RESEARCH ON OFF-GASSING AND SELF-HEATING IN WOOD PELLETS DURING BULK STORAGE

Prepared for

ETHANOL BC

Prepared by

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Foreword

Wood Pellet Association of Canada (WPAC) wishes to thank Ethanol BC for funding part of the research regarding off-gassing and self-heating in wood pellets during storage in bulk as reported in this document. WPAC in close collaboration with UBC Department of Chemical and Biological Engineering continues to build on the track record well known around the world as leading the research to mitigate the inherent safety and health risk associated with production and handling of wood pellets. The funding has been very helpful in supporting the research to better understand the mechanism of off-gassing and self-heating, both of which are major safety and health concern for our industry.

The previous contribution by BC Ethanol was also very helpful to prepare our industry for the challenge to fill the shortage of fibre due to the many saw mill closures. Many of our pellet mills have now mastered the art of using a blend of feedstock such as sawdust, planer shavings, bark, harvest residue and even hog and still end up with an acceptable quality pellet. Experimentation at BBRG also proved that partly decomposed hemlock and purposely grown crop such as hybrid poplar can be used as feedstock for making good quality pellets. The results from these studies have also had significant impact on the biomass classification system developed under ISO/TC 238.

The two consecutive funding contributions from BC Ethanol have been essential for the stability of our long term research which have been of both exploratory and applied nature in a field of science which is essential for preparing our resource based industry in BC for the future. The use of more diversified feedstock and still be able to operate with confidence regarding safety and health is in part contributed to the funding received from BC Ethanol in support of our research.

1. **Executive Summary**

As a consequence of fatal accidents on-board ocean vessel the Wood Pellet Association of Canada initiated the development of a Material Safety Data Sheet (MSDS) requiring support in terms of research related to self-heating and off-gassing from pellets. The work was initiated in 2003 and developed in to a formal 5 year research project under NSERC with UBC, Department of Chemical and Biological Engineering which eventually resulted in formation of the Biomass and Bioenergy Research Group (BBRG). Ground breaking research has since been conducted to quantify the emission factors for CO, CO_2 and CH_4 in combination with oxygen depletion. Recently additional research has explored other important parameters related to storage of pellets in large bulk, including determination of thermal conductivity and permeability of pellets in bulk. A large experimental reactor in the Clean Energy Research Center (CERC) at UBC has been used for studying the gas evolution over time with the objective to better understand the thermal balance in a vertical storage and the potential risk for stratification of gases. Temperature Increase Rate as well as Heat Front Velocity was also established in a large scale industrial silo. The collective knowledge developed so far provides a very unique knowledge of what happens within a large storage silo and will lead to improved design of ventilation systems as well as predictions models for how to safely operate large scale silos.

WPAC in close collaboration with BBRG is also supporting the Canadian effort to develop a complete family of quality classification and test methodologies for biomass, pellets and briquettes under ISO. These standards are becoming widely accepted and will gradually form the basis for product specifications of densified fuel products traded among the large power companies as a bulk commodity on the commodity exchange in Rotterdam.

The funding received from BC Ethanol has been very important to support the research conducted both within WPAC and in close collaboration between WPAC and BBRG and we are thankful for the strong support of our industry. The Canadian wood pellet industry has gone from an annual production of 1 million tonne in 2007 to 2 million tonne in 2011 and with a prospect of reaching 4 million tonne by 2014-2015, primarily in the export market such as Europe, USA and Southeast Asia. Our industry has in recent years become under pressure by the insurance underwriters due to accidents with explosions, fires and injuries due to off-gassing. The growth of our industry is heavily dependent upon safety and health in manufacturing operations as well as the logistics of handling the products in large volumes. The research in part funded by BC Ethanol has contributed to the research essential to mitigate the causes of these risk factors presented in this report.

Several scientific papers and technical bulletins have been published on the topics presented in this report and several more are in preparation.

2. **Introduction**

Before the fatal accident onboard MV Weaver Arrow on May 9, 2002 in the Port of Rotterdam during discharge of pellets from British Columbia there was no knowledge of off-gassing from pellets even though safety regulations issued by International Maritime Organization (IMO) many years earlier had general warnings of oxygen depletion caused by wood such as lumber, chips and logs, all with relatively high moisture content, during ocean transportation. This first recorded accident lead to intense research within the BC Pellet Fuel Manufacturers Association (BCPFMA) resulting in an immediate issuance of a "Shipper Cargo Information Sheet" (SCIS) and "Instructions for the Captain" to draw the attention to the risk with handling of wood pellets in large volumes. The finding of significant off-gassing and almost complete oxygen depletion caused by such a dry product as wood pellets were at the time perplexing. To better understand the mechanics and chemistry behind the off-gassing phenomenon from pellets Staffan Melin and Shahab Sokhansanj joined forces in 2003 and started a campaign to convince UBC to support a research project for pellets. UBC Department of Chemical and Biological Engineering (CHBE) invited the team to become part of the faculty and an ambitious research was started with a minimum of funding. During a BCPFMA board meeting in Kamloops, BC in 2004 the decision was made to start developing the first Material Safety Data Sheet (MSDS) for pellets and at the same time upgrade the association to a Canada wide organization in view of the common interest in safety during the shipment of pellets in ocean vessels. In December of 2005 the Wood Pellet Association of Canada (WPAC) was registered to replace BCPFMA. On November 19, 2006 the second fatal accident happened in the Port of Helsingborg with pellets from BC and WPAC decided to invest in the research at UBC under an NSERC Collaborative Research Development contract and the Biomass and Bioenergy Research Group (BBRG) was formed within CHBE. Almost immediately after the Helsingborg tragedy WPAC initiated a research project (Emission from Wood Pellets During Ocean Voyage – EWDOT) on-board MV Saga Horizon to establish the temperature and off-gassing profile during an entire ocean voyage from Vancouver to Port of Helsingborg in Sweden. Much of the results from this initiative have governed the subsequent research on off-gassing and self-heating in pellets as well as recommendations for how to ventilate large ocean vessels and provide guidelines for improved design of future ocean vessels carrying biomass products.

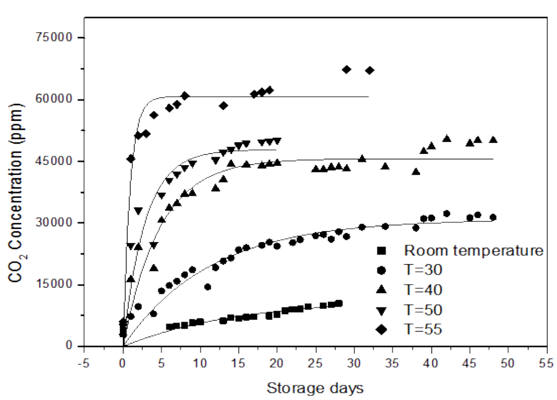
The MSDS over time has become the repository for much of the results of the research at UBC. Today, the MSDS developed by WPAC/BBRG is considered the standard around the world. However, there has been resistance to spread the MSDS to the market place since based on fear that the chemically reactive nature of pellets would hurt the pellet business. In 2007 we also published an MSDS for pellets sold as consumer product. This standard has gradually become accepted and in many jurisdictions around the world an MSDS is now required together with shipment of product across borders. Table 2 summarizes the known accident statistics for off-gassing. Beyond the severely injured number of people in the table there are a substantial number of mildly or temporarily injured people.

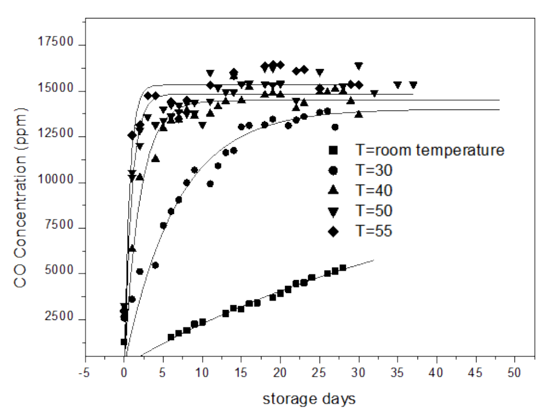
Table 2. Reported fatal accidents as a result of CO intoxication and/or oxygen depletion in confined spaces loaded with forest products (2011-10-30)										
Year	Place	Number people killed	Number of people severely injured	Circumstances	Source of information	Pellets	Wood Chips	Pulp logs	Saw logs	Green Lumber
2002	Rotterdam, The Netherlands	1	2	A stevedore entered a stairway between two cargo holds onboard MV Arrow Weaver	World Pellet Conference 2002, Stockholm	X				
2005	Gruvön, Sweden	1		Sailor entered a stairway next to a cargo hold onboard MV Eken with pulp logs	Transportstyrelsen, Swedish Maritime Administration Report B2006-2			X		
2005	US East Coast port	1		Stevedore was working in an open cargo hold onboard a Saga Forest Carrier vessel with green lumber and was overcome by oxygen depletion	Saga Forest Carrier					X
2006	Port of Helsingborg, Sweden	1	1	Sailor entered a stairway between two cargo hold onboard MV Saga Spray with pellets	Transportstyrelsen, Swedish Maritime Administration Report B2007-1	X				
2006	Port of Skelleftehamn, Sweden	1		Sailor entered a stairway next to a cargo hold onboard MV Noren with wood chips	Swedish Maritime Magazine, Issue 1-2007		X			
2007	Port of Timrå, Sweden	2		One sailor and the captain of the vessel MV Fembria enetered the stairway leading down to the cargo hold and was overcome by oxygen depletion and CO	Secotidningen June 2007				X	
2007	Finland	1		One person entering a pellet storage with 10 tonne	Vasa Arbetsskyddsdistrikt, Finland	X				
2008	Finland	1		One person entering a pellet storage with 10 tonne	Vasa Arbetsskyddsdistrikt, Finland	X				
2009	Bornholm, Denmark	2		Two crew members onboard MV Amirante loaded with pellets entered a stairway leading down to the cargo hold	Police Authority, Rönne, Bornholm	X				
2010	Germany	1		One person entering a pellet storage with 150 tonne	Propellets, Austria	X				
2010	Ireland	1		One person entering a pellet storage with 10 tonne	Health and Safety Authority, Dublin, Ireland	X				
2011	Switzerland	1		One pregnant woman entered a storage with 100 tonne pellets	Neue Luzerner Zeitung February 9, 2011	X				
	Total	14	3			8	1	1	1	1

Delta Research Corporation (DRC) participated as author in drafting 20% of 600 page The Pellet Handbook (http://www.earthscan.co.uk/?tabid=102497) published in 2010. Much of the research conducted by WPAC/BBRG was included in the handbook.

3. **Off-gassing from Biomass**

Research on off-gassing from biomass and pellets has been conducted since 2003 at UBC with the objective to verify the emission levels found at accident sites. The laboratory data nicely validate the measurements done in the field. Figure 3.1 illustrate the gas concentrations found by BBRG in laboratory experiments for CO, CO_2 and CH_4 from pellets made in British Columbia. The data clearly shows the lethal level reached after only a few days in an un-ventilated space in terms CO while the oxygen is depleted almost entirely. It should be mentioned that the maximum acceptable hygiene level for CO in a workplace is 25 ppm and in residential spaces 9 ppm.





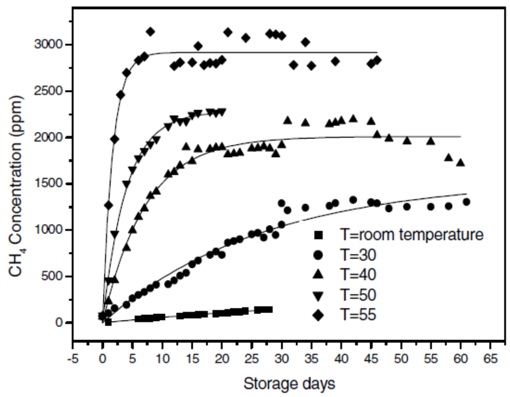


Figure 3.1

The emission levels found in our research is corroborated by actual measurements done in several ocean vessels besides MV Saga Horizon mentioned above.

The emission factors for CO, CO_2 and CH_4 emitted from pellets were established and are now given in the MSDS used by the pellet industry world wide. There are however differences in the emission spectrum depending on the feedstock used for production or pellets as well as the technique used for drying the feedstock prior to pelletization. So far the BBRG has the only facility in the world capable of doing controlled experiments with off-gassing. BBRG is currently testing materials coming in from other parts of the worlds and is also developing a technical ISO testing standard for off-gassing (see Section 8.).

Exploratory research to gain understanding of the gas evolution inside an enclosed storage silo has been done using the Large Research Reactor (LRR) donated by Pinnacle Pellets Inc and Pacific Bioenergy Corporation and located and running at room temperature in the Clean Energy Research Center (CERC). Figure 3.2 illustrates the LRR which is 16 feet high and 4 feet in diameter. The view from the top shows the terminals for the 9 vertical temperature cables arranged as an inner circle and outer circle plus a center cable. The smaller picture shows a sampling port for gas.

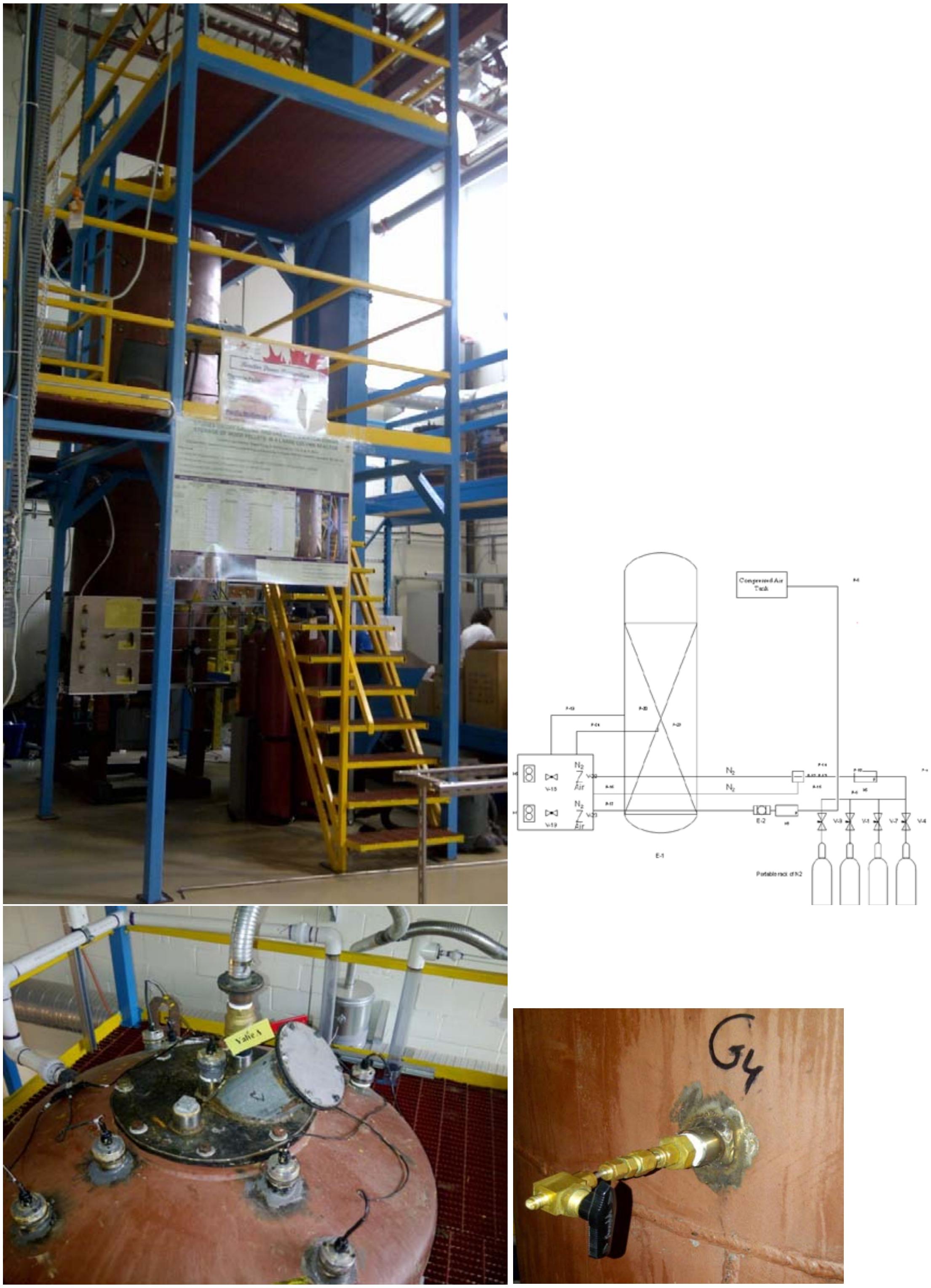


Figure 3.2

The LRR was loaded up in March 2011 with approximately 3 tonne of high quality pellets donated by Premium Pellet Ltd. The reactor is equipped with two data collection systems logging data from 336 temperature sensors and 6 pressure sensors for profiling the thermal conditions during extended storage periods. The sensors are arranged by means of hanging vertical cables donated by OPI Systems Ltd as well as cross-wise by means of rods. Gas samples were taken to establish a profile of the CO, CO_2, CH_4 and free H_2 concentrations from the bottom to the top of the reactor vessel. There are also 70 humidity sensors tracking the moisture migration in the silo. During the three initial phases of the research the LRR was sealed for approximately 30 days each.

Additional research is under way to explore the affect on the gas evolution during ventilation. The objective has been to establish if there is a stratification of gas at various levels which would prompt the potential use of special safety advice for large scale silos and to better understand the relation between oxygen depletion, gas evolution and self-heating. The impact of renewed oxygenation through intermittent ventilation after complete oxygen depletion provides a measure of potential safety concern. The discovery of free hydrogen (highly explosive when mixed with air) is significant since accumulation in pockets could be a safety concern in large storages. Comprehensive data analysis is providing important insight in to the mechanism causing severe oxygen depletion during storage of pellets. The experiment has also provided an insight in to the impact of internal convection in the reactor vessel.

The mass balance calculations conducted does not fully explain where the oxygen goes and further analysis may disclose the potential existence of adsorption or conversion of oxygen to solid oxides. Adsorption in the pellets of CO and CO2 has also been observed. The adsorption of CO_2 was tested at +40^{o}C for regular white pellets, torrefied pellets and explosion pulping pellets. The results indicate that torrefied pellets adsorb about twice as much gas as explosion pulp pellets, most likely as a consequence of the porous characteristics of torrefied wood. The adsorption for white regular pellets was between the torrefied pellets and the explosion pulp pellets. Adsorption increases with temperature and is reversely lowering as the temperature is decreasing. Additional work will be done to explore the adsorption of CO which appears to be excessive, perhaps due to a higher reactivivity.

4. **Permeability of Pellets in Bulk**

Ventilation of pellets in bulk is necessary to control the temperature in large silos. The permeability of pellets in bulk is a critical parameter when designing ventilation systems since it determines the size of fans requires and the design of plenum for distribution of the ventilation air. So far permeability numbers developed for grain and other granular products have been used in lieu of actual experimental numbers for pellets. BBRG has conducted experiments with 3 different qualities of 6 mm pellets to establish resistance to air flow for pellets with different length, specific density and moisture content. The characteristics of the three qualities are summarized in Table 4.

Table 4.

Physical Properties	Quality 1	Quality 2	Quality 3
Pellet diameter (mm)	6.0	6.2	6.2
Pellet length (mm)	6-26	10-33	10-42
Moisture content (%) db	2.8	5.4	8.1

Particle density(g/m^3)	1.32	1.32	1.08
Bulk density (kg/m^3)	739	720	704
Bed porosity (%)	0.39	0.43	0.45

Fines less than 4 mm were removed from the three qualities to minimize the number of parameters involved.

Figure 4.1 illustrates the laboratory setup. Compressed air was forced through a plenum at the bottom of a vessel filled with the wood pellets. The pressure of the air was monitored as well as the vertical pressure drop over the bed of pellets.

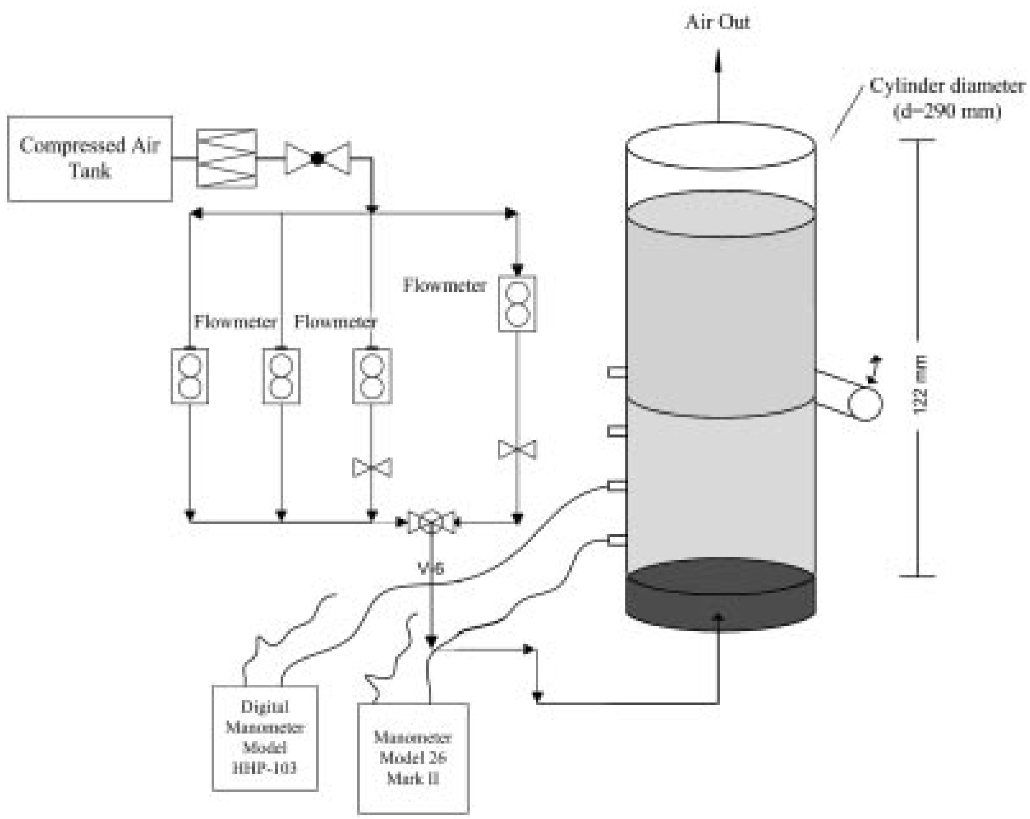


Figure 4.1

The permeability number for wood pellets was thus established to be 0.01 to 0.1 m^3/s/m^2 for a pressure drop between 1 and 50 Pascal/m. The comparative number for wheat and corn is 0.0002 to 0.02 m^3/s/m^2 (ASABE D272.3). Figure 4.2 summarizes the results and provides a measure of the actual experimental permeability (resistance to flow) for the three qualities of pellets. Quality 1 has overall smaller particles than the other qualities which explains the higher resistance (pressure drop) to flow due to higher packing density.

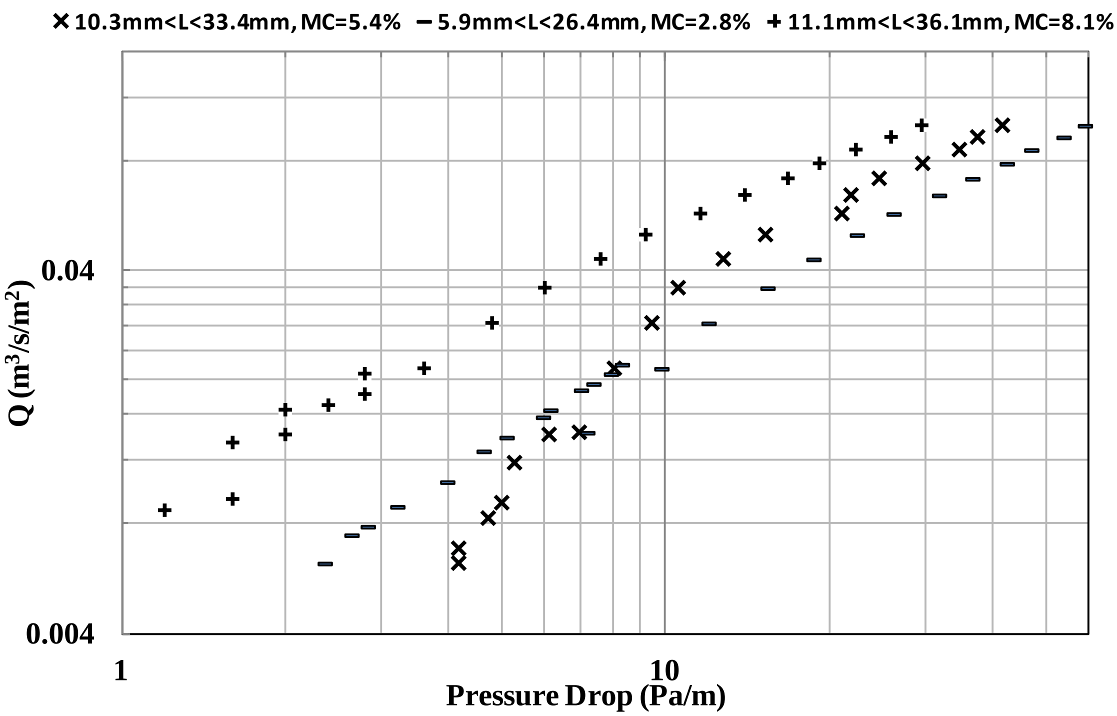


Figure 4.2

This type of test is also useful for determining the allowable rate of flow for the drying media in torrefaction reactors to control the fluidization of the material without displacing the bed. The test setup was also used by NORAM Engineering in the torrefaction study conducted in late 2010.

5. **Thermal Conductivity of Pellets in Bulk**

The thermal conductivity of wood pellets is an important inherent characteristic affecting the heat transfer from one area to another in large storages. The thermal conductivity also has a direct impact on the propensity for self-heating in pellets and the promotion of microbial decomposition, chemical oxidation and hydro-thermal moisture migration. Ground-breaking research has been conducted by BBRG to understand to mechanics of thermal conductivity (or resistivity) which shows that the major factor impacting the thermal conductivity is the moisture content of individual pellets and to a much lesser degree the bulk density of the material. Figure 5.1 illustrates the laboratory setup used for this research.

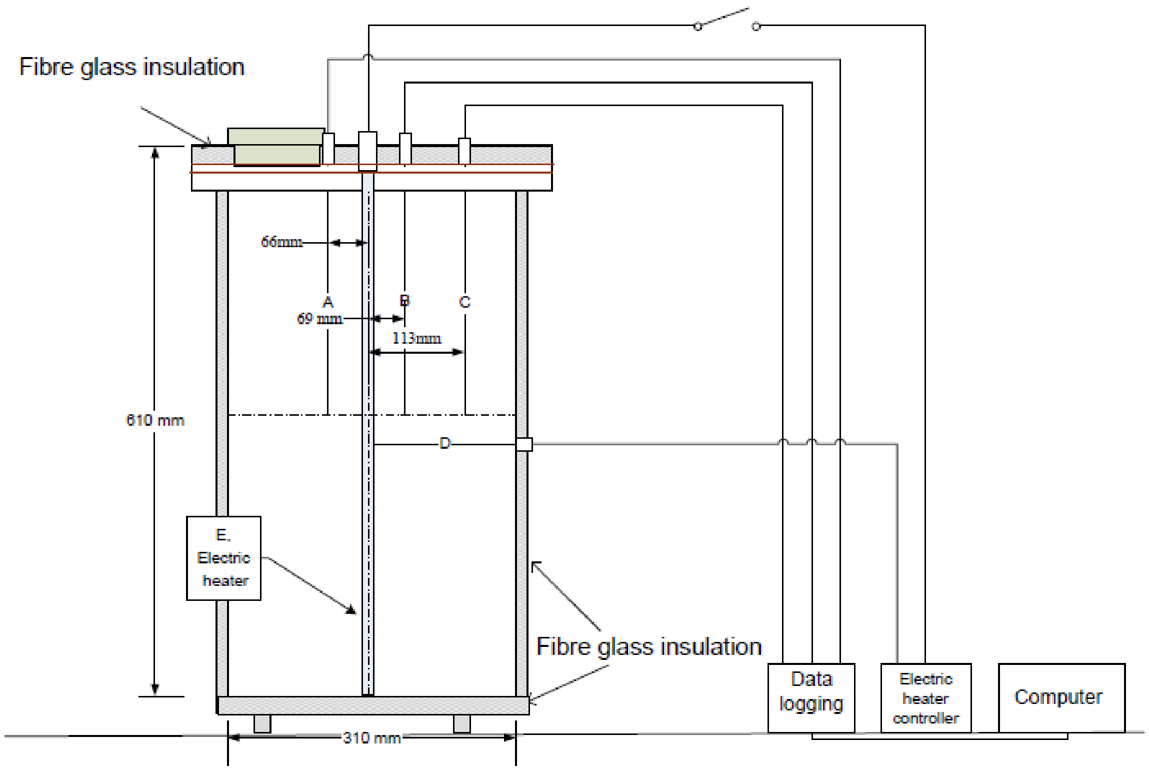


Figure 5.1

Figure 5.2 illustrates the thermal resistivity as a function of pellets moisture content.

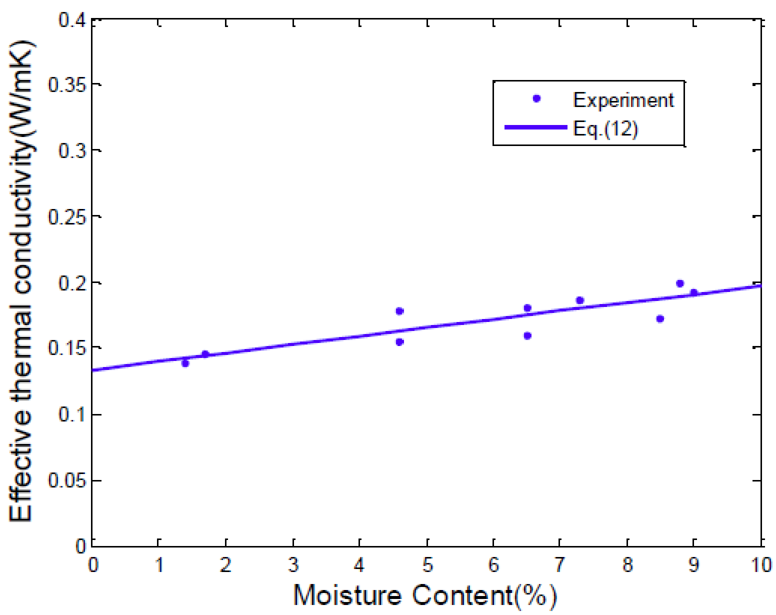


Figure 5.2

The heat convection transfer co-efficient was also established as 5 to 20 W/m^2K at air velocities from 1 to 5 m/s.

Both thermal conductivity and heat convection transfer co-efficient are of fundamental importance for proper design of safe storage facilities for pellets in bulk.

6. Self-heating of Pellets in Bulk

Research is currently on-going within BBRG to develop a detailed understanding of the self-heating mechanism in pellets. The three mechanisms involved in self-heating are microbial decomposition, chemical oxidation and hydrothermal moisture migration. Microbial decomposition is generally considered to be a minor factor unless the pellets have relatively high moisture content such as 12-15% or higher. Chemical oxidation is an inherent process related to the material and is considered to be the major contributor on the micro-level and is considered to be caused by oxidation primarily of fatty acids in the wood. The hydrothermal moisture migration is present when pellets are stored in large bulk, particularly in an environment when fluctuations in the ambient thermal conditions causes cyclical vaporization and condensation of moisture on the surface of the pellets, with moisture constantly moving upwards in a pile. The accumulation of significant moisture concentrations in the upper levels of large storages in combination with convection heat moving upwards promotes microbial growth which in turn initiates self-heating and off-gassing.

The BBRG research has focused on quantifying the chemical oxidation phenomenon in terms of heat release rate and activation energy and has found that the heat release is primarily dependent on the storage temperature which explains the un-proportionately rapid temperature increase in large storages when the ambient temperature or the temperature of new material loaded in to a storage is high. The chemical oxidation appears to be relatively insensitive to the age of the pellets and insensitive to the moisture in the pellets. However, with increasing age of the pellets the activation energy required is increasing which means that older pellets need more external heat in order for the self-heating process to get going.

The above findings are essential for the further development of a detailed understanding of the self-heating phenomenon in pellets. Current research is focused on determining the critical recommended maximum temperature for emergency dumping or recirculation of pellets in large storages. Tentatively this temperature appears to be in the range of +80^{o}C. Another critical temperature under investigation is the “runaway” temperature above which the self-heating is escalating and very rapidly approaching self-ignition without any recourse. The runaway temperature appears to be in the +160^{o}C range. A special laboratory setup is currently being prepared for ramping the temperature and at the same time monitor the activation temperature and heat release.

7. **Experimental determination of Temperature Rate Increases and Heat Front Velocity in Large Storage Facility**

A study was conducted of the thermal conditions inside a commercial size silo for pellets with a diameter of 21.9 m and a height of 23.2 m equipped with vertical temperature cables (OPI Systems), relative humidity sensor and ambient temperature sensor. Figure 7 illustrates the silo and the configuration of temperature cables. The silo has a permanent sweep auger at the bottom and an underground tunnel for discharge of pellets as well as a plenum and ventilation grates in the floor. The ventilation fan is providing cooling air and was switched on and off based on the temperature detected in the stored pellets. No ventilation was done when the relative humidity in the air exceeded 90%.

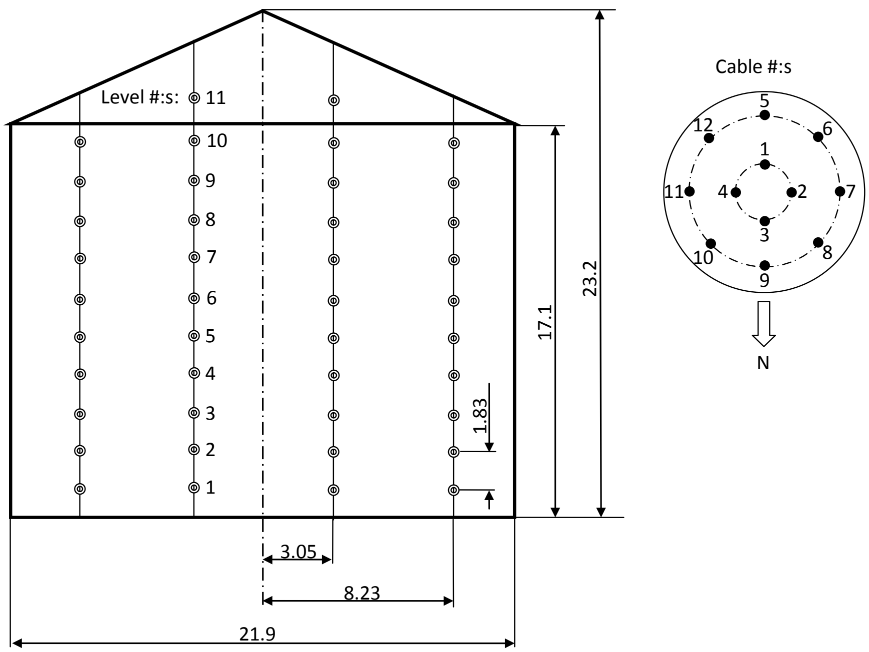


Figure 7.

The studies were conducted during normal operation of the silo. This meant that the experiment was not conducted in a controlled environment since material was loaded and discharged at various points in time. The temperature sensors allow for vertical as well as horizontal profiling of the thermal conditions inside the silo. The study revealed that the average Heat Front Velocity (HFV) was 2.5 cm/hour but could reach as high as 10 cm/hour. Temperature Rate Increases (TRI) of 1.7^{o}C/hour at discrete sensor locations were recorded. These values are important indications of the thermal dynamics inside a silo. The horizontal temperature profile varied substantially which may be explained by development of vertical funnels in some parts of the silo as a result of variation in bulk density such as local dust concentrations and variations in the reactivity of the different qualities of pellets loaded in to the silo. Additive temperature effects were also noticed in certain parts of the vertical temperature profile. In order to minimize hydro-thermal moisture migration in the pellet pile it was concluded that the ventilation should be controlled by a strategy using the ambient dew point temperature and the pellet temperature in the lower part of the silo as input parameters.

8. **ISO Standards Development**

DRC is currently Chair of Canadian ISO Technical Committee 238 Solid Biofuels and Convener for ISO/TC 238 Working Group #4. A number of CEN quality and testing Standards for solid biomass are in the final stage of being upgraded and approved as ISO Standards after a lengthy and meticulous revision process by the 32 participating nations since May of 2008. Figure 8 illustrates the migration path for over 14 national or regional Standards to a single ISO Standard for Solid Biofuels, a process to be completed before the end of 2013.

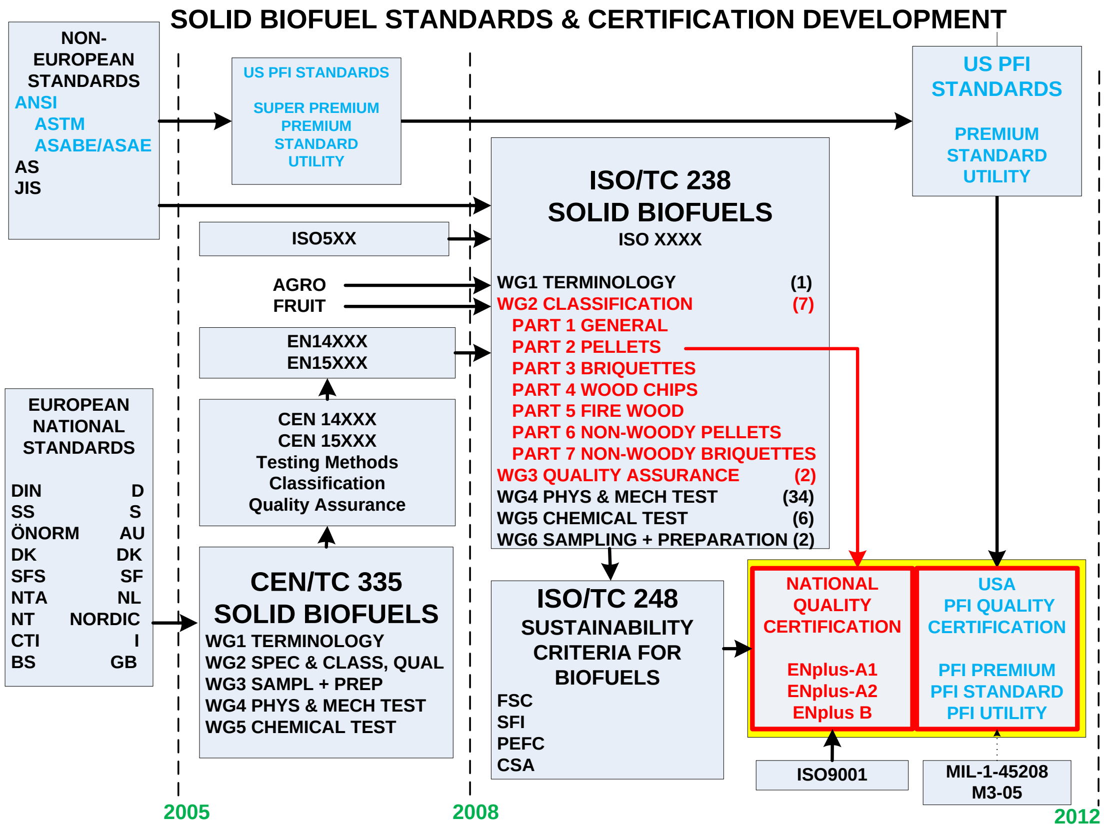


Figure 8.

Table 8.1 is listing the Standards which have been processed and are in the stage of being published as part of the ISO/TC 238 process under each of the 6 Working Groups.

Table 8.1 New Standards in Final Review Stage (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #1**
1	Terminology, definitions and descriptions

Table 8.2 New Standards in Final Review Stage (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #2**

1	Fuel specifications and classes – Part 1: General requirements
2	Fuel specifications and classes – Part 2: Graded wood pellets
3	Fuel specifications and classes – Part 3: Graded wood briquettes
4	Fuel specifications and classes – Part 4: Graded wood chips
5	Fuel specifications and classes – Part 5: Graded fire wood
6	Fuel specifications and classes – Part 6: Graded non-woody pellets
7	Fuel specifications and classes – Part 7: Graded non-woody briquettes

Table 8.3 New Standards in Final Review Stage (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #3**
1	Fuel quality assurance
2	Conformity assessment for fuels
3	Model quality assurance manual

Table 8.4 New Standards in Final Review Stage (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #4**
1	Moisture – total
2	Moisture - simple
3	Moisture – general <1mm
4	Total ash
5	Calorific value
6	Bulk density
7	Volatile matter
8	Particle size – Horizontally oscillating screen
9	Particle size – Vertically vibrating screen
10	Particle density
11	Durability - pellets
12	Durability - briquettes
13	Ash melting behaviour
14	Particle size distribution – disintegrated pellets
15	Length and diameter of pellets

Another major process within ISO/TC 238 Working Group 4 has been to draft a number of technical methodology standards for explosibility and flammability testing for dust generated by biomass. This effort is based on a demand for change due to a large number of accidents in the industry resulting in loss of property and production. There is an average of 1 major fire or explosion in the industry worldwide every week and the insurance underwriters are beginning to withdraw risk coverage for the pellets industry. New testing and product quality standards as well as safety guidelines have become a priority.

WPAC has engaged BC Forest Safety Council for development of a safety certification program which is currently being rolled out across Canada in an effort to stem the trend.

Table 8.2 summarizes the major new Standard related to explosibility being drafted by DRC for presentation and processing by the ISO working groups during 2012. Some are upgrades of ASTM, BSI, DIN and many other Standards and require collaboration with other ISO or CEN working groups outside ISO/TC 238.

Table 8.5 New Standards currently being drafted (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #4**
1	Minimum auto-ignition temperature of dust cloud
2	Minimum auto-ignition temperature of dust layer
3	Minimum ignition energy of dust cloud
4	Pressure and pressure rate for wood dust
5	Minimum explosible concentration of wood dust
6	Limiting Oxygen Concentration
7	Hot surface ignition temperature of dust layer
8	DC Resistance or conductivity
9	Flammability of wood dust

DRC in close collaboration with BBRG are developing a new family of testing Standards for quantifying off-gassing from biomass stored in un-ventilated as well as ventilated space. This is an area of special interest for Canada since Canada has been spearheading the research in the off-gassing research since 2003 and is considered on the leading edge in this field. A third standard under development may be added with focus on quantifying the rate of oxygen consumption (Real Dynamic Respiration Index - RDRI) for biomass with high moisture and inherent high content of microbes such as aged hog and harvest debris which has a tendency of catching fires when left alone for an extended period of time. These new standards are also expected to be published during 2012-2013 under ISO.

In addition to the above ISO/TC 238 is planning to develop other Standards as requested by the industry. Table 8.3 is listing the work items identified so far. It should be mentioned that the process from start to finish for development of an ISO standard is between 2-3 years since it has to go through a rigorous wetting process.

Table 8.6 Proposed new Standards (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #4**
1	Impurities
2	Particle size distribution - sieving
3	Particle size distribution – image analysis
4	Bridging properties
5	Wet-ability (hydrophobicity)
6	Hygroscopic Characteristics
7	Impact resistance
8	Permeability in storage
9	Angle of repose
10	Angle of drain

Table 8.7 Proposed new Standards (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #5**
1	Determination of total content of carbon, hydrogen, and nitrogen – Instrumental methods
2	Determination of total content of sulphur and chlorine
3	Determination of water soluble content of chloride, sodium and potassium
4	Determination of major elements
5	Determination of minor elements
6	Conversion of analytical results from one base to another
7	Determination of the chemical composition by XRF (X-ray fluotescence)

Table 8.8 New Standards in Final Review Stage (November 2011)	
Work Item	**Standards under development by ISO/TC 238 Working Group #6**
1	Sampling
2	Sample preparation

9. Summary and Conclusions

The research conducted by WPAC in close collaboration with UBC Department of Chemical and Biological Engineering, Biomass and Bioenergy Research Group (BBRG) has been focused on developing an understanding of the physical and chemical mechanisms causing pellets to pose a safety and health threat for workers involved with production as well as personnel involved with handling the product in large bulk. This research started in 2003 as a result of a number of unfortunate accidents involving fatalities and brain injuries caused by intoxication from off-gassing in combination with oxygen depletion. The research has focused on self-heating as a chemical process and kinetic modelling of off-gassing to establish a prediction model to be used by industry which is largely a result of self-heating. Research has for the most part been done on laboratory scale but more recently the Large Research Reactor (LRR) at the Clean Energy Research Center (CERC).

Fundamental parameter such as thermal conductivity, permeability, Temperature Rate Increases, Heat Front Velocity as well as quantification of gas evolution and oxygen depletion are now much better understood. Prediction models have been developed to assist the industry with recommendations for safe design and operation of facilities for storage and handling of pellets in large bulk.

WPAC has in parallel with the research at UBC played a significant role in developing the new ISO quality classification and testing standards for solid biofuels. Findings in the research at UBC are gradually being integrated in these standards and the Material safety Data Sheet (MSDS) for pellets. The most significant contribution is perhaps the new culture of quality and safety evolving in the pellets industry world wide. Protection of our free access to foreign markets has also been a driving force to actively participate in the ISO standards development.

The results of the research partly funded by BC Ethanol have been presented to the industry in terms of Research Updates, annual board meetings, international conferences in Europe as well as North America.

Biblography

The following reference list was partly authored by members of the BBRG (**in bold)** or used as source material for the research.

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