Blomqvist et al. (2017)** – *Isothermal calorimetry on wood pellets*
   Showed that **even small increases in moisture content drastically increase exothermic activity**.
   Calorimetric peaks more intense and earlier at higher temperatures and MCs.
5. **Bartknecht (1981)** – *Explosion protection in silos*
   Noted **self-heating risks are minimal below 15°C** and escalate rapidly above 25°C, especially when moisture reabsorption occurs.

DETECTION METHODS (BASKET HEATING TESTS (ISO 20049-2)

- A **sample of pellets or biomass** is placed in a wire mesh basket.
- The basket is heated in a furnace at **constant temperatures** (e.g., 120°C, 140°C, etc.).
- The **temperature inside the sample** is monitored continuously.
- If self-heating occurs, **internal temperature exceeds ambient**.

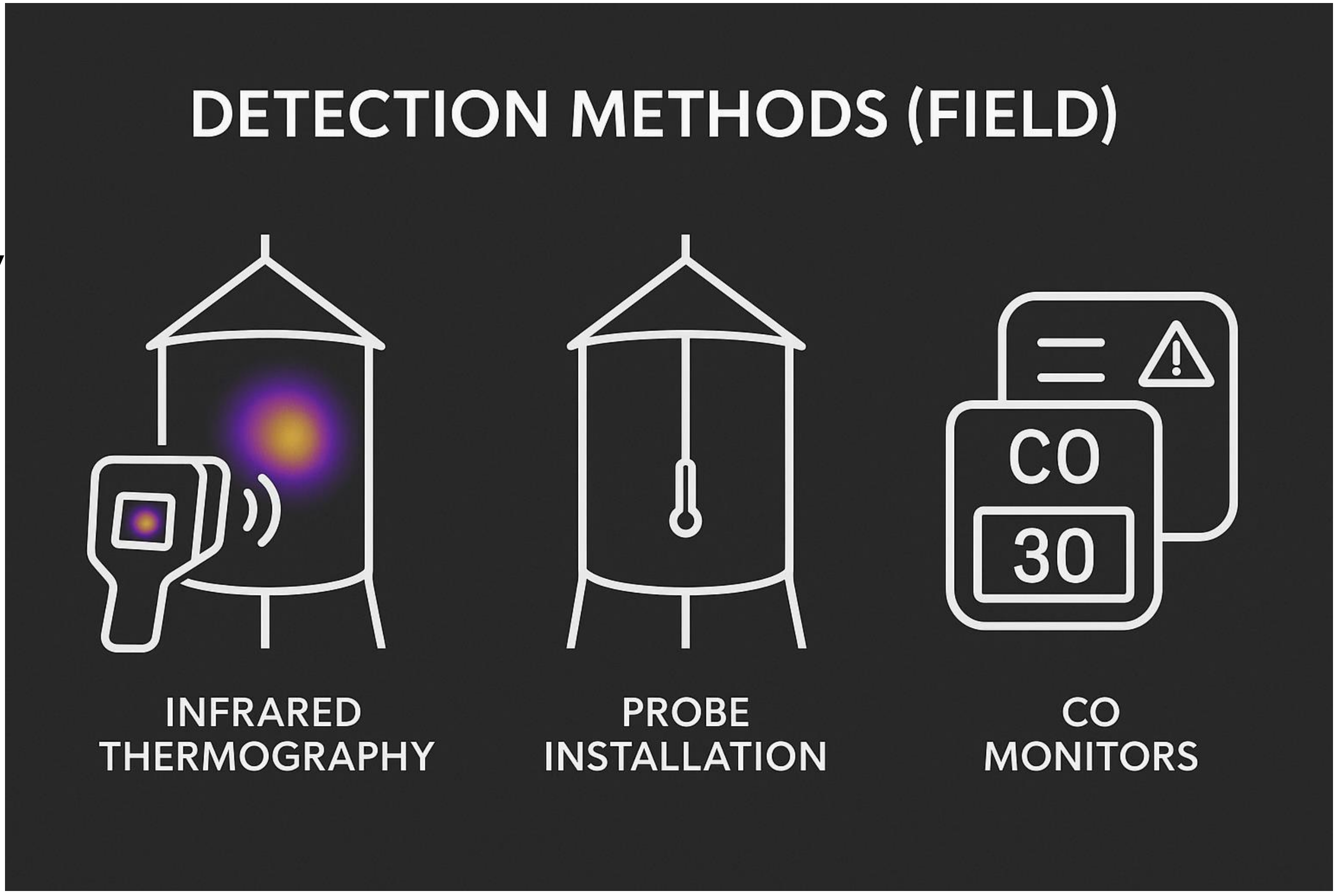
What does it measure?

- Self-heating tendency under defined conditions
- Onset temperature of thermal runaway
- Critical temperature (Tc) for ignition
- Used to classify materials and compare feedstocks



DETECTION METHODS (FIELD)

- Carbon Monoxide (CO) Monitoring
- Infrared (IR) Thermography
- Temperature Probes (Manual or Installed)
- Early Warning Signs (Human & Instrumental)



MENTIMETER QUESTIONS

KEY TAKEAWAYS: MANAGING THE RISK OF SELF-HEATING

Self-heating is a silent but serious threat
It can escalate without warning—monitoring is essential, not optional.

Intrinsic and operational factors both play a role
Wood species, moisture, and storage conditions are all part of the risk equation.

Early detection makes all the difference
Odors, off-gassing, and temperature anomalies are critical early warning signs.

Proactive prevention strategies work
Cooling, inerting, regular inspection, and controlled humidity can prevent escalation.

KEY TAKEAWAYS

Temperature Matters:
Lower storage temperatures significantly reduce the risk of self-heating. Higher temperatures accelerate both initial oxidation and secondary auto-oxidation triggered by moisture.

Oxygen Plays a Supporting Role:
While oxygen can contribute to heat release during storage, its impact is significantly amplified in the presence of **moisture**. In dry conditions, oxygen-driven heating tends to remain low and more controllable.

Moisture Is the Main Driver:
When moisture (humidity, rain, wetting) is present, **secondary heat release** from auto-oxidation can be **15–18 times greater** than the primary heat release—making it the **most critical risk factor**.

Thank you!

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