Safer Operation of Rotary Drum Dryers

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Executive Summary

The Wood Pellet Association of Canada (WPAC) convened a multi-stakeholder Working Group in 2024–2025 to reduce fires and explosions associated with rotary drum dryers.

Rotary drum dryers remain the most common and practical drying technology in Canadian pellet plants because they are robust, heat-efficient, and responsive to changing feed moisture. At the same time, incident history demonstrates recurring pathways to harm within the integrated system that extends from the furnace and dilution duct, through the rotary drum and cyclones, to the induced-draft fan and quench section. This report consolidates lessons from Working Group meetings, incident reviews, and bowtie diagrams developed for the Vanderhoof and Pacific BioEnergy facilities into clear expectations for safer, auditable operation.

Scope

The scope of analysis follows the drying line as it is actually operated in mills. It begins with fuel quality and combustion control in the furnace, continues through temperature conditioning in the dilution duct and convective drying in the drum, and proceeds to particulate separation in cyclones, draft management by the induced-draft fan, and temperature conditioning in the quench prior to downstream pollution-control equipment. This end-to-end view was used to identify credible initiating events, escalation factors, and barriers, and to test whether existing controls perform under stress rather than only in steady-state conditions.

Conclusions

The principal conclusions are straightforward. The periods of highest risk are loss of draft caused by induced-draft fan trips or power interruptions, as well as startup and shutdown. These transients allow the accumulation of combustible gases, promote backflow, and increase the probability of ignition. Additional risk drivers include variability in infeed quality (moisture, species, fines and contaminants), unstable combustion, deposit and dust accumulation in the drum and ducts, ingress of air through worn seals and leaking airlocks, and instrumentation that is either poorly located, fouled, or not maintained to specification. Human and organizational factors—alarm flooding, bypassed permissive, missed inspections and clean-outs, and insufficient drills—regularly amplify technical weaknesses.

The consensus set of controls focuses on proving draft and atmosphere, managing fuel variability, and assuring barriers. Purge should be verified by both time and flow prior to light-off; feed and light-off permissive should be tied to live confirmation of induced-draft fan status and minimum airflow; feed should be held automatically and abort or vent paths opened upon trip; and control systems should have ride-through power with backdraft protection where practicable. Multi-point oxygen measurement at the furnace outlet, dryer inlet, and pre-cyclone, supported by carbon monoxide measurement at pre-cyclone, provides early warning of unsafe atmospheres. These instruments require defined calibration and cleaning schedules as well as physical protection from deluge or condensation. Infeed screening and deliberate blending to control moisture, together with upstream moisture monitoring, stabilize combustion. Deposits and dust are managed by trending cyclone differential pressure, setting and acting on clean-out triggers, and maintaining the integrity of airlocks and seals. Isolation and venting where engineered, together with adequate quench capacity, limit consequences if ignition occurs. Each safety-critical barrier should have a performance standard, a defined proof-test method and frequency, and an accountable owner, all tracked in a barrier register.

The Working Group also identified industry-wide gaps that warrant coordinated action. These include:

- Standardizing oxygen and carbon-monoxide measurement locations and alarm strategy.
- Specifying purge and abort performance standards with annual flow-verified testing.
- Defining leak criteria for seals and airlocks and linking those criteria to maintenance actions.
- Proper operators’ training to understand leaks and the influence of leaks in the process.
- Establishing and drilling induced-draft fan trip playbooks.
- Improving access for inspection and cleanout.
- Advancing data analysis.
- Developing predictive models.
- Adopting common performance indicators supported by a cross-industry learning forum.

With these measures in place, rotary drum dryer incidents are preventable, and performance can be sustained at a higher, verifiable standard.

1. Introduction

1.1. Background

Biomass feedstock drying is a key operation for producing durable and storage-stable pellets. The operation reduces the average moisture content from about 50% (wet mass basis) to 5%-7% moisture content. Most Canadian pellet plants rely on rotary drum dryers for this step because they are robust, heat-efficient, and responsive to changing feed moisture[1,2]. Over the past decade, however, industry has experienced multiple safety incidents linked to dryer operations, underscoring the need for a coordinated response.

The Wood Pellet Association of Canada (WPAC), in co-operation with the BC Forest Safety Council, and media partner *Canadian Biomass*, held the *Drum Dryer Symposium* on April 04, 2024. The purpose of the symposium was to share the learnings from these incidents and for individual operators to share in-house safe operating procedures with their industry colleagues. Over 100 people from across Canada participated in the symposium to hear from producers and subject matter experts on their learnings and experiences, the current state and new approaches to drum dryer safety.

A key outcome of the symposium was the establishment of a Rotary Drum Dryer Working Group. Over the subsequent year, the group met regularly to examine trends in historical and recent incidents; identify opportunities for technical, operational, and training improvements; and formulate practical recommendations for safer, incident-free dryer operation. The present report consolidates the Working Group's findings, integrates them with relevant scientific literature and industry standards, and highlights both achievements and remaining gaps. It is issued publicly through WPAC to support continuous improvement in drum dryer safety and to strengthen the sector's safety culture.

1.2. Rotary Drum Dryer Working Group

The Rotary Drum Dryer Working Group was composed of 24 members with representatives from Wood Pellet Association of Canada (WPAC), BC Forest Safety Council (BSFSC), dryer manufacturers (TSI, Wellons), pellet producers (Drax, Premium, Weyerhaeuser, Tolko, Shaw), safety solution providers (Fike, REMBE, Firefly), consultants, academics (University of British Columbia (UBC) Biomass and Bioenergy Research Group), and technology providers. Chairs and co-chairs were selected from WPAC and pellet producer members to lead and facilitate the meetings. Appendix A. Rotary Drum Dryer Working Group Members lists the members of the Working Group.

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[1] Jensen PD, Temmerman M, Westborg S. Internal Particle Size Distribution of Biofuel Pellets. Fuel. 2011;90:980–6.

[2] Rezaei H. Physical and Thermal Characterization of Ground Wood Chip and Ground Wood Pellet Particles. Ph.D. Dissertation, University of British Columbia (UBC). [Vancouver]: University of British Columbia (UBC); 2017.

1.3. Project Scope

The objective of forming a Working Group is to evaluate and assess risks associated with the operation of rotary drum dryers for biomass and identify opportunities for improvement. This project focuses on the drying system components typically supplied for pellet plants, beginning with the furnace infeed bin or fuel bin for a dust bin, with the assumption that equipment feeding into these bins is maintained under a strict maintenance program. The scope does not include hammermills located after the dryer, the pellet press and post-production pellet handling and storage.

The scope encompasses three main components:

- **Heat Energy Source:** This includes the furnace, gas burner or bark burner that provides the hot gas used in the drying process.
- **Dryer System:** Dryer drums where the hot gas and moist biomass meet and provide enough residence time to dry wet biomass. Both existing and new dryer designs were evaluated, with consideration of system variations such as single-pass and triple-pass dryers. Particular attention was given to the unique challenges presented by triple-pass dryers compared to single-pass designs. Systems that incorporate recycling materials within the dryer will also be analyzed for their operational and safety implications.
- **Pollution Control Equipment:** While the project included this equipment (e.g., wet Electrostatic Precipitator), it does not provide an in-depth analysis of its functionality, focusing instead on its connection with the dryer system.

The Working Group reviewed equipment and safety controls at the dryer infeed and determined whether additional controls or equipment are needed to improve safety levels. The review included external ignition sources and the safety systems associated with rotary drum dryers, grouped as the following items:

- **Prevention:** Spark detection and extinguishment, flame detection, temperature, rate-of-rise, smoke and combustion-gas detection.
- **Fire Protection:** Automatic sprinklers and deluge systems with manual bypass.
- **Explosion Protection:** Venting, isolation and suppression.
- **Interlocks:** Diverters, fire dumps, sequential shutdown and alarms.

The primary emphasis was on identifying and addressing fire, flash fire and explosion risks within the dryer, ducting and cyclone systems. This scope extends from the furnace/burner systems and concludes at the start of the quench duct leading to pollution control equipment.

Insights from the belt dryer project on infeed cleaning and contamination removal are incorporated where relevant. Material preparation, including contaminant removal (e.g., magnets and rock scalpers), was excluded from scope; robust maintenance is assumed for equipment leading into the dryer system.

2. Process Flow and System Description

2.1. Narrative Overview

The drying line begins with a heat generation system, where either biomass fuel (bark, sawdust etc.) or natural gas is combusted to generate hot gases. Figure 1 shows a grate furnace as an example. The details of other common furnace types is discussed in Section 4.

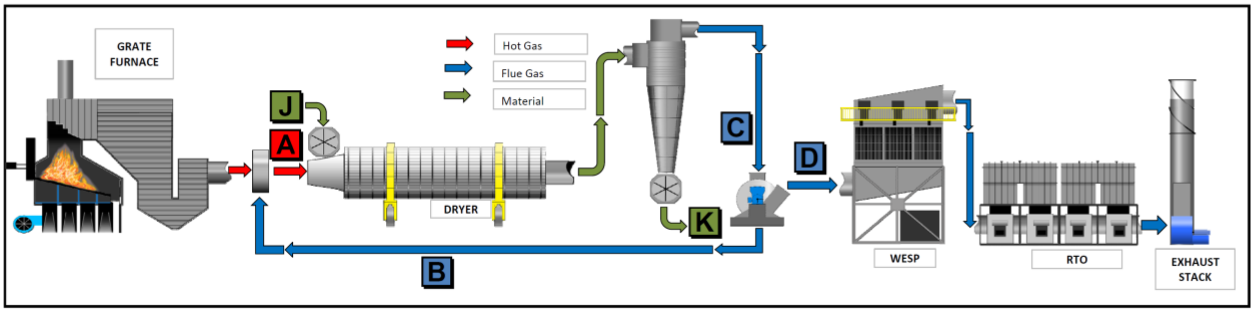

Figure 1. Process flow of rotary drum drying line in biomass processing operations; equipped with furnace, dilution duct, rotary dryer, cyclones, induced-draft fan, wet electrostatic precipitator (WESP), regenerator thermal oxidizer (RTO), and exhaust stack (adapted from Working Group presentations).

The hot gases flow through a dilution duct where either air recycled from the cyclones (Stream B) or fresh air may be added to adjust gas temperature before entering the rotary drum dryer. Depending upon the moisture content of moist biomass, the operating temperature for such dryers is around 300-600°C (Figure 2)[3]. Such a high temperature maximizes the rate of moisture evaporation and shortens the biomass's residence time in the drum.

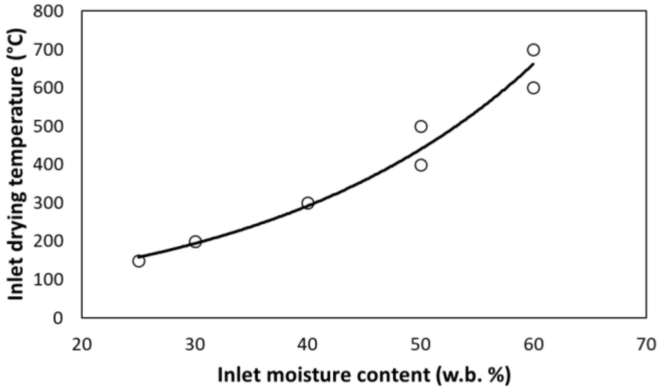

Figure 2. Inlet drying temperature of hot gas versus the inlet moisture content of biomass[4]. Back-loop control system of the dryer controls the inlet hot gas temperature to achieve the final 5%-7% moisture content.

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[3] Fagernäs L, Brammer J, Wilén C, Lauer M, Verhoeff F. Drying of Biomass for Second Generation Synfuel Production. Biomass Bioenergy. 2010;34:1267–77.

[4] Sokhansanj S, C. Wood H, Venkatesan. V. Simulation of Thermal Disinfection of Hay in Rotary Drum Dryers. Transactions of the ASAE. 1990;33.

Most dryer units operate concurrent flow in which hot gas and wet fibre entering from the same end to utilize evaporative cooling at the front end and to keep the fibre surface temperature below critical thresholds. Therefore, wet biomass (Stream J) and diluted hot gas (Stream A) meet each other in dryer inlet duct and then enter the drum dryer. Inside the dryer, wet fibre would be lifted and cascaded through the hot gas stream, reducing its moisture content from roughly 50% wet basis to 5%–7% wet basis moisture content.

The mixture of partially dried fibre and flue gas then would be conveyed and enters the cyclone separation system (or a series of cyclones) to separate entrained biomass pieces from the air. A portion of the cleaned gas stream might return back to the air dilution section as a recycling stream (Stream B) to reuse the energy contained in it.

The remaining portion of the air (or all the air in case there is no recycle stream) is conveyed onward through the induced draft fan and into downstream pollution-control devices (Stream D), typically a wet electrostatic precipitator (WESP) and/or regenerative thermal oxidizer (RTO), before discharge through the exhaust stack.

Meanwhile, collected fines from the cyclones can be returned to the process via a recycling loop, stabilizing moisture profiles. Optional bypasses and abort stacks provide relief and redundancy during upset conditions. The quench duct ensures gas temperatures are lowered and conditioned before the wet electrostatic precipitator (WESP), reducing the risk of ignition in downstream controls.

2.2. Fire Reasons in Rotary Drum Dryers—Reported by Scholarly Research

Rotary drum dryers are by far the most popular systems for drying fibrous and leafy material. The dryers are efficient at heat transfer and in maintaining a uniform final moisture content, with an immediate response to changes in incoming moisture contents. The dryers are generally cheaper than other dryer types and much easier to operate. None of the other types of dryers, especially belt dryers, come close to the adaptability of the rotary drum dryers.

However, the use of a rotary dryer for biomass has always been a point of contention because they were originally designed for non-fibrous minerals with much higher thermal tolerance, and the dryer's high temperature might be operationally acceptable for those non-fibrous materials. Fibrous materials like lignocellulosic biomass feedstock tend to burn more easily than non-fibrous materials. The design of this dryer is not modified substantially for the biomass industry, and fire is a common incident. It means the problem with incidents of fires needs to be addressed, especially for fibrous forestry and agricultural materials.

In a 1990 study, Patil and Sokhansanj[5] found that chopped alfalfa exposed to 300–800°C flows ignited within 15–45 seconds, well under industrial residence times measured in

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[5] Patil RT, Sokhansanj S, Arinze EA, Schoenau G. Thin layer drying of components of fresh alfalfa. Canadian Society for Bioengineering. 1992;34:343–6.

minutes. This demonstrates that the basic thermal environment of rotary dryers inherently overlaps with ignition thresholds.

Although the rotary drum's axial temperature drops due to the evaporative cooling process[6,7] , the drum's local temperature may be excessive for a biomass particle and cause partial oxidation, generating flammable syngas concentrations. Later studies confirm that moisture, particle size, and density strongly influence whether evaporative cooling prevents or accelerates ignition.

Studies confirm that fibrous biomass begins to generate flammable gases and smoke at a much lower temperature than the ignition temperature, and is called the smoking temperature. Smoking temperature is the minimum temperature at which feedstock particles start to devolatilize and generate visible smoke[8] . The smoking temperature for a wide range of biomass is relatively low at the range of 170-190°C (Figure 3)[9], far below typical inlet gas conditions of 300-600°C. Once ignition occurs, smouldering or flaming combustion can spread quickly in deposits or entrained dust clouds. That is why blending various biomass species with different particle densities and drying behaviour (or moisture loss rate) is a source of fire risk in high-temperature dryers.

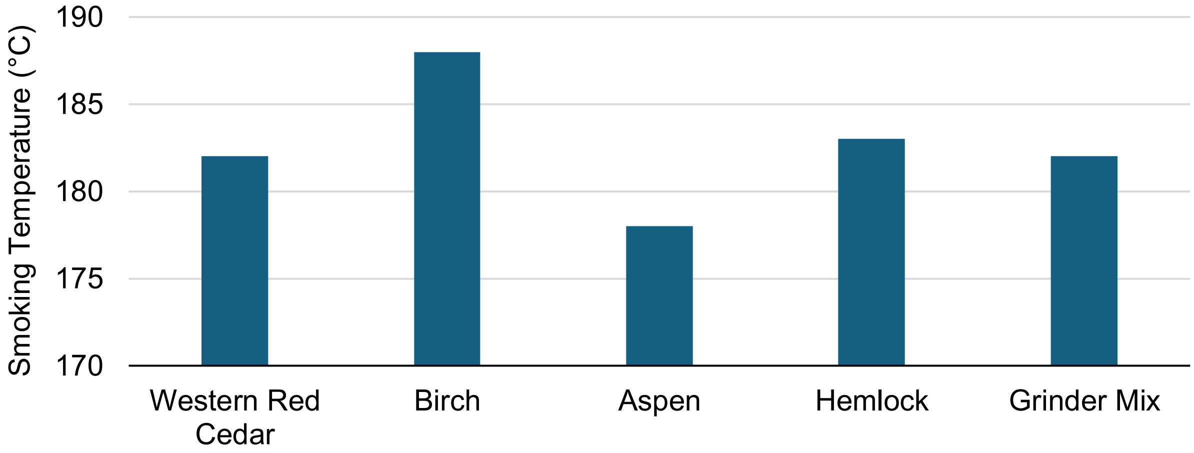

Figure 3. Smoking temperature for five biomass species/mixtures.

The operators of Pacific BioEnergy pellet plants noted in 2018 that mixing even a small level of western red cedar with SPF (White spruce/Engelmann spruce, lodgepole pine, sub-alpine fir) leads to a fire incident in the dryer. Then, University of British Columbia researchers at the Biomass and Bioenergy Research Group (BBRG) initiated the research on *Reasons of Fire in Rotary Drum Dryers in Pellet and Bioenergy Industries*. The researchers found that the western

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[6] Mani S, Sokhansanj S, Bi X. Modeling of Forage Drying in Single and Triple Pass Rotary Drum Dryers. ASAE. 2005.

[7] Hui YH. Food Drying Science and Technology: Microbiology, Chemistry, Applications. Lancester. 2008.

[8] Rezaei H, Lim J, Sokhansanj S. Comparison of Drying Rates of Ground Western Red Cedar with Hemlock, Birch, Aspen, and Spruce/Pine/Douglas Fir. ASABE. 2020;36:159–65.

[9] Ibid.

red cedar and some other species, like aspen, dry much faster than SPF (even with a similar particle size distribution and initial moisture content) under the same thermal conditions and get bone dry and are still exposed to higher than their smoking temperature mid-way of its rotation and tumbling (Figure 4)[10]. Therefore, the hypothesis was that the newly added biomass species emit higher levels of combustible gases than SPF blends during drying. The elevated concentration of combustible gases falls in the flammable zone by definition of Standard ISO 10156 (2010).

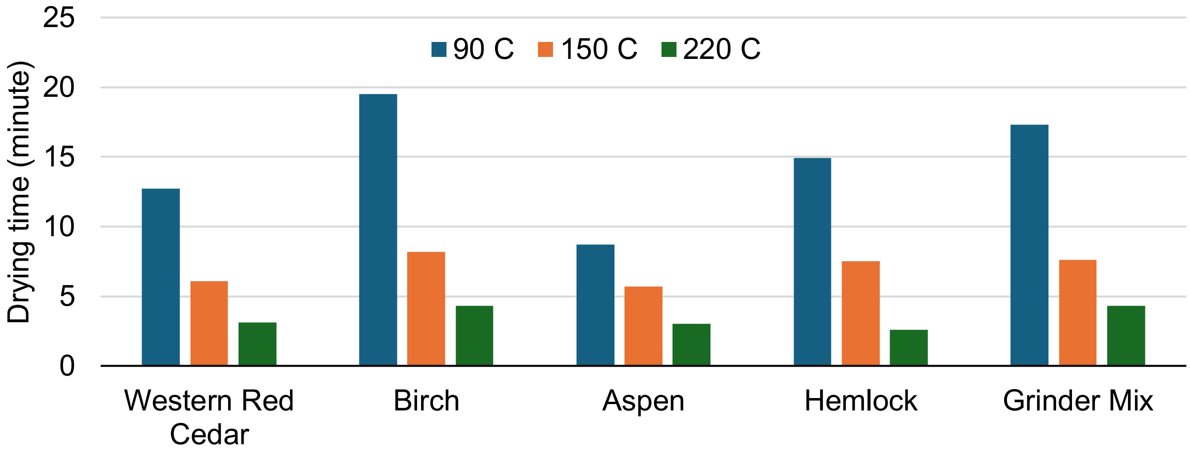

Figure 4. Time required for five biomass species/mixtures to dry from an initial moisture content of about 50% to 10%[11]*. All five biomass feedstock samples were ground using a 1/8" screen, and the particles were sized in the range of 0.5-2 mm.*

As part of analyzing the causes of fires in rotary drum dryers, University of British Columbia researchers developed a complex numerical model to simulate the flow of air and biomass in the drum. The purpose of the model was to quantify the interaction between flowing air and biomass and to evaluate the mixing of the biomass in the drum. Based on experimental measurements and the model's outputs, University of British Columbia researchers suggest the following strategies to reduce the potential of fires in rotary drum dryers[12].

1. Screen out small particles (smaller than 0.5 mm) to bypass the dryer to prevent over-drying and ignition.
2. Reduce the inlet hot gas temperature and increase the biomass residence time by increasing the length of the dryer.
3. Increase the distance between the firebox (burner) and the drum to provide separation between flame fronts and fibre, and prevent sparks from entering the drum.

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[10] Rezaei H, Lim J, Sokhansanj S. Comparison of Drying Rates of Ground Western Red Cedar with Hemlock, Birch, Aspen, and Spruce/Pine/Douglas Fir. ASABE. 2020;36:159–65.

[11] Ibid.

[12] Rezaei H, Yazdanpanah F, Lim J, Lau A, Sokhansanj S. How to lower the chance of rotary drum dryer fires. Biomass Magazine. 2020.

2.3. Potential Hazards and Risks—Reported by Industry

Based on published literature, incident investigations, and the Working Group's observations, a consistent set of hazards has been identified in relation to rotary drum dryer operations. The presentation of Drax's team provided a clear framing of the most critical hazard situations for rotary drum dryers, drawn from both industry experience and incident history. The Working Group discussion insights underscore that the majority of significant incidents in the Canadian pellet industry—including those at 100 Mile House, Burns Lake, Williams Lake, Slave Lake, Entwistle, and Houston—have been linked to the dryer and its associated systems. These incidents highlight systemic weaknesses and recurring patterns of failure.

High-risk situations arise most commonly during power interruptions, startups, and shutdowns. When induced-draft fans trip or power is lost, gases can stagnate in the system, creating pockets of combustible syngas. Startups and shutdowns also create elevated oxygen concentrations, which, if combined with residual fuel or hot deposits, increase the probability of ignition. These transitional phases are consistently reported by operators and manufacturers as the most dangerous times in the drying process.

Key Risk Situations

- **Power outages and induced-draft fan failures:** Loss of draft quickly leads to backflow of gases and buildup of syngas.
- **Startup and shutdown phases:** Oxygen levels rise, and purge effectiveness may be limited.
- **Component failures:** Feeders, seals, dampers, and drums can introduce tramp air or destabilize combustion.
- **Fire protection failures:** Spark detection or deluge systems offline or bypassed, remove essential safeguards.
- **Operator distraction:** Inattention or divided focus prevents early detection of abnormal conditions.

The physical locations most frequently associated with fires and explosions include dryer cyclones, tubular guards, and ducting. These areas are prone to deposit accumulation, smouldering nests, and air leakage. Ducts connecting cyclones to induced-draft fans and recycle systems are especially vulnerable because they combine entrained dust with variable airflow. While the current scope ends at the quench duct, experience shows that downstream systems such as wet electrostatic precipitators (WESPs) and scrubbers have also experienced fire incidents when upstream problems were not contained.

Hazard Drivers

- **Syngas buildup:** Especially in older dryers without purge systems.
- **Incomplete combustion:** Faulty burners or poor blending lead to sparking and carryover of unburned gas.
- **Material buildup:** Deposits in drums, ducts and cyclones act as persistent ignition fuel.
- **Dust explosion conditions:** Over-drying, cyclone plugging and poor blending create combustible dust clouds.
- **Mechanical weaknesses:** Failures in trunnions, bearings, seals and dampers provide ignition sources.

Narrative accounts from industry confirm that these drivers often overlap. For example, a power outage may disable induced-draft fans, leading to syngas buildup, while material deposits provide the ignition source. In such cases, the lack of functioning deluge or spark detection systems has directly contributed to catastrophic incidents.

Maintenance and Inspection Imperatives

The Working Group stressed that mitigation relies heavily on disciplined inspection and preventive maintenance. They highlighted:

- Routine cleaning and inspection of induced-draft fans, recycle ducts, and dampers.
- Calibration of dampers and thermocouples so the operator displays match field conditions.
- Seal leak inspections to prevent tramp air entry.
- Preventive maintenance on trunnions and bearings to reduce the risk of mechanical sparks.
- Deluge and spark detection systems are kept active and never bypassed.

In summary, industry experience shows that hazard events in rotary drum dryers are not random; they follow predictable patterns linked to equipment failures, human factors, and poor maintenance practices. By systematically addressing known risks and reinforcing barriers at multiple points, operators can significantly reduce the probability of fire and explosion events.

3. Infeed Fibre Quality—Taken from Belt Dryer Safety Report

Pellet operators are obtaining their infeed fibre from wider sources besides local sawmills. There has been a significant shift from controlled feedstock from a connected sawmill (planer shavings and dried residuals relatively free of contaminants) to a wide range of feedstock from external sources. As operations increase the amount of external feedstock, such as bush grind and hog fibre, the content of contaminants increases. Many pellet infeed systems are not designed to process the amount of external infeed types and remove the potentially larger amounts of contaminants (refer to *Belt Dryer Safety Report* to see the pictures of infeed material and contaminants).

Several pellet plants provided block diagrams representing their process flow (*Belt Dryer Safety Report*). Upon arrival of the feedstock at the plant, the biomass is separated into piles in open and closed storage, depending upon the available facilities.

Typically, dry planer shavings and clean dry sawdust are stored under a shed. Some of the biomass feedstock arriving at the plant contains contamination that needs to be separated from the infeed fibre. Contaminants such as rocks, ferrous and non-ferrous metals and other undesired items that may cause sparks inside the drying unit are separated and removed from the infeed materials.

Elimination of contaminants in the infeed fibre is important because the manufacturers of the dryers stated that they assume the infeed fibre arrives at the dryer free of contaminants. The manufacturers' risk assessments and design of the internal safety controls are based on the assumption that the material is clean and does not contain foreign material that may cause a spark or overheating. Both biomass and airflow should be free from sources that may introduce sparks into the dryer.

3.1. Infeed Fibre Analysis: UBC Research

University of British Columbia Biomass and Bioenergy Research Group (BBRG) analyzed the infeed material received from the four participating pellet plants in British Columbia. The infeed material is comprised of six types of material: sawdust, shavings, chips, hog grind (sawmill residue), mixed fibre and bush grind (forest residue). The images and descriptions of each group of infeed fibre are presented in the *Belt Dryer Safety Report*.

Table *1* lists the composition of six types of infeed materials from four plants in British Columbia. The data indicate a significant shift from clean, dry infeed material to alternative infeed stock with higher potential for contaminants. The data shows that the share of feedstock from sawdust and shavings is as low as 12% in Plant 4. Hog was 58 wt.% share of the infeed. The remaining infeed was chipped, probably from the pulp log. Two plants, Plant 1 and Plant 2, did not receive any wood chips, but most of their infeed was sawdust and shavings.

Table 1. The range of the percentages of six types of infeed materials used in four pellet plants.

Feedstock Type	Plant 1	Plant 2	Plant 3	Plant 4
Shavings	29.7%	22.8%	35.1%	12.0%
Sawdust	45.6%	18.6%	20.2%	
Hog	3.3%	0.0%	9.4%	58%
Grind – Bush, Yard, Mix	11.0%	2.4%	33.5%	0.01%
Logs – Chipped, Ground	0.0%	36.5%	0.0%	n/a
Other	9.0%	19.7%	1.8%	30%

The sampled materials were tested for moisture content, ash content, bulk density, minimum smoking temperatures, drying time at 90°C and net calorific value. Table 2 lists these values for the tested materials. It summarizes the ranges of moisture content, ash content, bulk density and on-set smoking temperature.

Table 2. Moisture, ash, bulk density, and minimum smoking temperature of the received and analyzed samples.

Process line	Type	Moisture content (% wb)[1]	Ash (% db)[2]	Bulk density (kg/m^3)	Smoking temperature (°C)[3]
Woody biomass feedstock at plant gate	Sawdust	44-54	0.2-2.5	195-254	155-171
	Shavings	9-12	0.3-0.8	41-117	154-170
	Chips	12-39	0.4-0.5	178-303	155-168
	Hog grind	32-63	0.4-4.7	198-366	154-170
	Bush grind	21-45	0.2-3.0	137-276	165-177
Infeed to the dryer	Feedstock mix	33-45	0.3-1.5	197-377	158-172

[1] *Wet mass basis*

[2] *Dry mass basis*

[3] *Smoking temperature is the minimum temperature at which feedstock particles start to devolatilize and generate visible smoke.*

Sawdust and hog grinds originating from sawmills had the highest range of moisture contents 44%-54% wb (wet mass basis) for sawdust and 32%-63% wb for hog grind. As expected, shavings were the least moist infeed. Bush grind and hog grind had the largest ash content of 3.0% and 4.7%, respectively. It is not clear how much of this ash is biogenic and how much of the dirt is due to soil contamination. Bulk density varied from a low of 41 kg/m^3 (4 lb/ft^3) to 366 kg/m3 (22 lb/ft^3). This wide range of bulk density poses a challenge for a loader operator in preparing uniform loads for the dryer. A low bulk-density feedstock occupies more space (volume). Smoking temperature is when a particle of feedstock, exposed to hot air or in direct contact with a hot surface, starts making smoke prior to burning.

The smoking temperature reported in Table 2 was measured using a Thermogravimetric Analysis (TGA) method, in which a small sample of biomass is heated gradually, and the reduction in mass is monitored closely. The smoking temperature is defined as the temperature at which the biomass starts losing weight and generates smoke. The onset of smoking temperature is lower than the American Society for Testing and Materials (ASTM) Standard E2021-06 ignition temperature. The lowest smoking temperature was 154°C. Exceeding the temperature at any point within the dryer may indicate that a fire is imminent.

Table 3 lists the manufacturers' specified desired particle size for biomass rotary drum dryers. According to the manufacturer, the maximum limit is set to prevent clogging of the dryer screw conveyor. The minimum limit is set to avoid large pressure drops, which will result in higher energy consumption and to minimize dust agglomeration and emissions.

Table 3. The desired biomass particle size for rotary drum operation.

Supplier	**Allowed fine content [1] (%)**	**Optimum (mm)**	**Maximum (mm)**
TSI	15%	15-16 mm (5/8")	Not specified

[1] Fine is defined as particles that pass through a ¼" round hole.

3.2. Blending Analysis

To demonstrate the variability introduced by blending a larger range of materials, a blending analysis was performed. Wood pellet plants may only use sawdust and shavings (blend 1) or a wide range of infeed that includes sawdust, shavings, chips, hog, bush grind and other mixed feeds (blend 2).

As seen in Figure 5 and Figure 6, the range of moisture content, as well as the size fraction smaller than 0.5 mm of Blend 2, is larger than Blend 1. This increase in variability in moisture and particle sizes might result in uneven drying, which happens rapidly because moisture does not distribute evenly when different infeed materials with different moisture contents are blended. The non-homogeneous particle size and large variability in the amount of fine particles may also increase the risk of fire because fine particles are easier to ignite by sparks.

Table 4. Blend compositions 1 and 2 used in the blending analysis.

Biomass species	**Blend 1**	**Blend 2**
Sawdust	75.00%	16.70%
Shavings	25.00%	16.70%
Chips	0.00%	16.70%
Hog Grind	0.00%	16.70%
Bush Grind	0.00%	16.70%
Mixed Feeds	0.00%	16.50%

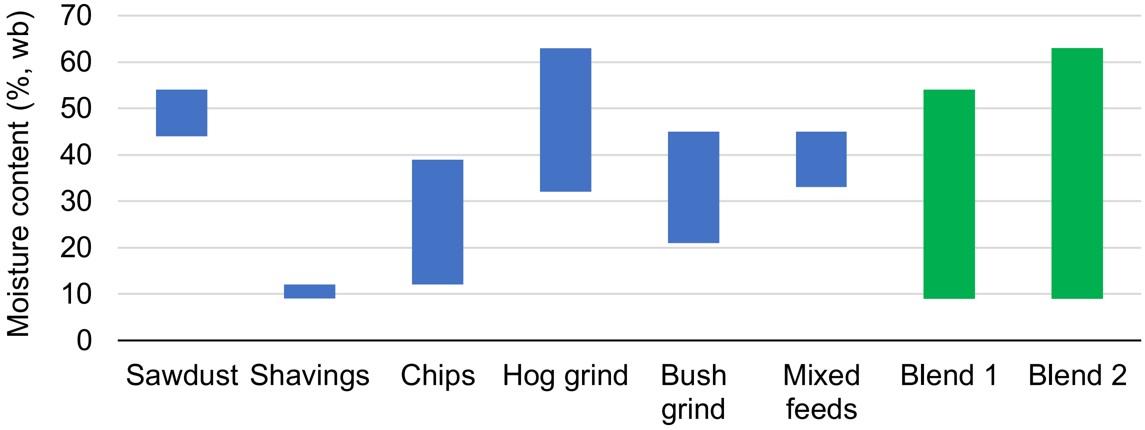


Figure 5. Moisture content ranges of infeed materials and two blends. Blend 1 contains 75% sawdust and 25% shavings. Blend 2 contains equal portions of sawdust, shavings, chips, hog, bush grind and mixed feeds.

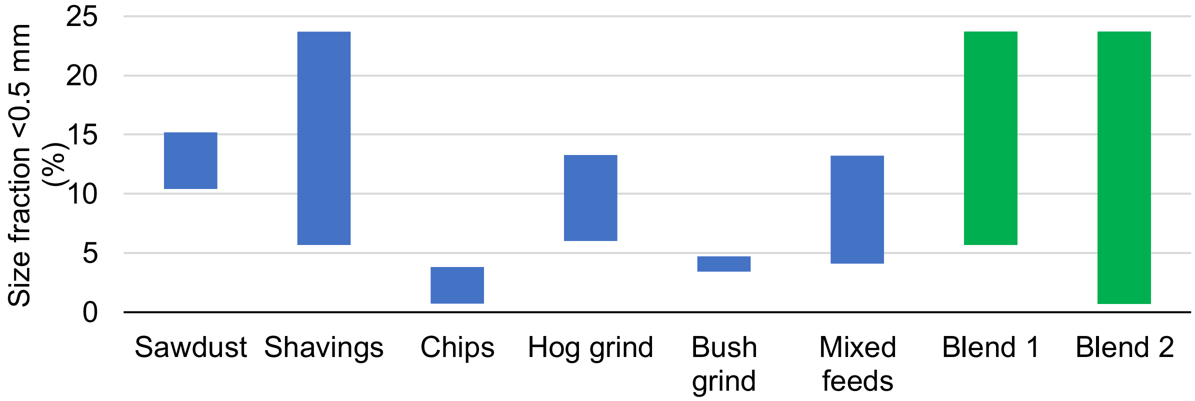


Figure 6. Percentage of size fraction with particles less than 0.5 mm of infeed materials and two blends. Blend 1 contains 75% sawdust and 25% shavings. Blend 2 contains equal portions of sawdust, shavings, chips, hog, bush grind and mixed feeds.

Figure 7 displays the cumulative mass fraction distribution of a sample of particles before and after green hammermill. The lower blue lines give the mass fraction distribution for the in-feed after the green hammer mill. For particles before the green hammer mill, about 50% of the particles are larger than 8 mm. This percentage drops to less than 40% for particles on a sieve size of 8 mm. About 22% of particles are larger than 16 mm. This percentage number drops to less than 8% for particles after the green hammermill. No particles are larger than 32 mm after the green hammermill.

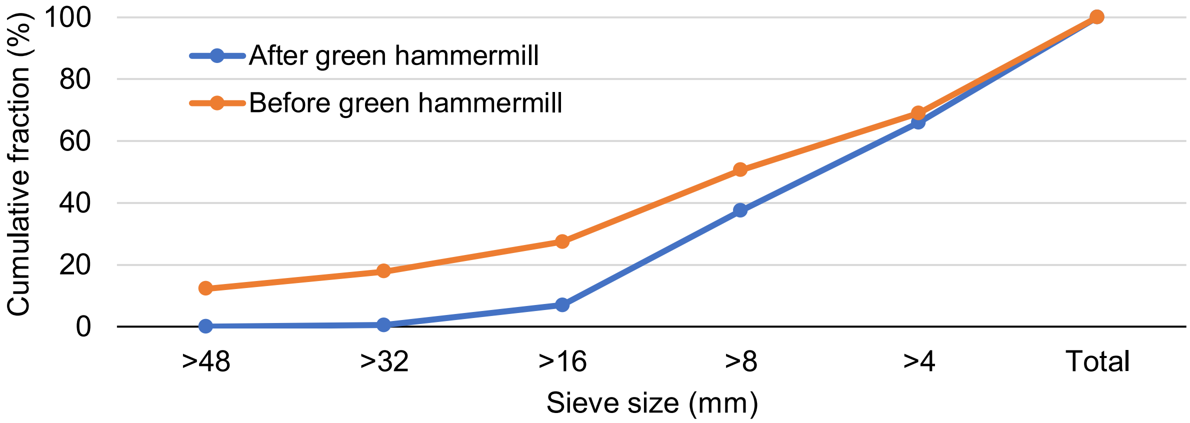


Figure 7. Cumulative mass fraction distribution of a sample of particles before and after green hammermill.

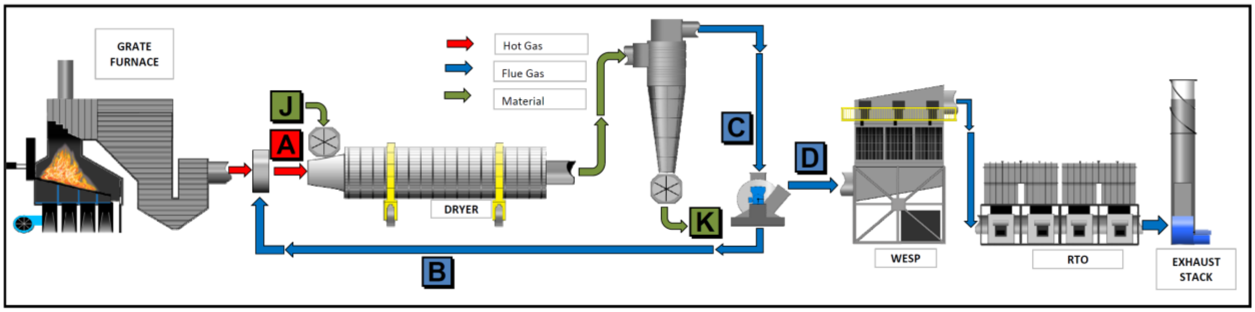
Having a good understanding of infeed quality, contamination levels, and fibre composition helps the operation with production rates, pellet quality, and overall safety. The Working Group determined that increased knowledge and management of infeed quality will play a significant role in the overall success of the operation, including safety. Developing and implementing effective operational controls, such as a formal infeed fibre quality control program, as well as well-maintained equipment controls, can minimize infeed fibre contaminants.

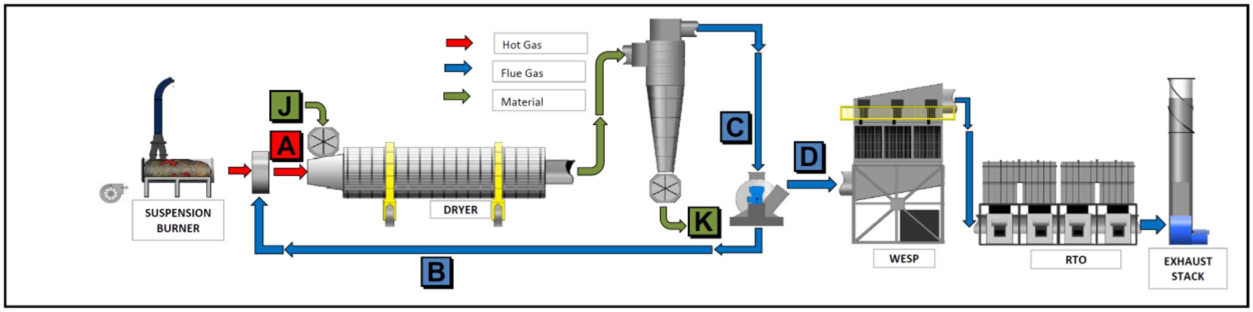
4. Heat Generation System

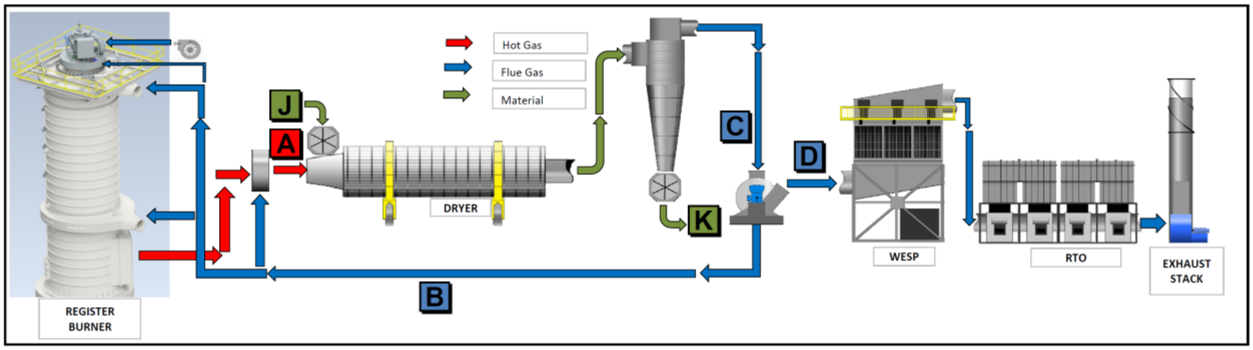
The furnace is the heart of the drying line, providing high-temperature process gas to the drum. The heat generation system is the primary driver of safety and efficiency in the drying line. Its performance and reliability directly determine drying efficiency and safety margins. How the furnace is designed, fired, and operated directly shapes ignition risk. The Working Group noted that dryer incidents often originate with unstable combustion conditions in the furnace.

Direct-fired furnaces are most common, where bark, sawdust, natural gas or mixed fuels are burned in a chamber, and the hot gases are directed into the dilution zone and then to the drum. These systems are simple and efficient but introduce a risk of flame and hot-particle carryover. Indirect-fired furnaces transfer heat through exchangers, avoiding direct contact between flame gases and fibre, but pose their own risks, such as exchanger fouling and hot spots. Furnaces used in pellet facilities for rotary drum dryers are typically direct fired, burning bark, sawdust, natural gas, or a combination thereof.

The most common types of direct-fired furnaces in current pellet plants are (1) grate furnace, (2) suspension burner, (3) register burner, and (4) gas burner; and displayed in Figure 8:







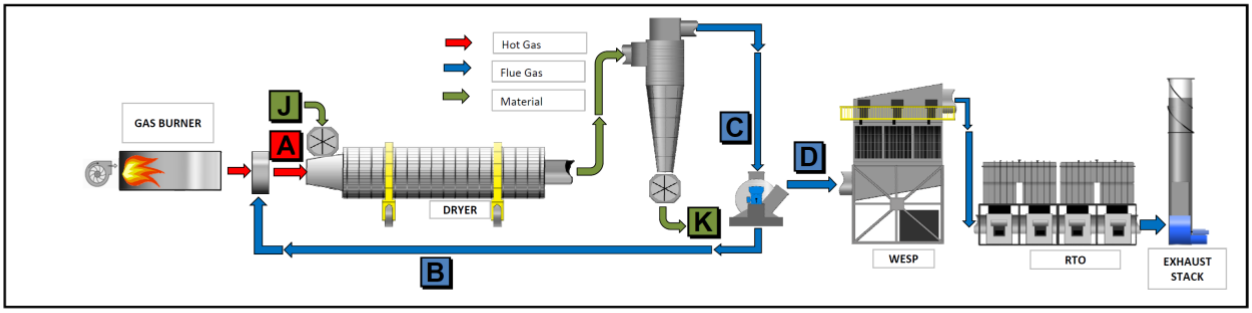


Figure 8. The full process of rotary drum drying of biomass using four various furnace types in pellet plants.

The furnace must be supported by a burner management system (BMS) and clear interlocks. Critical steps include purge cycles before and after light-off, tight shutoff of fuel valves, flame detection, and permissive tied to induced-draft fan operation. Failures in these steps have been implicated in past pellet-plant explosions. The induced-draft fan is particularly critical: its trip or failure removes draft, allowing gases and flames to back-propagate into the drum and ducting. For this reason, the group emphasized the need for fan permissive, trip alarms and redundant monitoring of fan status.

Case studies reviewed by the group and in published investigations show that gas accumulations in dilution zones, or flame instability at startup, were root causes of ignition events. For example, a WorkSafeBC investigation into a 2020 pellet-plant explosion documented how incomplete burner purge and variable fuel moisture led to combustible gas pockets near the dilution zone. When the furnace restarted, these gases ignited, causing a pressure wave that propagated through the ducting and damaged downstream equipment.

Investigators highlighted that inadequate oxygen and carbon monoxide monitoring, combined with inconsistent interlock function testing, contributed to the severity of the incident. This illustrates why conservative purge logic, responsive oxygen/carbon monoxide instrumentation, and routine function testing of interlocks are indispensable safeguards. These examples illustrate the importance of conservative purge logic, responsive oxygen/carbon monoxide instrumentation, and routine function testing of interlocks.

4.1. Fuel Specification

Meeting fuel specifications is critical for stable combustion. The out-of-scope fuel specification and variability/inconsistency in the infeed fuel specification (such as moisture, particle size and ash/contamination) directly impact furnace stability and, consequently, expose dryer operation to safety risks. High-moisture fuels demand more energy to evaporate water, often quenching the flame and leading to incomplete combustion. Conversely, very dry fuels can push flames to the undesired spots inside the furnace, raise furnace temperatures above design limits, stress refractory linings and generate sparks that may travel downstream. Particle size distribution matters as well. Excessive fines combust explosively, while oversized chunks fail to burn completely and emerge as embers. Ash and mineral contaminants introduce further complications, as they melt into slag that coats burner throats, narrows passages, and degrades refractory.

Table 5 summarizes some of the most common out-of-spec effects and the consequences that might occur if variable, inconsistent fuel is fed to the burners. Moisture swings in entering biomass fuel, in particular, were highlighted as a recurring source of oxygen and carbon monoxide excursions. Tramp materials such as stones and scrap metal were also noted for their destructive impact on fuel screws and refractory linings.

Table 5. Feedstock properties and furnace impacts.

Property	Out-of-Spec Effect	Consequences	Heat Energy Type
High moisture content (>55%)	Flame instability, incomplete combustion	Elevated carbon monoxide (CO), unburned gas pockets, ignition risk downstream	Grate furnaces
Low moisture content (<35%)	Over-firing, flame temperature spikes	Increased nitric oxides (NOx), refractory stress, spark carryover	
High fines (<1 mm)[1]	Rapid combustion	Flame surges, unstable temperature control	
Oversized particles (>50 mm)	Incomplete burnout	Char/ember carryover to ducting	Suspension furnaces
Ash/contaminants high	Slagging, refractory damage	Reduced furnace efficiency, increased downtime	

[1] *definition of fine depends on the manufacturer's fuel specification.*

The Working Group emphasized that fuel quality is not just an economic parameter but a primary safety determinant. Many of the challenges operators encounter running furnaces under variable fuel conditions arise from the mismatch between the design assumptions of combustion systems and the actual quality of fuel received at pellet plants. Plants that lack consistent supplier specifications often experience unstable furnace operation, forcing operators to constantly adjust air/fuel ratios and dampers.

4.2. Safety Risks from Out-of-Spec Fuel

Operating furnaces on fuel that does not meet specifications introduces a range of interrelated safety hazards:

- **Carbon monoxide and syngas accumulation:** Poor burnout leads to combustible gas buildup in the dilution zone, ducting and even downstream equipment. These pockets of syngas serve as invisible, highly volatile ignition sources that can flash when conditions change.

- **Spark/ember carryover:** Oversized particles and incompletely burned biomass chunks often survive the furnace and emerge as glowing embers, which can be transported directly into the dryer, creating immediate fire and explosion threats. This safety risk rarely occurs in grate furnaces, as they have ash-dropout chambers, and is more common in suspension burners.
- **Backfires:** Unstable flame conditions, especially during startup or when fuel quality changes rapidly, can cause backfires that push flames and pressure pulses into fuel bins or feed conveyors.
- **Thermal stress:** High-ash fuels exacerbate the situation by accelerating refractory wear and promoting slag deposits that concentrate heat and create local hot spots, which, in turn, lead to structural stress, lining spalling and potential hot-gas leaks.

Together, these factors illustrate why strict control of feedstock quality is not merely an efficiency issue but a critical barrier to preventing major incidents in rotary dryer operations.

4.3. Dependence on Induced-Draft Fan

Loss of induced draft is one of the most hazardous events in the drying line. Induced-draft fan trips or power interruptions remove draft, allowing hot gases and combustion products to stagnate or backflow toward the drum and ducts. The Working Group highlighted the need for:

- Tight permissive tying light-off and feed to verified induced-draft fan status and minimum airflow.
- Automatic hold-feed and initiation of purge/abort sequences upon trip, with defined restart criteria.
- Periodic verification of damper movement, fan run feedback, and purge-flow measurement so that what operators see on the human-machine interface (HMI) matches the field.

Cross-references: See Section 5 for drum-side implications of furnace behaviour and Section 7 for oxygen/carbon monoxide instrumentation and placement.

4.4. Other Operational Challenges

Seasonal and weather-related effects add another layer of complexity, making winter operations particularly problematic when frozen or rain-soaked fuel enters the system. Foreign materials, such as stones or scrap metal, not only damage screws and grates but also cause sudden operational disruptions. Furthermore, instrumentation and oxygen-trim systems were frequently reported to lag in response to rapid shifts in fuel quality, reducing their effectiveness in stabilizing the furnace.

Maintenance-related issues—such as fuel-bin fires, plugged feeders and refractory erosion—were also repeatedly cited, underscoring the need for disciplined inspection and cleaning regimes.

4.5. Critical Controls and Best Practices

Establishing and maintaining strong controls is essential to mitigating furnace-related hazards.

- **Fuel screening & quality control:** Fuel screening and quality control represent the first line of defense: scalpers, magnets, and systematic sampling reduce the chance of contaminants and allow operators to anticipate shifts in ash and moisture.
- **Moisture blending:** Moisture blending techniques, such as live-bottom bins, not only stabilize combustion but also reduce the amplitude of swings that stress controls.
- **Combustion monitoring:** Combustion monitoring must go beyond single-point oxygen analysis; redundant sensors and complementary carbon monoxide measurements provide a fuller picture of stability (see Section 7 for sensor technologies and placement guidance).
- **Purge and light-off interlocks:** Interlocks for purge and burner light-off are critical to preventing startup explosions, and these must be tied into clear permissive logic that operators understand.
- **Refractory inspection:** Refractory inspection programs—combining visual checks, thermography and documentation—help to detect degradation before it causes leaks or hot spots.
- **Operator training:** Operator training is an indispensable control; even the best hardware cannot compensate for untrained or distracted personnel. Training should include recognition of abnormal flame signatures, interpretation of alarms, and appropriate corrective responses (see Section 9).

Together, these controls create overlapping barriers that significantly reduce the likelihood of furnace-driven incidents.

5. Rotary Drum Dryer

The rotary drum dryer is the central thermal unit in the drying line. The dryer starts from mixing diluted hot gas and wet fibre from the upstream feed system (Streams A and J in Figure 8) at the dryer inlet transition. Mixed streams enter the dryer and undergo tumbling and cascading during the biomass' residence time in the drum. The dryer reduces fibre moisture to pelletizing targets while maintaining safe, stable operating conditions. Because the drum concentrates heat, combustible dust, and variable residence time in a single vessel, it is also a primary locus of fire and explosion risk. The Working Group identified the drum as a frequent point of ignition, with many events first becoming visible downstream (e.g., at cyclones or the stack) rather than inside the shell.

5.1. Design and Operating Modes

Design selection for rotary drums balances heat transfer efficiency, controllability and safety margin. For woody biomass at approximately 50% moisture (wet basis), co-current operation exposes the wet fibre to the highest air temperature, reduces the exposure of the driest fibre to peak temperatures, and simplifies control of oxygen and carbon-monoxide levels at the discharge. Currently, rotary drums used in Canadian pellet plants are predominantly co-current (concurrent) flow to limit thermal shock and to achieve high initial drying rates. Counter-current configurations exist, but elevate ignition risk at the discharge end because the hottest gas contacts the driest fibre.

Geometry and prevalence: The Working Group further noted that single-pass drums are now the prevailing configuration due to simpler gas–solid flow paths and fewer internal dead zones. Triple-pass machines—once adopted to boost thermal efficiency—are largely legacy equipment. No Working Group member reported the current operation of a triple-pass drum in the pellet facilities represented. Historically, triple-pass designs were commonly applied to very high-moisture agricultural biomass (more than 80% wet basis), where extended residence and heat recovery were advantageous; this geometry is generally unnecessary for woody biomass entering about 50% moisture content, which dries reliably in single-pass drums.

Gas-solid ratio and pressure profile: Drum performance depends on the gas-to-solids ratio and pressure profile. The Working Group observed that triple-pass geometries tend to require higher volumetric airflow to sweep fibre through concentric annular passages. Consequences include greater fines entrainment, higher cyclone/duct loading, increased differential pressure across the line, and reduced purge effectiveness during transients—factors that were specifically raised as concerns in discussions about multi-pass designs.

Internals and residence-time distribution (RTD): Flight (lifter) design, wear, and replacement frequency govern cascading efficiency and the residence-time distribution. Worn or bent flights reduce mixing, create hot surfaces where deposits adhere, and widen residence-time distribution spread, which increases the probability of over-dry fines.

Key operating parameters. Inlet-gas temperature, gas-to-solids ratio, drum speed and slope, feed rate, recycle fines ratio, and seal integrity together determine moisture uniformity and thermal margin.

5.2. Interfaces and Ingress Points

Interfaces into and out of the drum are persistent weak points because they combine mechanical movement, high temperatures and combustible dust. The inlet transition must deliver uniform gas–solid mixing; maldistribution leads to localized overheating and aggressive fines carryover, which stresses cyclones and induced-draft fans. Seals and access doors largely determine the line's oxygen budget; recurring leakage not only erodes efficiency but also shifts conditions toward flammability. Recycle connections, while useful for moisture control, materially change dust loading and differential pressure if mis-set or fouled, and therefore require routine verification.

- **Inlet transition:** Gas–solid mixing must be uniform; mal-distributed flow causes localized overheating and fines entrainment.
- **Inlet and discharge seals/doors:** Primary tramp-air paths; poor sealing elevates oxygen and dust carryover and erodes thermal efficiency.
- **Recycle connections:** Re-entrained fines alter residence-time distribution and dust loading; blocked or leaking recycle lines increase pressure drop (ΔP) and ignition likelihood.

5.3. Instrumentation and Monitoring

Instrumentation should be specified and operated as a safety-critical system. Redundant measurements at different locations allow cross-checks that are robust to fouling and drift. There are nominally three types of analyzers.

- **Extraction-type analyzers**: Introduce sampling lags and have special maintenance requirements
- **Insertion-type (or in-situ) sensors**: may appear to provide faster response because they are directly in the process. Filters or flame arrestors in the tip may reduce response time despite being close to the process. They are typically more prone to build up, require shielding and rigorous maintenance (see Section 7).
- **Close-coupled extractive analyzers**: Balance fouling and maintenance requirements with speed of response. Gas sampling may be driven by aspiration or convective flow in high-particulate applications.

Importantly, other analyzer technologies, such as lasers, may be used for combustion but are typically not used in high particulate or sticky residue applications.

Alarm philosophy should combine absolute limits with rate-of-change triggers to surface developing instability, and critical instruments require scheduled calibration and function testing.

- **Oxygen (O_2):** Multi-point monitoring at furnace outlet, dryer inlet, and pre-cyclone provides redundancy and cross-checks for sensor drift or fouling.
- **Carbon monoxide (CO):** Continuous monitoring at drum outlet or pre-cyclone provides an early indication of smouldering or incomplete combustion.
- **Temperature:** Distributed thermocouples along the shell and gas path; alarms on rate-of-change and absolute thresholds; optional infrared (IR) pyrometer cameras for external shell scans; borescopes for internal examinations.
- **Pressure/flow:** Suction pressure at the drum, cyclone pressure drop, and damper positions to diagnose instability.
- **Vibration and speed:** Trunnion, gearbox, and ring vibration; verification of drum rotational speed.

Based on the recommendations of the manufacturers, the following is a summary of the features for each category of sensors:

1. **In-situ**
    a. **Zirconia:** Even though the analyzer body is in the process gas does not mean the response time is short. Gas diffusion through the filter may take up to 90 seconds. (Figure 9). Zirconium cells measure oxygen at 677°C, so the process gas should be below this temperature. Typically, they only measure oxygen.
    b. **Laser:** Very quick to give individual readings and are often averaged over several seconds. Typical maximum temperature is 850°C. It can measure oxygen, carbon monoxide, methane, water and temperature. It can be fixed to the process with a single-point probe or a cross-stack arrangement of transmitter and receiver.

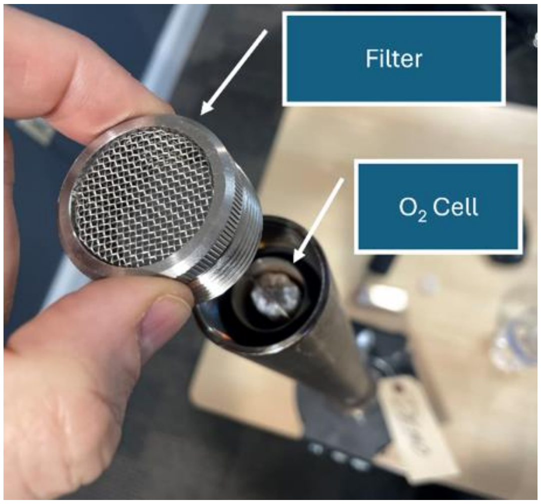


Figure 9. Filter and oxygen (O_2) cell in insertion-type sensors.

2. **Extractive**
    1. **Aspirated magnetic oxygen sensor:** Oxygen in a magnetic field deflects either a mirror or a microswitch, providing oxygen percentage readings. The sensor must be kept at lower temperatures, typically 50°C, so extraction from the hot process is the only option. As this low temperature may cause condensation of pitch and tars, proper sample conditioning should be done to remove these condensates prior to analysis. It can be combined with other analyzers, such as infrared (IR), to read carbon monoxide. Response time depends on the tubing dimensions and pump flow rate.
3. **Close-coupled extractive**
    1. **Aspiration:** Compressed gas provides motive force for the process gas through a precision orifice or jet. The Venturi effect draws process gas into the sampling loop. Response times are on the order of fifteen seconds. Oxygen, carbon monoxide and methane can be measured.
    2. **Convective:** For high particulate process gases, a convective block provides the motive force for sample transport without using an aspirator. It is a natural "chimney-effect" created by temperature and density differences between the hot process gas and the heated analyzer internals. The probe and filter are typically less than four feet long. Typical response times are approximately 30 seconds.

Furthermore, the manufacturers provided the best practices of using the gas analyzers which are listed as follows:

1. **Gas intake**
    1. **Tubing diameter:** Not applicable for in-situ analyzers. Standard sizes for close-coupled analyzers. Extractive analyzers should have gas intake dimensions designed to achieve the expected results.
    2. **Insertion depth:** Probes for in-situ zirconium and in-situ lasers, as well as close-coupled and extractive analyzers, should reach between 33% and 50% of the way across the inside of the space being measured. Laser transmitters and receivers are typically at or near the extremities of the space, but can be brought closer using insertion tubes.
2. **Gas exhaust:** Either return to the process or vent. Typically, for this application, the process gas returns to the process downstream of the intake.
3. **Process temperature:** Zirconium cells should be operated at or near 677°C to enable efficient and stable oxygen measurements. Paramagnetic oxygen and infrared (IR) analyzers are typically operated with process gas flows cooled to approximately 50°C. It is important to mention again that this low temperature may cause condensation of pitch and tars, proper sample conditioning should be done to remove these condensates prior to analysis.

4. **Particulates:** In the drum dryer, particulates may damage the probe or laser lenses, so care must be taken, for example, by using a shield or a protective gas blanket. Heat and pressure may soften or plasticize lignin, which can adhere to probe surfaces and eventually slow or prevent measurement. Having a quick exchange mechanism to replace the probe without removing the analyzer base may be useful, for example, with close-coupled extractive analyzers.
5. **Protection:** In Canada, protection from environmental extremes is worth noting. The electronic controls or automated calibration devices should be wrapped in blankets during winter and shielded from the sun in summer.
6. **Cleaning:** Concentration response and flow measurement in the analyzer system indicate when probes should be cleaned. If the drum dryer is to be cleaned, ensure the probe is fully retracted and out of the way before workers enter.

5.4. Hazards and Leading Indicators

Within the shell, risk is governed by biomass residence time inside the drum and by local heat and oxygen conditions. Although the average axial gas temperature declines due to evaporative cooling, individual particles or fine fractions may experience hotter micro-environments—particularly if they lodge on heated metal or if mixing is poor at the inlet. Changes in fibre blend, feed moisture or loading shift the biomass residence time and might create cohorts of over-exposed particles while others remain wet.

The Working Group's experience indicates that many dryer events begin with this unevenness rather than a single gross malfunction and then propagate downstream as smoldering carryover or dust-cloud ignition. The principal ignition mechanisms arise from the interaction of heat, oxygen, and fuel (fibre and dust):

- **Over-drying and thermal over-exposure of particles:** Over-dry fines or fibre trapped against hot metal exceed smoking temperature and begin devolatilizing; partial oxidation generates carbon monoxide, hydrogen and light hydrocarbons, producing flammable syngas mixtures.
- **Smouldering deposits:** Accumulated material in dead zones can smoulder under low airflow and re-ignite when air supply or turbulence increases; multi-pass geometries increase the number of potential lodging locations.
- **Dust cloud formation:** Intense cascading liberates fines; if dispersion coincides with an ignition source and sufficient oxygen, flash fire or explosion is possible.
- **High-airflow effects in multi-pass designs:** Where higher volumetric flow is required to sweep concentric passes, entrainment of fine particles rises, line pressure drop increases, and purge effectiveness during transients diminishes. These conditions heighten the probability of smouldering carryover and dust-explosion scenarios.

- **Mechanical ignition:** Flight contact with foreign objects, shell hot spots from refractory loss, and misaligned rings/trunnions can create sparks or conductive heating near combustible dust.
- **Tramp-air ingress:** Seal leaks at the inlet and discharge raise oxygen levels, cool local gas streams, and destabilize combustion balance.
- **Ember carryover from the furnace:** Incompletely burned particles can enter the drum and serve as ignition kernels within fibre curtains.

Table 6. Drum leading indicators - what "bad" looks like, likely causes, and immediate actions.

Indicator	What "bad" looks like	Likely cause	Immediate action
Shell/gas temperatures (profiles, ΔT)	Rising/unstable bands; hot-spot alarms; rapid rate of change (ROC)	Deposit formation, poor inlet mixing, over-drying	Hold/slow feed; verify draft; check oxygen/ carbon monoxide (O_2/CO); prepare inspection/ clean-out
Carbon monoxide (CO) increases at pre-cyclone; Oxygen (O_2) increases at dryer inlet (steady firing)	Carbon monoxide (CO) above baseline or fast rate of change (ROC); oxygen (O_2) rising unexpectedly	Smouldering in drum/ducts; tramp-air leaks; draft instability	Hold feed; initiate purge; verify induced-draft fan/damper states; inspect seals/airlocks
Vibration/ovality (lifters, rings, trunnions)	Upward trend in vibration/temperature; abnormal shell expansion	Flight damage, misalignment, bearing wear	Reduce load; schedule inspection; verify lifter condition and drive alignment
Discharge-moisture variance	Frequent under/ over-dry cycling; widened spread	Residence time distribution (RTD) instability; feed-moisture swings; recycle mis-set	Stabilize feed; adjust gas-to-solids; review recycle/damper settings

5.5. Operating Scenarios

Transient states—startups, shutdowns, hot stops and power disturbances—dominate the risk profile of rotary drying because process conditions traverse combustible regimes while equipment states change. The Working Group emphasized disciplined, rehearsed sequences with explicit permissions, time delays and confirmation steps to prevent the introduction of fibre into marginal atmospheres and to avoid premature termination of purges.

- **Startup:** Execute verified purge; confirm induced-draft fan status and correct draft; ramp gas temperature conservatively before introducing fibre. Admit feed only when oxygen, carbon monoxide, and temperature profiles indicate a stable, non-flammable environment.

- **Steady state:** Maintain a stable gas-to-solids ratio; monitor oxygen/carbon monoxide at dryer inlet and outlet; control discharge moisture spread. Trend temperature difference (ΔT, inlet-to-outlet), shell temperature bands, and cyclone pressure drop as early-warning signals.
- **Normal shutdown:** Remove fuel/heat first; continue purge and rotation to strip heat from deposits; verify carbon monoxide decay before isolation.
- **Power loss or induced-draft fan trip:** Highest-risk condition. Immediate actions: hold feed; execute abort/vent per design; initiate purge using available fans; apply deluge only where engineered for the drum/ducts to avoid thermal shock to sensors or the shell.

Successful management of these scenarios depends on graded responses: slow-down and purge should be available before a full trip; abort paths must be proven effective and routinely tested; and post-event restart should be conditioned on normalization of oxygen, carbon monoxide, and temperature—not merely on elapsed time.

5.6. Controls and Interlocks

Effective control logic is grounded in independent, layered barriers. Feed permissive should interlock with verified fan status, acceptable oxygen/carbon monoxide, and stable temperature, with no single signal able to defeat the barrier. Trips and aborts must be deterministic and visible to operators, and proof-testing of interlocks—at intervals aligned with risk—sustains reliability. During high-risk states, pre-programmed sequences should take precedence over manual interventions to reduce reaction time and error.

- **Feed permissive:** Block fibre feed unless induced-draft fan status is confirmed, oxygen/carbon monoxide are within limits, and inlet temperature is stable.
- **High-risk interlocks:** Automatic hold-feed and purge on carbon monoxide high, oxygen out of range, induced-draft fan trip or rapid temperature rise.
- **Abort paths:** Fast-acting dampers and quench/abort ducting to prevent flame or syngas propagation downstream.
- **Seal-integrity management:** Alarms on sustained oxygen elevation at dryer inlet/outlet; routine seal inspection and defined replacement thresholds.

5.7. Inspection, Maintenance and Drum-Side Operating Practices

Asset integrity and operator practice are two halves of the same barrier. This section consolidates the inspection/maintenance expectations for the drum with the operating practices that most directly influence risk at the dryer. Site-wide training programs, drills and playbooks are addressed separately in Section 9.

- **Internal condition (inspection & cleaning):** Schedule inspections via access doors; remove deposits; verify flight condition and attachment; check for refractory loss or shell scoring. Document findings and link actions to restart criteria.
- **Alignment and drive (condition monitoring):** Measure shell ovality, ring creep, and trunnion alignment at defined intervals; trend bearing temperatures and vibration; maintain lubrication quality and records.
- **Seals and doors (oxygen budget control):** Apply a replacement cadence based on leak testing and visual wear; verify door interlocks. Treat persistent oxygen elevation at the dryer inlet/outlet as a leak indicator and investigate seals/airlocks.
- **Cleaning and verification (post-work checks):** After clean-outs, re-establish baselines before returning to service: confirm oxygen/carbon monoxide normality, temperature stability during warm-up, and seal performance after thermal expansion settles.
- **Moisture and species management (operating practice):** Control blend variability (see Section 3) to limit over-dry fines and residence time distribution (RTD) spread; avoid mixes known to create instability unless operating limits are adjusted.
- **Standard Operating Procedures for transients (operating practice):** Keep clear, practiced procedures for startup, hot stops, cold stops, and power-fail recovery. Ensure permissive rely on verified draft and stable oxygen/carbon monoxide/temperature before admitting feed.
- **Alarm management (operating practice):** Use rationalized set-points and escalation paths to prevent alarm flooding and desensitization; prioritize induced-draft fan status, purge flow, oxygen/carbon monoxide and critical damper positions.
- **Shift handover and management of change (MOC) (operating practice):** Record fibre mix, set-point changes, equipment condition, and deviations from normal; apply management of change for any modifications to flights, seals or control logic.

In summary, rotary drum dryers are robust and efficient, but their combination of high temperature, combustible dust, and variable residence time demands disciplined design, instrumentation, and operations. The Working Group recommends reinforced monitoring (oxygen/carbon monoxide/temperature), coherent interlocks tied to induced-draft fan status and gas conditions, strict seal management, and inspection/clean-out programs to keep ignition sources and fuel accumulation below critical thresholds.

Even when comprehensive prevention measures are in place, the potential for an explosion within the rotary drum dryer cannot be completely eliminated. Therefore, facilities should integrate explosion-mitigation technologies—such as venting or suppression systems—where practical, taking into account the physical and operational constraints of drum geometry and process conditions. In cases where direct mitigation is technically limited, engineered explosion isolation must be implemented to prevent the transmission of pressure and flame fronts from the dryer to connected systems. Proper design, inspection, and verification of isolation barriers are essential for ensuring that an internal event remains contained within the vessel of origin.

6. Post Dryer Stages

The post-drying stages are cyclones (either one or a series of cyclones), an induced-draft fan, a wet electrostatic precipitator (WESP; sometimes referenced as WESB in plant documentation), a regenerative thermal oxidizer (RTO), where installed, and the exhaust stack. RTOs can be a bottleneck in an operating plant, caused by dryer inefficiencies such as high seal leakage or air ingress through holes in ductwork, if not properly addressed. RTOs are also very common in the US, but not in Canada, since the VOC emissions are not as regularly regulated.

The Working Group's formal scope covered cyclones, induced-draft fans, and quench interfaces. The detailed operation of wet electrostatic precipitator (WESP) and regenerative thermal oxidizer (RTO) was out of scope. These units remove particulates, maintain draft, condition gases and ensure compliant discharge. They also represent critical control points at which upstream instability can be contained or amplified.

6.1. Cyclone System

Cyclones provide primary separation of entrained fines upstream of the induced-draft fan and downstream air-pollution controls, discharging through fibre dumps/airlocks. Under stable conditions, they exhibit characteristic differential pressure drop and outlet temperature profiles that reflect the drying load. Deviations from these baselines are early indicators of unsafe accumulation or air leakage. Fine, over-dried material may adhere to internal surfaces—particularly cones and vortex breaker boxes —forming smouldering deposits that can reignite when airflow or oxygen availability changes. Well-maintained fibre dumps and rotary airlocks not only convey material but also act as flame-propagation barriers and help preserve negative pressure.

Table 7 lists the typical challenges and risks, the leading indicators operators should monitor, and the corresponding critical controls and practices agreed by the Working Group.

Table 7. Cyclone risks, indicators and controls.

Item	Description / Notes
Typical challenges & risks	
Smoldering deposits and nesting	Fine, over-dried fibre adheres to walls/cones, creating latent ignition sources that flare when airflow/oxygen changes.
Plugging and re-entrainment	High dust loading or fibre-dump blockages elevate pressure drop (ΔP), increase re-entrainment, and push material downstream.
Tramp-air ingress	Worn rotary airlocks and poor seals admit air, raising oxygen and destabilizing upstream combustion control. Worn airlocks can also lead to poor particle separation, which will result in carry-over of material and/or can result in surging of material into the airlocks, increasing the risk of a plug.
Erosion and hot-spot formation	High-velocity elbows/inlets erode liners, expose metal, and increase spark risk.
Leading indicators	
Pressure drop (ΔP) rise across cyclone / mist eliminator	Sustained or rapid pressure drop (ΔP) increase relative to baseline.
Abnormal profile of temperature, carbon monoxide (CO) and/or oxygen (O_2) at cyclone outlet	Deviations from normal outlet temperature; carbon monoxide (CO) spikes signaling smoldering. Abnormal level of oxygen (O_2) at cyclone outlet indicates poor sealing airlocks.
Recurrent fibre-dump/airlock alarms; visible carryover	Frequent alarms or visible dust/embers approaching the induced-draft fan.
Critical controls & practices	
Pressure drop (ΔP) trending with alarmed clean-out triggers	Trend pressure drop (ΔP) with defined limits that trigger clean-out and safe slow-down logic.
Airlock condition management	Leakage checks, blade clearance, chain/sprocket inspections; treat airlocks as flame-propagation barriers.
Internal inspection / cleaning	Use scopes, access doors; define safe deluge application points.
Explosion protection (where applicable)	Compliant venting/suppression; back-flap valves on recycle ducts; bonding/grounding for static control.

Even when effective preventive measures are applied, the possibility of an explosion within cyclones remains. Operators should therefore incorporate suitable explosion mitigation strategies—such as pressure venting or suppression systems—designed for the cyclone's configuration, material load, and process conditions. Equally important, explosion isolation must be employed at strategic interfaces to prevent flame and pressure propagation into adjoining ductwork, the induced-draft fan, or downstream pollution control units. The implementation of isolation barriers should follow recognized engineering standards, with documented proof testing and maintenance intervals to assure ongoing performance.

6.2. Induced-draft Fan and Draft Management

The induced-draft fan maintains negative pressure and a stable flow from the furnace through the dryer and quench section. Because the fan represents a single-point dependency for draft, a power dip, variable-frequency drive (VFD) fault or mechanical failure can permit hot-gas reversal, rapid syngas accumulation and flame roll-back within seconds. Fan health is tightly coupled to system stability: cyclone plugging increases load and vibration; mis-calibrated dampers cause hunting and flow oscillations; upstream seal leaks raise oxygen and place additional demand on the fan. Accordingly, permissive linking furnace light-off to confirmed fan operation and automatic purge/abort sequences on trip are essential safeguards (system permissive and purge/abort minimums are detailed in Section 4.3.

Table *8* lists the typical challenges and risks, the leading indicators operators should monitor, and the corresponding critical controls and practices agreed by the Working Group for the induced-draft fan and draft system.

Table 8. Induced-draft fan and draft management—risks, indicators and controls.

Item	**Description / Notes**
Typical challenges & risks	
Trip or power loss	Immediate loss of draft enables hot-gas backflow, syngas pockets, and flame roll-back.
Mechanical failure	Blade erosion/fouling, imbalance, bearing overheating, or variable-frequency drive (VFD)/motor faults causing draft instability.
System interactions	Cyclone plugging elevates fan load; damper mis-calibration drives unstable flow; upstream leaks raise oxygen demand.
Leading indicators	
Vibration/temperature/motor current	Rising vibration or bearing temperature; abnormal amperage draw.
Suction pressure instability	Step changes in drum/cyclone suction; oscillating damper positions.

Item	Description / Notes
Nuisance low-flow/draft alarms	Frequent alarms are indicative of marginal draft or control hunting.
Critical controls & practices	
Interlocks and permissive	Inhibit light-off without confirmed fan status; automatic purge/abort on fan trip.
Ride-through and backdraft protection	Standby power for controls/purge; backdraft dampers to prevent reversal.
Condition monitoring	Trend vibration and bearing temperature with defined shutdown criteria.
Precision maintenance	Balance/alignment program; periodic non-destructive testing on blades/shafts; disciplined lubrication/coupling inspections.

6.3. Quench Duct

The Working Group treated the quench duct as the interface boundary to downstream pollution control, emphasizing temperature conditioning and abort/vent routing during upsets. Detailed operation of a wet electrostatic precipitator (WESP) was out of scope. Quench duct rapidly reduces gas temperature and humidity ahead of downstream equipment, preventing hot streaks and smouldering carryover. Provide a reliable route for abort/vent to keep hot gas out of the wet electrostatic precipitator (WESP) when draft is lost or carbon monoxide spikes upstream.

Table 9 lists the interface-focused challenges and risks, the key indicators at the quench boundary, and the critical controls/practices confirmed by the Working Group.

Table 9. Quench duct interface—risks, indicators and controls.

Item	Description / Notes
Typical challenges & risks	
Inadequate quench / poor distribution	Hot streaks pass downstream; uneven conditioning increases ignition potential.
Pooling / poor drainage	Low-point accumulation causes slugging and re-entrainment of hot material.
Cold-weather freezing	Freezing lines and drains compromises quench delivery and drainage.
Leading indicators	
Rising interface temperature	Increasing pre-WESP temperature or reduced quench temperature drop.
Drain/sump irregularities	Erratic levels/flows; audible steam hammer indicating maldistribution.

Item	Description / Notes
Critical controls & practices	
Interface temperature & flow limits	Enforce maximum interface temperature and minimum quench-flow with verified indication (not just valve command).
Abort/vent sequencing	Route hot gas away from downstream equipment on induced-draft fan trip or high temperature.
Reliable drainage & winterization	Maintain drains/sumps; heat-trace/insulate exposed lines and drains.

6.4. Critical Controls and Best Practices (Post-Drum Chain)

The items below capture the specific controls discussed and aligned by the Working Group for the downstream chain (cyclones → induced-draft fan/dampers → quench interface). They are focused on preventing escalation during transients (startups, shutdowns, power dips/induced-draft fan trips) and on containing smoldering carryover.

- **Prove draft and purge paths:** Tie light-off and fibre-feed permissive to verified induced-draft fan status and minimum airflow; on loss of draft or high carbon monoxide at pre-cyclone, hold feed and abort/vent automatically.
- **Pressure drop-driven cyclone maintenance:** Alarm trending with defined clean-out triggers; post-clean verification before returning to normal load; keep airlocks tight and interlocked to prevent tramp-air ingress.
- **Damper governance:** Positive position feedback and periodic field checks; reconcile human-machine interface (HMI) states to physical positions; define safe positions for upset and restart.
- **Temperature governance to interface:** Enforce a maximum temperature at the quench interface and a minimum quench flow with verified indication; protect against hot-streak carryover.
- **Condition monitoring of the induced-draft fan:** Trend vibration, bearings and power; clean/inspect and balance to control loss-of-draft risk.

(Alarm displays/drills and broader training elements are addressed in Section 9).

7. Oxygen Sensors Placement

Oxygen sensors are among the most important instruments in the drying line because oxygen concentration drives both combustion stability and explosion risk. Too little oxygen creates incomplete combustion, producing carbon monoxide and unburned gases that can ignite downstream. Too much oxygen, particularly when combined with high temperatures and dust concentrations, creates a flammable atmosphere. In practice, maintaining the right oxygen balance is one of the key defenses against fires and explosions.

Real-time oxygen measurement allows operators to respond to fuel swings, tramp air leaks, and smouldering deposits before they escalate into unsafe conditions. The Working Group stressed that without reliable oxygen data, operators are essentially “flying blind” with respect to combustion safety.

Reliable oxygen monitoring is fundamental to the integrity of interlocks and alarms. Permissive for burner light-off, low-oxygen cutback, high-carbon monoxide trip points, and sequential shutdowns all depend on accurate oxygen data. Poorly placed or malfunctioning sensors undermine these barriers and have been a contributing factor in past incidents. Therefore, WPAC members should treat sensor placement, calibration, and maintenance as core safety practices, on par with deluge or explosion venting systems.

7.1. Types of Existing Oxygen Sensors

The work group reviewed different forms of oxygen sensors, each with strengths and limitations:

- **Insertion:** Typically, use a zirconia ceramic sensor. When heated above 600°C, this material conducts oxygen ions, generating a voltage proportional to the difference in oxygen partial pressure between the process gas and a reference (ambient air). This gives continuous, real-time oxygen readings.
- **Extraction:** Extraction-type systems draw a slipstream of process gas into a conditioned cell, protecting the sensor from harsh environments at the cost of slower response. Therefore, extraction systems provide reliable reading but with a slower response.
- **Close-coupled extraction:** Close-coupled extraction analyzers use a zirconia ceramic sensor located close to, but outside of, the process. The probe delivers process gas to the sensor via aspiration or convective heating. The objective is a balance between speed of response and harsh environment while still giving real-time oxygen and carbon monoxide readings.
- **Electromagnetic or optical:** Electromagnetic or optical systems, while less common, can measure oxygen concentration without direct exposure of a ceramic tip, offering improved durability in wet or dirty conditions.

Insertion probes are the most common type of oxygen sensor used in the pellet industry, providing real-time measurements. But the ceramic tip of the sensor is always exposed to the flowing gas, making it prone to fouling and water damage. Due to the high temperature of the ceramic sensor tip, it is brittle to water or thermal shock. The Working Group noted that insertion probes face specific challenges such as cracking when exposed to water spray or condensation, which can corrode or damage them and compromise readings. In addition, very high temperatures inside the furnace might exceed the glassy condition and block the sensor tip from providing accurate readings.

These insights reinforced the need to carefully select sensor type and location based on plant conditions and to implement protection strategies against moisture and fouling. This failure mode underscored the vulnerability of unprotected probes and the importance of both shielding sensors from water spray and establishing inspection protocols to identify early signs of cracking or deterioration.

7.2. Optimum Sensor Locations and Rational

Placement is as important as technology. The Working Group emphasized that sensors should not be concentrated at a single point but distributed along the process for redundancy and early warning. Typical placements include:

- **Furnace outlet:** Tracks combustion completeness and reveals unstable flames or incomplete burnout.
- **Drum inlet:** Detects tramp air ingress, oxygen imbalances, syngas formation or sudden swings in fuel quality before gases enter the drying chamber.
- **Pre-cyclone (dryer outlet):** Identifies off-gassing, smouldering deposits or residual combustion products leaving the drum.

The Working Group discussed the logic for installing two oxygen sensors for the grate furnace, which are designed with two furnace chambers: one sensor is located close to the primary chamber to capture rapid fluctuations in combustion; here, the gas temperature is higher, turbulence is greater, and readings are more variable due to clinker formation on the probe. The second sensor is installed further downstream, in the secondary chamber area, where gas conditions are cooler, more stable, and less prone to clinkers. While this second sensor responds more slowly to changes, it provides a steadier, more representative average of furnace conditions. By combining the two sensors across the two chambers, operators gain early warning near the flame and balanced measurements downstream, significantly improving combustion control, safety, and reliability.

Figure 10 and Figure 11 (provided by Novatech Analytical Solutions) illustrate recommended placements in the furnace system, dryer entrance, and cyclone entrance. Locating sensors at these points creates a layered monitoring strategy, giving operators both upstream and downstream visibility.

The Working Group shared their experience and highlighted the need to shield probes from deluge spray and fouling, most specifically the fouling and glassing conditions in the furnace. The group noted that poor placement or delayed response from oxygen probes has been a factor in several incidents, and standardized guidance for location and calibration will materially improve safety outcomes.

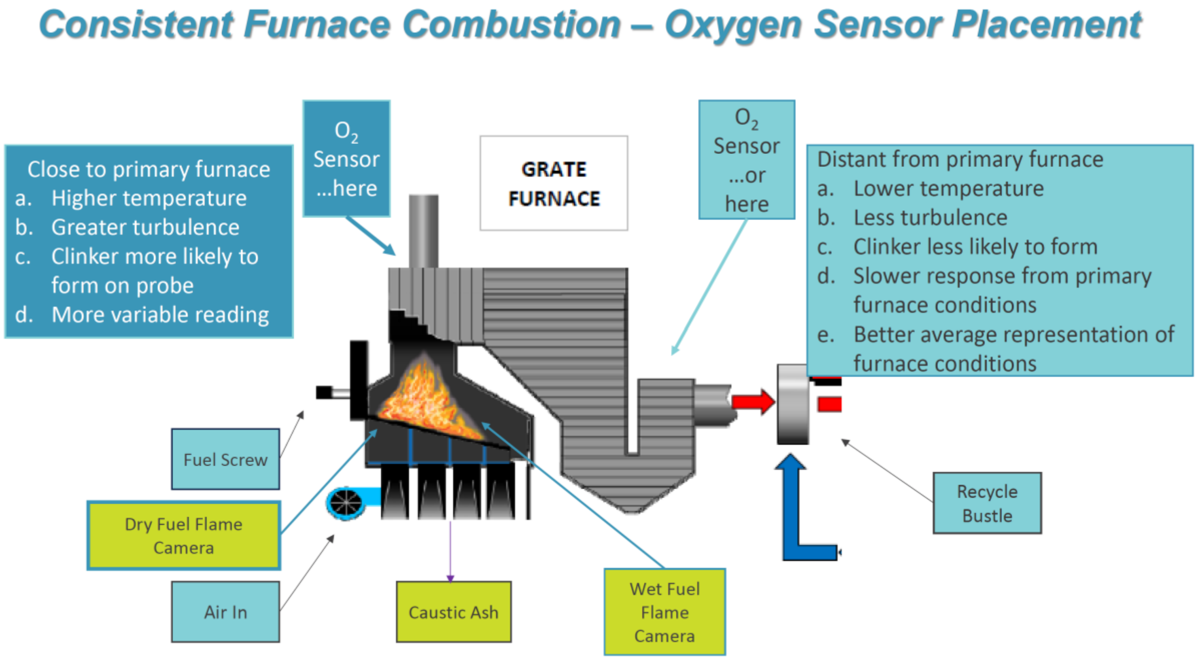


Figure 10. Optimum location of oxygen analyzers in grate furnace system (provided by Novatech Analytical Solutions).

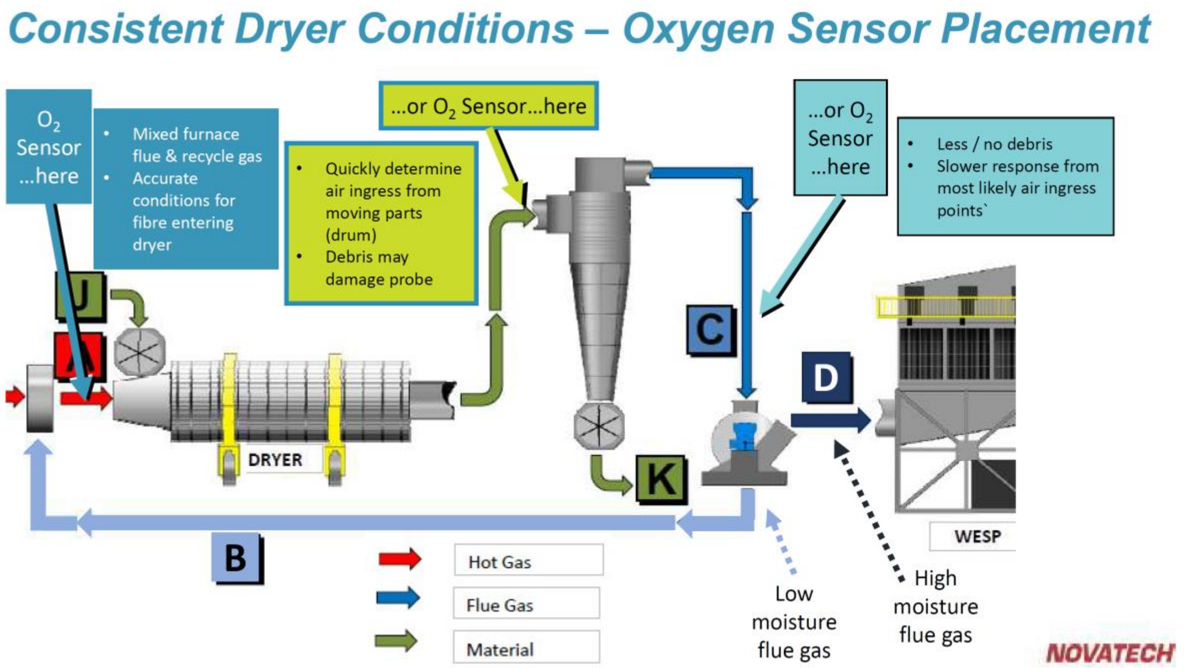


Figure 11. Optimum location of oxygen analyzers at entrance of dryer and cyclone (provided by Novatech Analytical Solutions).

8. Bowtie Analysis

This section synthesizes what the Working Group learned from reviewing bowtie diagrams prepared for two operating contexts in British Columbia: Pacific BioEnergy and Vanderhoof. The bowtie method was used to make hazards, initiating threats, escalation factors, and safety barriers explicit across the drying line from the furnace and dilution duct through the rotary drum and cyclones to the induced-draft fan and quench interface (downstream pollution control operation remained out of scope). This section reviews the bowtie charts prepared for the Vanderhoof plant and the Pacific BioEnergy plant, and then compares the two facilities' charts.

The Working Group emphasized that the bowtie alone is necessary but not sufficient; effective risk reduction also requires operator training and alarm rationalization, plus data-driven trend displays and predictive analytics to detect precursors in time (see Sections 9).

Note on figure size and access. The Vanderhoof and Pacific BioEnergy bowtie diagrams are high-resolution and not embedded in this report due to space/legibility limits. Readers can review the full charts via the following links: *Pacific BioEnergy Dryer Bowtie (PDF)* and *Vanderhoof Dryer Bowtie (PDF)*.

8.1. Purpose and Method

The Working Group and their reviews were used to:

- Define a common top event (loss of control resulting in fire or explosion in the dryer/cyclone/duct system).
- Identify credible threats that could lead to the top event (e.g., induced-draft fan trip/power loss, unstable combustion, tramp-air ingress, purge not proven, smouldering deposits, off-spec infeed).
- Document preventive barriers intended to stop threat progression (e.g., purge/abort logic tied to verified flow and fan status; multi-point oxygen with carbon monoxide at pre-cyclone; seal/airlock integrity; pressure drop-based cyclone clean-out; alarm philosophy).
- Document mitigative barriers that limit consequences if ignition occurs (e.g., abort/vent path, deluge/spark detection where engineered, explosion venting/isolation on cyclones/ducts, quench capacity, emergency procedures).
- Capture degradation factors (what can make a barrier fail) and assurance tasks (tests, inspections, calibrations) to keep each barrier effective.

8.2. Pacific BioEnergy Dryer Bowtie—Key Learnings

This subsection summarizes the Pacific BioEnergy bowtie discussion as captured in the Working Group meetings. The top event was defined as loss of control leading to fire or explosion within the drum/duct/cyclone system. The table below consolidates the meeting-verified threats, preventive and mitigative barriers, and assurance activities recorded during the review.

Table 10 lists the prominent threats identified by the Working Group, the preventive and mitigative barriers discussed, and the assurance activities agreed in the Pacific BioEnergy bowtie review.

Table 10. Pacific BioEnergy bowtie analysis—threats, barriers and assurance.

Item	Description / Notes
Threats	
Loss of draft (induced-draft fan trip/power dip)	Back-flow and syngas build-up leading to flame roll-back.
Unstable combustion/off-spec fuel	Moisture/species/fines variability; ember carryover; carbon monoxide (CO) rise.
Tramp-air ingress	Worn seals or leaking airlocks shifting oxygen (O_2) into flammable regimes.
Purge not proven	Inadequate pre-start or post-trip purge before admitting fuel/fibre.
Smoldering deposits	Accumulation in drum/cyclones that re-ignite with airflow changes.
Preventive barriers	
Interlocked permissive	Inhibit light-off and feed without confirmed induced-draft fan status and flow-verified purge.
Instrumentation	Oxygen (O_2) at furnace outlet, dryer inlet, pre-cyclone; carbon monoxide (CO) at pre-cyclone; temperature profiles; cyclone pressure drop trending.
Mechanical integrity	Seal/door condition criteria; airlock leakage limits; inspection/clean-out access.
Operating discipline	Standard operating procedures (SOPs) for startup/shutdown/hot stop; alarm rationalization (e.g., carbon monoxide (CO) increases with oxygen (O_2) drift, pressure drop rise).
Mitigative barriers	
Abort/vent path	Divert hot/unstable gas away from downstream equipment.
Deluge/spark detection (where engineered)	Use where designed for ducts; defined restoration checks after use.
Explosion protection	Venting/isolation on cyclones/ducts where applicable.
Quench/interface temperature governance	Maintain capacity and limits at the interface.
Assurance activities	
Calibration/functional/flow-verified tests	Weekly instrument calibration/cleaning; monthly functional tests of interlocks; annual flow-verified purge checks; barrier register with owners/frequencies.

8.3. Vanderhoof Dryer Bowtie—Key Learnings

This subsection summarizes the Vanderhoof bowtie discussion from the Working Group meetings. The top event was defined consistently with Pacific BioEnergy to enable comparison: loss of control leading to fire or explosion within the drum/duct/cyclone system. The table below consolidates the meeting-verified threats, preventive and mitigative barriers, and assurance activities that were recorded during the review.

Table 11 lists the prominent threats identified by the Working Group, the preventive and mitigative barriers discussed, and the assurance activities agreed upon in the Vanderhoof bowtie review.

Table 11. Vanderhoof bowtie analysis—threats, barriers and assurance.

Item	Description / Notes
Threats	
Induced-draft fan dependency / damper mis-positioning	Initiators of loss of draft and flow instability.
Material variability	Over-drying and fines liberation; smoldering carryover into cyclones.
Seal/airlock leakage	Oxygen (O_2) ingress destabilizing combustion balance.
Purge/sequence errors	Errors during startup/shutdown and other transients.
Preventive barriers	
Prove draft/flow	Tie permissive to live fan and damper state before light-off and feed.
Cyclone pressure drop (ΔP) governance	Alarmed clean-out triggers; verified post-clean baselines.
Oxygen/carbon monoxide (O_2/CO) location strategy	Multi-point oxygen (O_2) plus carbon monoxide (CO) at pre-cyclone; protect sensors from deluge/condensation.
Damper governance	Position feedback and periodic field reconciliation to human-machine interface (HMI).
Mitigative barriers	
Abort/vent	On draft loss or high carbon monoxide (CO) at pre-cyclone.
Explosion isolation/venting	Consistent with equipment rating on cyclones/ducts.
Emergency response	Controlled slow-down and purge; inspection points before restart.
Assurance activities	
Field/ human-machine interface (HMI) reconciliations & leak checks	Routine field/human-machine interface (HMI) reconciliations; seal/airlock leak checks; documented clean-out verification.

8.4. Comparative Analysis—Pacific BioEnergy vs. Vanderhoof

Two bowtie reviews share core hazards and barrier families but emphasize different precursors and implementation details. The table below reflects the points verified by the group members and highlights opportunities to harmonize practices.

Table 12. Comparative analysis of bowtie emphases and alignment opportunities: Pacific BioEnergy vs. Vanderhoof.

Dimension	Pacific BioEnergy emphasis	Vanderhoof emphasis	Opportunity / Alignment
Top-event focus	Syngas accumulation and smoldering carryover; dust-cloud ignition in cyclones.	Startup/shutdown oxygen (O_2) management; loss of draft as a primary initiator.	Adopt a common transient-state playbook with purge verification and induced-draft fan trip actions standardized.
Power loss / induced-draft fan response	Ride-through power for controls where provided; generator readiness checks; manual deluge operability and valve line-up; verify purge path before restart.	Trip-response drills, backdraft prevention, and purge-path verification emphasized.	Standardize ride-through/abort sequences and include verification steps in drills at both sites.
Instrumentation	Multi-point oxygen (O_2) + carbon monoxide (CO) at pre-cyclone; calibration/cleaning cadence highlighted.	Redundancy and purge-verified startup gating stressed.	Standardize locations and alarm strategy; share calibration/cleaning routines.
Seals and tramp air	Door/seal condition inspections to limit oxygen (O_2) ingress.	Leak checks linked to permissive and restart conditions.	Align test methods and acceptance criteria for leakage.
Recycle and cleaning	Emphasis on condition-based cleaning and safe access.	Access/clean-out constraints acknowledged.	Converge on pressure drop/carbon monoxide (CO)-triggered clean-outs and formalize access improvements.
Deluge/spark systems	Keep systems enabled; verify valve positions; avoid bypass.	Coordinate with isolation/venting on ducts/cyclones where installed.	Incorporate readiness checks for coverage/ valves and confirm isolation coordination during drills.

Dimension	Pacific BioEnergy emphasis	Vanderhoof emphasis	Opportunity / Alignment
Alarm management	Rationalization to reduce alarm floods and surface true precursors.	Role clarity and escalation paths during trips.	Combine: a limited alarm set with clear role cards for trip scenarios.
Training/drills	Emphasis on restart conditions (oxygen/ carbon monoxide (O_2/CO)/temperature normalized).	Emphasis on trip playbooks and purge verification.	Integrate both focuses into a single drill matrix per site.

9. Operator Training

The Working Group repeatedly underscored that operator training and attentiveness are essential to the safe operation of rotary drum dryers. Discussions tied several incidents to human-factor contributors—notably distraction in the control room, misinterpretation of alarms, incomplete purge and delayed response when the draft is lost. Training was framed as a practical means to ensure operators execute the correct actions during the most hazardous phases of operation: startup, shutdown, and power interruptions (including induced-draft fan trips). The following sections list the risks and challenges mentioned by the Working Group and also the suggested practices mentioned.

9.1. What the Working Group Observed

- **High-risk phases:** Startup and shutdown present elevated oxygen conditions; power loss/induced-draft fan trips remove draft and allow syngas build-up. Operators must be prepared to hold/stop fibre, confirm purge path, and stabilize conditions before restart.
- **Distraction risk:** Control-room distraction (e.g., mobile phones) was cited as a recurring contributor; maintaining focus on dryer trends during plant upsets is critical.
- **Protection layers must be in service:** Events have involved spark detection or deluge systems that were offline/bypassed or valves closed. Training reinforces that these systems must remain enabled and verified.
- **Field vs human-machine interface (HMI) mismatch:** Members reported cases where dampers/instruments were out of calibration, so the screen showed one value while the field showed another. Routine calibration and field confirmation were emphasized.
- Recognizing early signs: Operators should watch for a rise in carbon monoxide at the pre-cyclone, unusual pressure drop trends, smoke/odour, and temperature abnormalities that indicate smouldering or material build-up in drums, ducts, or cyclones.
- Inspection and maintenance culture: The group stressed regular inspection/ clean-out of induced-draft fans, recycle/inlet dampers, ducts, and checks of seals/airlocks; training must align with these routines, so operators know what “normal” looks like and when to escalate.

9.2. Practices Cited by Members

- Conduct pre-start checks and verify purge by time and flow before admitting fuel/fibre.
- Confirm induced-draft fan status and damper positions after any power dip or trip before restart.
- Keep deluge/spark detection active and confirm valve positions; do not bypass without formal authorization.
- Perform line-walks and inspection points tied to smouldering risk (drum, recycle ducts, cyclones).
- Maintain focus in the control room during transients; avoid using non-work devices.
- Escalate when instruments disagree (human-machine interface vs field), and do not proceed until alignment is restored.

10. Recommendations for Future

The Working Group recognizes that certain topics discussed during the meetings extend beyond the immediate scope of this report and are more appropriately addressed through dedicated follow-on initiatives, which would require additional time, resources, and coordination to achieve meaningful and durable outcomes. These items are therefore recommended as priorities for future projects rather than actions to be completed within the current effort.

Operator Training and Competency Development: While the Working Group consistently emphasized the importance of operator knowledge, situational awareness, and response discipline, developing a comprehensive, industry-wide training program was not within the scope of this project. Future work should focus on translating the bowtie analyses, incident learnings, and agreed control philosophies into structured training materials. This may include standardized training modules, scenario-based exercises, and refresher programs addressing startup, shutdown, purge verification, induced-draft fan trip response and alarm management. Such an initiative would support consistent execution across facilities and strengthen the human-factor barriers associated with rotary drum dryer operation.

Data Analysis and Predictive Risk Modelling: The Working Group also identified the need for more advanced use of operational data to support early hazard detection and decision-making. Developing predictive risk models was outside the scope of this report, but future projects could focus on standardizing data collection, defining key safety-critical indicators, and applying analytical or modelling techniques to identify emerging risk conditions. Over time, this work could enable proactive intervention, cross-plant benchmarking and continuous improvement of rotary drum dryer safety performance at an industry level.

11. Other Useful WPAC Resources

- Belt Dryer Safety (report)
- Critical Control Management (presentation video)
- Combustible Gas Risk Reduction in Wood Pellet Production Drum Dryers (report)
- Best Practices for Managing Combustible Gas in Rotary Drum Dryer (video)
- Drum Dryer Symposium (presentation video)
- Online Interactive Operator Safety Training (fact sheet)

Appendix A. Rotary Drum Dryer Working Group Members

Participant(s)	**Company**
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Jeff Johnston	Drax
Other members	
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Daniel Obarski	CV Technology
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Gary Dean	Drax
Jon Ross	Drax
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Jim Kapron	Novatech Analytical Solutions
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Julie Griffiths	Shaw Renewables, WPAC Safety Committee Chair
David Jarrett	TSI
James Sabo	TSI
Nick Jones	TSI
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