Emissions from Woodpellets During Ocean Transportation (EWDOT)

Research Report

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January 16, 2008

Prologue

"From the hatch,
ill can catch,
may caution prevail,
when thee set sail,
safety at sea,
must always be"

Staffan Melin 2007

ACKNOWLEDGEMENT

It is our hope that the results coming out of this Project will provide significant contribution to increased safety at sea during transportation of wood pellets. As part of the investigation we have also identified a number of issues which calls for further research in view of the potential exposure to risk which exist when transporting wood pellets. The Project has opened up many valuable connections in the research community upon which we hope further work can be built.

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About the Authors

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Melin holds an engineering degree from Sweden in 1964 and has extensive experience in a number of engineering disciplines, ocean transportation logistics and international trade. Melin has his own consulting company Delta Research Corporation in Vancouver, British Columbia where he lives since 1980. He was instrumental in establishing the export of wood pellets from Canada to Europe beginning 1997 starting with economic modelling of the transportation logistics and arranging for export financing, marine transportation instructions and product quality specification and quality assurance procedures. In 2003 Melin initiated discussions with the faculty at Department of Chemical and Biological Engineering at University of British Columbia and together with Dr Shahab Sokhansanj developed guidelines for research in the area of feedstock engineering and currently holds a position within the faculty as Honorary Research Associate and is a member of the Biomass & Bioenergy Research Group (BBRG) at the university. Since 2005 Melin is also the Research Director for the Wood Pellet Association of Canada and is on the Board of the Canadian Bioenergy Association.
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Executive Summary

As a result of two serious accident since 2002 during discharge of wood pellets from ocean vessels the EWDOT Research Project was initiated by the Wood Pellet Association of Canada and carried out onboard the vessel MV Saga Horizon during the period January 26 and March 17, 2007 by researchers in Canada and Sweden. The findings of the research are described in some detail in this Report and can be summarized as follows;

- lethal concentrations of the highly toxic carbon-monoxide (CO) was registered in the stairway adjacent to the cargo hatch filled with wood pellets
- oxygen is depleted down to a lethal level
- gas generated in the cargo space is leaking in to the enclosed stairway when the cargo hatch is closed
- due to the very limited circulation in the stairway space there has to be forced circulation of the air from the bottom up prior to entry by personnel or alternatively continuous air circulation of the stairway space as long as the cargo hatch is sealed, including sea time
- established operational procedures for safe entry in to stairway or cargo space should be strictly enforced and safe conditions should be established by simultaneous measurements of CO and oxygen concentrations. One or the other is not sufficient and could cause exposure to life threatening conditions
- the complex intra-relationship between the ambient conditions such as air temperature, humidity, barometric pressure as well as ocean water temperature was established and may be used for developing guidelines for safer ocean as well as land transportation of wood pellets
- the emission of gases from wood pellets can be decreased to a degree by a gentler handling in terms of less fines (dust) since dust is likely increasing the gas generation due to increased surface area and exposure to oxygen
- water temperature rather than air temperature is affecting the thermal dynamics in the cargo hatch due to thermal conduction through the hull of the vessel

The EWDOT Project is already used as guidance in lab research, primarily at research laboratories in British Columbia, Canada as well as in Sweden, where research is on-going to explore the more complex issue of the chemistry involved in the generation of gases and depletion of oxygen related to wood pellets. As is already known, most other wood products are generating CO and CO_2 in combination with depleting oxygen. The research can be expected to explain these phenomena in detail and prescribe preventive measures to avoid accidents.

1. Introduction

Wood pellets are today transported in large bulk volumes in ocean vessels carrying anywhere from a few thousand metric tonne up to 40,000 tonne in a single shipment every month year round. The duration of the shipments vary from 24 hours to 9 weeks. Different types of vessels are servicing this trade. Modern open hatch box-shaped bulk carriers may have anywhere from a single hold up to 12 cargo holds. Other bulk carriers may be V-shaped with deck overhang. Access to cargo holds is sometimes by means of enclosed stairways adjacent to the cargo holds and in other cases the cargo holds are accessed by ladders inside the cargo holds. In all cases, however the personal working the vessels are likely to be exposed to gasses from the pellets or oxygen depletion unless proper ventilation procedures have been followed. The exact composition of gasses is not fully known, nor the mechanism releasing the gasses from the pellets or the depletion of oxygen. The accidents onboard Weaver Arrow on May 9, 2002 in Rotterdam and Saga Spray on November 16, 2006 in Helsingborg, both vessels carrying wood pellets, clearly points to the requirement for more in depth research in order to understand the physico-chemical processes in action during storage of wood pellets. The phenomenon of off-gassing and oxygen depletion is not unique for long duration ocean transportation of pellets. It has also been detected after short voyages of only a few days as well as in enclosed storage spaces on land. In this respect wood pellets are somewhat similar to most other biomass products, including grain, green sawn lumber etc. and indeed also various types of fossil fuels such as thermal coal.

As a consequence of these serious accidents onboard ocean vessels carrying wood pellets a research project was initiated in December of 2006 by the Wood Pellet Association of Canada (WPAC) with the objective to better understand the root causes of the accidents and to explore how future accidents of the same nature could be prevented. The accidents have in some cases been fatal and in other cases the victims have fallen offer to various levels of intoxication and asphyxiation due to the off-gassing from pellets or oxidation processes depleting the oxygen content in the air. Product documentation provides warning for off-gassing and guidelines for safe handling of the product but additional information and attention is obviously needed in order to avoid accidents from happening again.

WPAC assigned the management of the research project to Delta Research Corporation (DRC) and a Research Project Plan was established by DRC dated January 26, 2007 outlining a method for on-board measurement of the thermodynamic processes thought to be causing the off-gassing. A method was developed for quantifying the off-gassing by means of on-board electrochemical measurement of gases during transit. A more accurate method for measurement of gases using a transportable Fourier Transform Infrared (FTIR) analyzer immediately before discharge of the pellets in the receiving port was also developed in close cooperation with Dr Svedberg at Department of Occupational and Environmental Medicine at Sundsvall Hospital. The gas analysis was done by Jerker Samuelsson at FluxSense AB (affiliated with Chalmers University of Technology) who is a well known expert in industrial FTIR analysis.

The ocean vessel MV Saga Horizon carrying wood pellets from Vancouver, British Columbia to Helsingborg, Sweden was selected for the project and equipment was installed on-board the vessel during a port call on January 26, 2007 when the vessel was loading wood pellets manufactured in British Columbia. The vessel discharged in Helsingborg, Sweden after approximately 7 weeks at sea without opening the cargo hatches holding the wood pellets.

This Report is focused primarily on the off-gassing. However, it is believed that the off-gassing also is directly related to the degradation of the product during handling and the Project was therefore also including sampling and analysis intended to quantify related parameters such as generation of fines and changes in moisture content.

The research in Canada, Sweden and The Netherlands has been accelerated as a consequence of the accidents and has opened up unique opportunities for international research collaboration.

A secondary objective with the Project was to define areas where more detailed research might be carried out to further the knowledge of how biomass and wood pellets can be transported with uncompromised quality and highest degree of safety. This Report is including a list of such areas as a direct result of the findings in the Project.

It should be noted that parts of the investigation is not following rigorous scientific procedures since the main purpose was exploratory to prove the existence of suspected phenomenon and to suggest potential causes and relationships in preparation for more in depth research. Therefore intuitive assumptions have in some cases been used in order to allow reasonable explanations. It is up to future research to verify and quantify the findings in this Report.

1.1 Anatomy of Accidents Caused by Off-gassing Onboard Ocean Vessels
IMO (International Maritime Organization) regulations stipulate that;
1. When transporting a bulk cargo which is liable to emit a toxic or flammable gas, or cause oxygen depletion in the cargo space, an appropriate instrument (13) for measuring the concentration of gas or oxygen in the air shall be provided together with detailed instructions for its use
2. The shipper has to provide a Shipper Cargo Information Sheet (14) to the master of the ocean vessel about the properties of the cargo
3. Many products are classified as Material Hazardous in Bulk (MHB) (12), including wood in such forms as packaged timber, roundwood, logs, pulpwood, props (pit props and other propwood), woodchips, woodshavings, woodpulp pellets, wood pellets and sawdust. Such products are subject to restrictions in handling, stowage and segregation, ventilation and emergency actions in case of fire

There appears to be a typical scenario for accidents with gas exposure onboard ocean vessels even though the detailed circumstances may be somewhat different. In the case of MV Weaver Arrow and MV Saga Spray, both carrying wood pellets, the onboard crew

and stevedores entered the enclosed stairway space without proper ventilation and without proper gas detection equipment. In both cases the cargo hatch and adjacent stairway had been sealed for almost seven weeks during transport from Vancouver, British Columbia, Canada. No precautionary steps, such as air and gas measurements, had been taken prior to entering the sealed staircase (Australian ladder), although the Shipper Cargo Information Sheet stipulated such requirement.

In the Weaver Arrow case one stevedore was killed, three other stevedores developed serious brain injuries and several rescue workers sustained less severe injuries after entering the unventilated stairway.

In the Saga Spray case one crew member was killed, one stevedore was seriously brain injured and a large number of stevedores and rescue worker sustained less serious injuries after entering the unventilated stairway. The injured stevedore was removed from the contaminated atmosphere after approximately 10 minutes and the dead crew member after approximately 15 minutes.

Entry in the cargo hatch itself loaded with cargo such as pulp logs, wood chips or green lumber has resulted in fatalities on several other vessels over the years.

A combination of poor dissemination of information about the regulations, a lax discipline onboard ocean vessels and the absence of gas measurement devices appears to be at the heart of the problem. In addition, there appears to be a poor knowledge of how to ventilate properly. There also appears to be a perception in the shipping industry that an oxygen meter is sufficient for establishing whether or not life sustaining atmosphere is at hand. In the cases where multi-gas meters are used it appears as if many of these meters do not have suitable range capability to quantitatively measure the gases of interest, only to initiate alarm.

1.2 Oxygen Deficiency
The U.S. National Institute for Occupational Safety and Health (NIOSH) defines an oxygen deficient atmosphere as one with an oxygen partial pressure less than 132 torr (or mmHg), equivalent to about 17.2 % oxygen at sea level. Above this level no physiological effects are expected due to oxygen deficiency. However a 19.5% oxygen level is recommended for most work situations and provides a margin of safety.

1.3 Toxicity of Carbonmonoxide (CO)
CO binds to hemoglobin (Hb) forming a CO-Hb complex which inhibits the ability of hemoglobin to bind oxygen. The level of CO saturation in the blood is measured % COHb. Most people whom die from CO poisoning have a % COHb level above 60%. The normal level in smokers is 3-8% COHb. The ACGIH biological exposure index (BEI) is 3.5 % COHb at the end of shift [4]. The Swedish occupational exposure limit is 35 ppm (8-hour) and 100 ppm (15-min) and the ACGIH's TWA is 25 ppm [6],[4]. The U.S. National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances (NAC/AEGL Committee) has produced interim report on carbon monoxide toxicity [5]. The strictest level (AEGL-3) above which it is predicted that the general

population, including susceptible individuals, could experience life-threatening health effects or death is 1700 ppm at 10 minute exposure and 600 ppm at 30 minute exposure.

1.4 Simultaneous Exposure to Carbonmonoxide and Oxygen Deficient Atmosphere.

The available scientific information regarding the combined toxic effects of carbon monoxide exposure and oxygen deficiency is non-existing. CO binds competitively to hemoglobin ~200 times stronger than oxygen. It can be expected that reduced oxygen partial pressure increases the available sites for CO-binding and a toxic effect is caused at lower CO concentrations. Physical work load will increase the uptake of CO.

1.5 Discussion

The shipping industry is characterized by temporary and mobile work-force. The communication to crew on the hazards associated with wood material should be effectively implemented and the responsibility outlined. The CO-meters used on board should also be performance tested for memory effects from exposure to very high CO concentrations. In the case of optical meters the non-linear absorption of CO over large concentration ranges will lead to a potentially large underestimation of the concentration, if the calibration is done far off the actual level. A faulty reading might lead to unwanted risks at entry. However, the availability of high CO-level meters is not considerable and some product development may be needed by concerned manufacturers.

Theoretically, if 10,000 ppm (= 1%) of CO is introduced in a volume of fresh air, the natural oxygen and nitrogen is displaced yielding a final mix of 1% CO, 20.7% oxygen and 78.3% nitrogen. If only oxygen is measured in such atmosphere, the condition will appear to be safe but will in fact result in unconsciousness and death within seconds or minutes.

It has been shown that carbon monoxide (molecular formula CO, CAS registry number: 630-08-0) and other one-carbon compounds like methanol, formic acid, formaldehyde, are emitted from wood pellets during storage (4). The authors also report emissions of aldehydes such as hexanal and pentanal from freshly produced wood pellets. Hexanal and other alkanals are proposed to be formed by a radical-induced oxidative degradation of natural lipids, particularly the polyunsaturated linoleic acid. The biochemical mechanism by which the shorter compounds are formed is not clear but again the oxidation of fatty acids and other components in the wood seems likely. The oxidative processes occur below room temperature but are enhanced by elevated temperature.

Only a portion of the oxygen depletion can be explained by the formation of CO. The greater part of oxygen loss is instead explained by the radical-induced oxidative degradation of natural lipids, particularly the polyunsaturated linoleic acid. In this process the majority of oxygen is believed to remain chemically bound within the wood structure without producing gaseous compounds. Common linseed oil is a mixture of linolenic, oleic acid and linoleic acid , the latter being the dominating acid in wood and wood pellets. We have recorded CO concentration of 1000 ppm and an oxygen level of ~ 7% in the headspace of raw linseed oil which was let to sit in its original plastic bottle. It is

believed that the air-tight bottle was deflated due to reduction of oxygen in the head-space air, a phenomenon often seen on the linseed oil bottles on shelves in paint shops.

2. Objectives with the Research Project
The reactivity in wood pellets manifesting itself as generation of gas or depletion of oxygen is a sign of chemical processes in the material which are not well understood. The Project was designed to develop a gas emission spectrum of the more prominent non-condensable gas species generated from wood pellets during transportation in bulk.

The Project included provisions for measuring the thermo-dynamics in and around the cargo hatch in terms of temperature, pressure and humidity. This data will be correlated with data generated in reactors at UBC running tests on wood pellets under controlled conditions.

The result from the investigation consist of several issues, each analyzed separately from a scientific standpoint as well as coupled together since they are interacting. The investigation was focused on the following;

1. Quality degradation of the wood pellets at loading, during ocean voyage and at discharge in the receiving port
2. Thermo-dynamic conditions in the cargo hold based on the temperature measurement in the cargo (pellets), headspace, ambient air and ocean water temperature
3. Atmospheric impact based on the ambient conditions such as air temperature, humidity, barometric pressure as well as ocean temperature
4. Gas concentrations in the cargo hold as well as the related stairway space
5. Working environment onboard the vessel and hygiene aspects to consider when transporting wood pellets

The data presented in this report cover to time from closing the hatch covers (pontoons) after completion of loading of the wood pellets at 17.00 on January 26, 2007 until completion of discharge of the wood pellets around 14.00 on March 17. 2007.

The immediate objective with the Project was to establish whether or not the environment in the cargo hatch poses a health risk for personnel working in or around the cargo hatch.

3. Project Description
The parameters of primary interest to measure in cargo hatch as well as stairway are arranged in two groups:
       1) during ocean voyage,
       2) prior to opening the hatch and stairway at discharge as per Table 3.

Table 3.		
Parameter	During Ocean Voyage	Prior to opening of hatch at discharge
Variations in oxygen concentration	Inside pile of wood pellets (3 levels) In headspace	Inside pile of wood pellets (3 levels) In headspace
Variations in gas concentration	Inside pile of wood pellets (3 levels) In headspace	Inside pile of wood pellets (3 levels) In headspace
Variations in temperature	Inside pile of wood pellets (3 levels) In headspace Ambient air	
Variations in humidity	Ambient air Headspace	
Variations in barometric pressure	Ambient air	
Variations in ocean temperature	Ocean water	

It was assumed that gas distribution is evened out in horizontal layers throughout the steady state conditions in the enclosed cargo space and therefore it is probably sufficient to measure the gas profile in the three layers as proposed in the attached schematic. As it appears, the convection in the under deck space is also evening out the gas distribution vertically and only limited stratification was noticed.

3.1 Synchronized Data Collection
All measurements were synchronized in time in order to offer best possible correlation of thermal and gas data. The changes of the temperature and humidity in the cargo hatch were measured by sensors every second and logged as an average every hour. The ambient conditions (relative humidity, air temperature, barometric pressure and ocean water temperature) were logged on the bridge of the ocean vessel and recorded three times per 24 hours 8 hours apart;
- 06.00 before the heat from the sun had impacted the cargo space
- 14.00 when the heat from the sun was at maximum
- 22.00 when the sun had been down for 3-4 hours and the effect of the cooler night would show up in the temperature recordings

In order to match these ambient observations with the hourly readings of the temperature sensors, the ambient data has been extrapolated as an approximation between observations.

3.2 Gas Sampling Points in Cargo Hatch
During loading tubes for sampling the gas in the cargo hold were placed with the sampling head about 2 meters in to the pile of pellets from the wall on the portside of the cargo hatch at four levels (at the 1 meter from the bottom, 5 meter from the bottom and 10 meter from the bottom and one in the open headspace). Schematic 3.2.1 below

illustrates the cargo hatch and the location of the tubing. Each sampling head was protected with a course metal mesh in order to avoid contamination to enter the gas tubes.

ONBOARD LOCATION OF SAMPLING AND MEASUREMENT POINTS
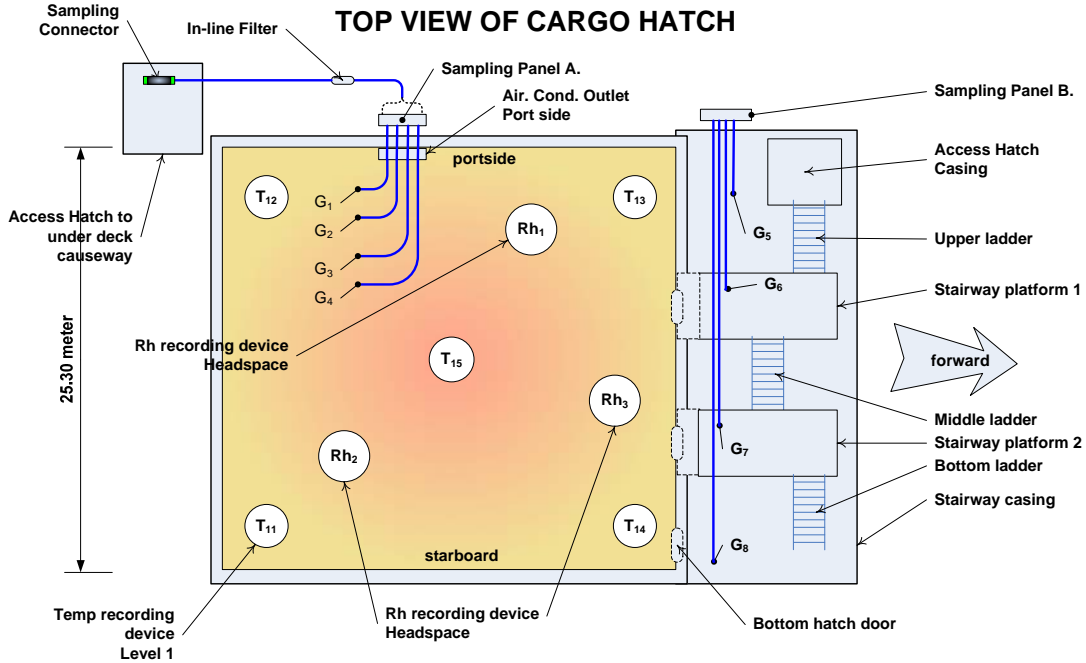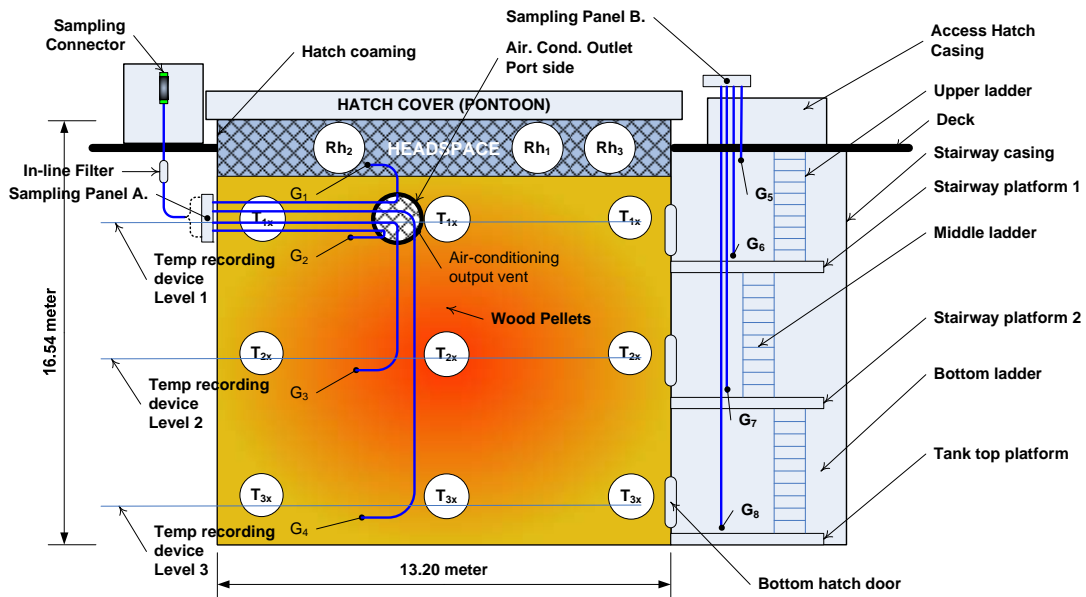
Schematic 3.2.1 Location of gas sampling tubes and temperature sensors

The tubes were fed through the air-conditioning output vent in the upper area of the cargo hatch in to the underdeck causeway where Sampling Panel A was located.

All tubing and special fittings for feed through were inspected by a classification inspector to make sure all SOLAS (Safety Of Life at Sea) regulations issued by IMO (International Maritime Organization) were followed. Care was taken to make all feed through as gas tight as possible to avoid unnecessary leakage.

Picture 3.2.2 Feed through of tubing coming from cargo hatch in to the causeway with Sampling Panel A mounted on the wall. One tube is disconnected to show the white "parking" stud for the tubing. The right hand picture shows the under deck causeway

Sampling Panel A was equipped with an in-line dust filter to avoid contamination of the instruments used for the gas measurements (see Appendix E for more details).

3.3 Gas Sampling Points in Stairway
During loading tubes for sampling the gas in the stairway at approximately the same distance from the bottom as the sampling points in the cargo hold (see Schematic 3.2.1), corresponding to the stairway platforms equipped with access doors leading in to the cargo space.

Picture 3.3.1 Tubing taped to hand rail in the stairway (viewing upwards)

The tubing leading from the Sampling Points G5 to G8 in the stairway were taped to the handrail and terminated at Sampling Panel B located outside the stairway space in order to allow sampling of gas accumulating in the stairway without opening the space. The tubing was fed through the hatch coaming (see Picture F.1.6 below).

Each stairway (Australian ladder) in this type of vessel allows access only to one cargo hatch which means there is no leakage between cargo holds through a stairway. The stairway for the selected Access Hatch # 9 is located forward of # 9 cargo hatch.
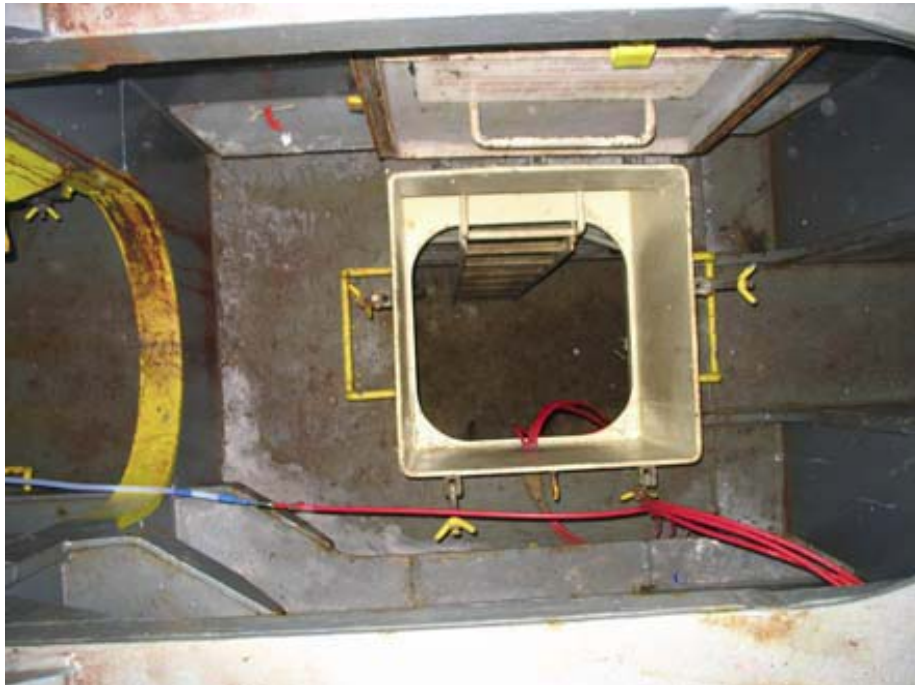
Picture 3.3.2 Stairway sampling tube and outdoor Sampling Panel B.

Feedthrough of tubing for
Sam[ling Points G5 to G8

Picture 3.3.3 Stairway access hatch opening

During the discharge in Helsingborg the instrumentation was located on the dock alongside the vessel on the portside with tubing connected to Sampling Panel A via the causeway and the aft portside access hatch (see Picture x).

Port Side Access Hatch

Picture 3.3.4 Port side Access Hatch to under deck causeway seen from the deck and from the under deck causeway

3.4 Temperature Sampling Points in Cargo Hatch

The temperature measurement in cargo hold # 9 was done by means of self-contained sensors (data loggers) dropped in to the cargo with internal recording of data throughout the voyage. The sensors were located on the same levels as the gas sampling points as described in section 3.2.

Both R_h data loggers were located in the headspace of the cargo hold. The two units were be separated in height to provide a reading of the humidity immediately at the layer of the pellets as well as immediately under the hatch cover. The distance between the underside of the hatch cover and the top of the pellets is usually about 15 cm (average) immediately upon completion of loading. Since the pellets were compacting during the sea voyage this distance reached 125 cm at the time of the discharge. Stratified layers of humidity occur in the upper section of the cargo hold, particularly in the headspace. This stratification is of importance to understand since it is related to water vapor condensation in the top layer of the pellets.

Picture 3.4.1 illustrates the mounting bracket for the lower Rh_1 data logger which is combined with a mounting of the Sampling Head G1. This Head is directly connected to the onboard sampling with the gas meter described in section F.1 and needs to be located at a distance from the pellets in order to avoid dust inhalation and pointed downward to avoid water ingress in the tube from condensation.

The upper Rh_2 data logger in mounted on a bracket immediately under the cement hole cover in the pontoon (cargo hatch cover) in order to provide a measure of the moisture content at the top of the headspace. Picture 3.4.2 illustrates the location of the cement hole in the pontoon and the Rh_2 data logger mounted on the underside of the cement hole cover.

Picture 3.4.1 Bracket for Rh_1 data logger combined with support for Sampling Head G_1

Picture 3.4.2 Cement hole cover in pontoon and mounting of Rh_2

FORWARD

T_{13}
T_{23}
T_{33}

T_{14}
T_{24}
T_{34}

VENTILATION OPENING
SAMPLING TUBES

Rh_1

PORTSIDE

Rh_2

T_{15}
T_{25}
T_{35}

STARBOARDSIDE

T_{12}
T_{22}
T_{32}

T_{11} TOP
T_{21}
T_{31} BOTTOM

AFT
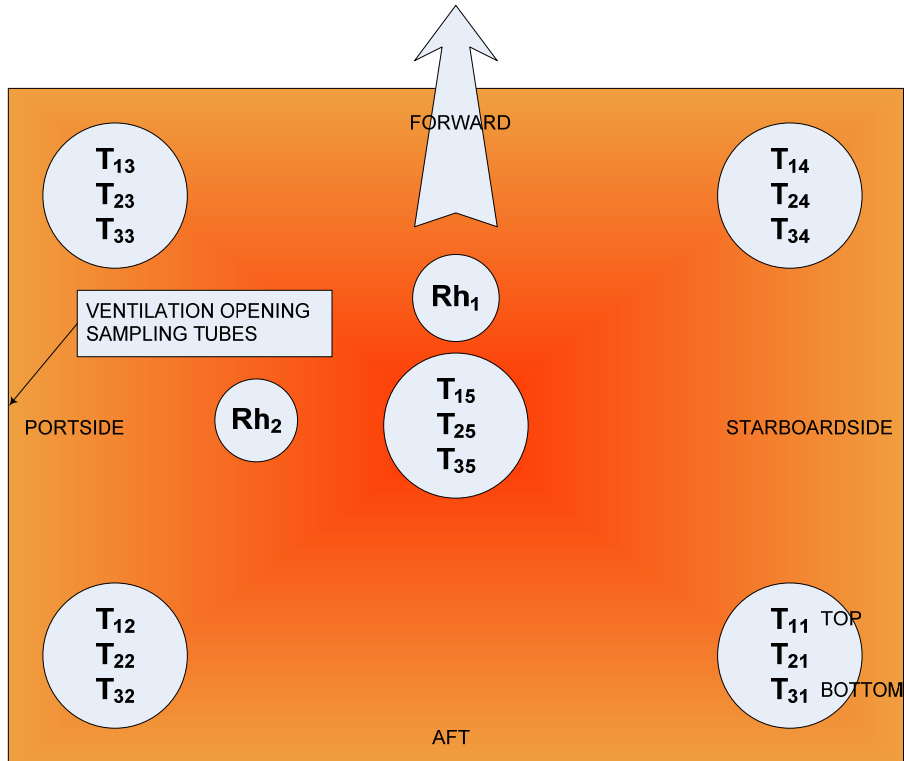
Schematic 3.4.3 Placement of temperature loggers

Two data loggers for tracking the relative humidity (Rh) were placed in the headspace of the hold, one on top of the pellets and the other on the underside of the hatch cover (pontoon).

The units were activated immediately before the loading commenced, thrown in to the pellets in cargo hold # 9 during the loading and anchored (see picture below) with a string at the top of the cargo hatch. At discharge the units were retrieved by "fishing" them out of the cargo hold and when retrieved the data logging was de-activated. All units were retrieved except T_{31} which was lost due partly to bad weather (wind gusts of more than 34 m/s) during the discharge clamming operation during.

4. Analysis of Wood Pellets Characteristics
The physical properties of the pellets shipped with Saga Horizon were analyzed as part of the EWDOT Project. The results give rise to some questions. The analysis of the samples taken at loading and discharge were done by the same laboratory in order to minimize the variance due to differences in analysis procedures and instrumentation.

4.1 Lab Tests of Wood Pellets
Physical parameters of the wood are summarized and discussed in the following sections and the chemical characteristics analyzed are specified in Appendix A.

Cargo hatch # 6 was loaded first and # 9 last in Vancouver. Cargo hatch # 9 was the subject of this Research Project. The sampling in Vancouver was a total composite for

the two holds together. Sample # 1 taken during the discharge in Helsingborg came from cargo hold # 6 and sample # 2 from cargo hold # 9.

4.2 Wood Pellets Size Distribution

Table 4.2 summarizes the results from the analysis of the main parameters.

Table 4.2.1 Mechanical properties of pellets as measured at loading and discharge					
Parameter	Measure	Standard	Loading	Discharge	
			Total composite sample	Sample lot # 1	Sample lot # 2
Fines Content	% of weight	ISO 2591 < 3.15 mm	0.4	4.4	6.7
Durability of pellets	% of weight	CEN/TS 15210-1	98.2	98.7	98.7
Moisture content	% of weight	CEN/TS 14774-1,2	5.6	9.1	5.8
Bulk density	kg/m^3	CEN/TS 15103 mod.	712	725	751

The significant difference in the moisture content in hold # 6 can not easily be explained by the data available but is of peripheral interest since this investigation focuses on hatch # 9. There is a slight increase in the moisture content from 5.6 to 5.8 % in hatch # 9 although there is some uncertainty in these numbers since there was no sample segregated for hatch # 9 during loading.

The size distribution of the **pellets as delivered** was analyzed and is summarized in the following Table 4.2.1.

Table 4.2.1 Size distribution of pellets as delivered									
	Loading, total composite			Discharge, sample lot 1			Discharge, sample lot 2		
Fraction (mm)	Weight (g)	Weight (%)	Acc. Weight (%)	Weight (g)	Weight (%)	Acc. Weight (%)	Weight (g)	Weight (%)	Acc. Weight (%)
> 10.0	0	0.0	100.0	0	0.0	100.0	0	0.0	100.0
8.0 – 10.0	0	0.0	100.0	1	0.0	100.0	0	0.0	100.0
5.6 – 8.0	2458	90.9	9.1	4645	86.8	13.1	4528	84.5	15.5
4.0 – 5.6	162	6.0	3.1	307	5.7	7.4	334	6.2	9.3
2.0 – 4.0	54	2.0	1.1	176	3.3	4.1	199	3.7	5.5
1.0 – 2.0	12	0.4	0.6	103	1.9	2.2	123	2.3	3.2
0.5 – 1.0	8	0.3	0.3	78	1.4	0.7	109	2.0	1.2
< 0.5	9	0.3	0.0	39	0.7	0.0	65	1.2	0.0
Total	2,703	100.0		5348.8	100.0		5357.3	100.0	

The size distribution is of importance to the user when the pellets are processed before combustion. The pellets may be crushed in to granules, hammer milled in to powder or in

some cases used in its original form depending on combustion technology used. Each preprocessing is optimized based on a limited variance of the characteristics of the in-feed material in relation to the final fuel product.
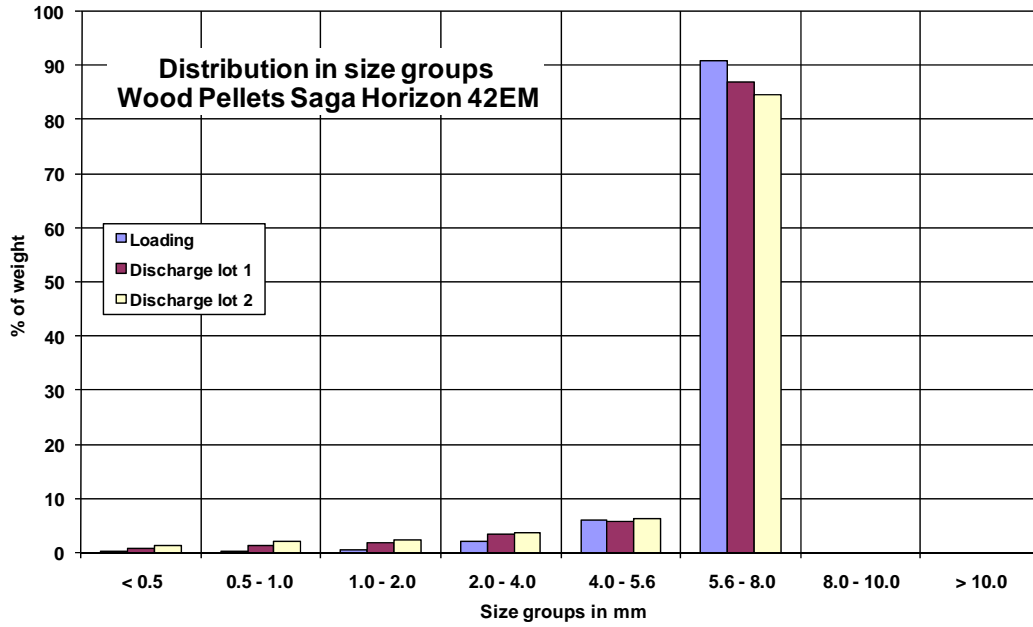
Graph 4.2.3
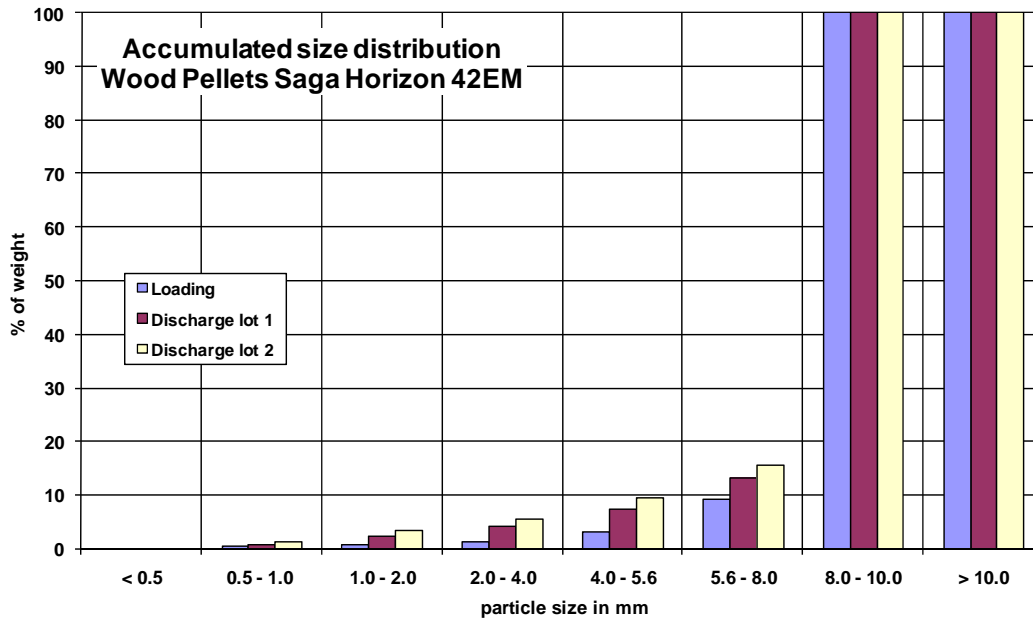
Graph 4.2.4

Graph 4.6 illustrates the distribution according to the methods used for determining the fines content. A modified ISO 2591 Standard was used for the lab analysis for all sizes except 3.15 mm which has been extrapolated from adjacent data point in an attempt to match the value (4.4 and 6.7 % respectively) for fines as established in a separate test at

the lab. Graph 4.2.5 is truncated for the larger particulate size (above 8 mm) in order to retain the resolution in the graph.
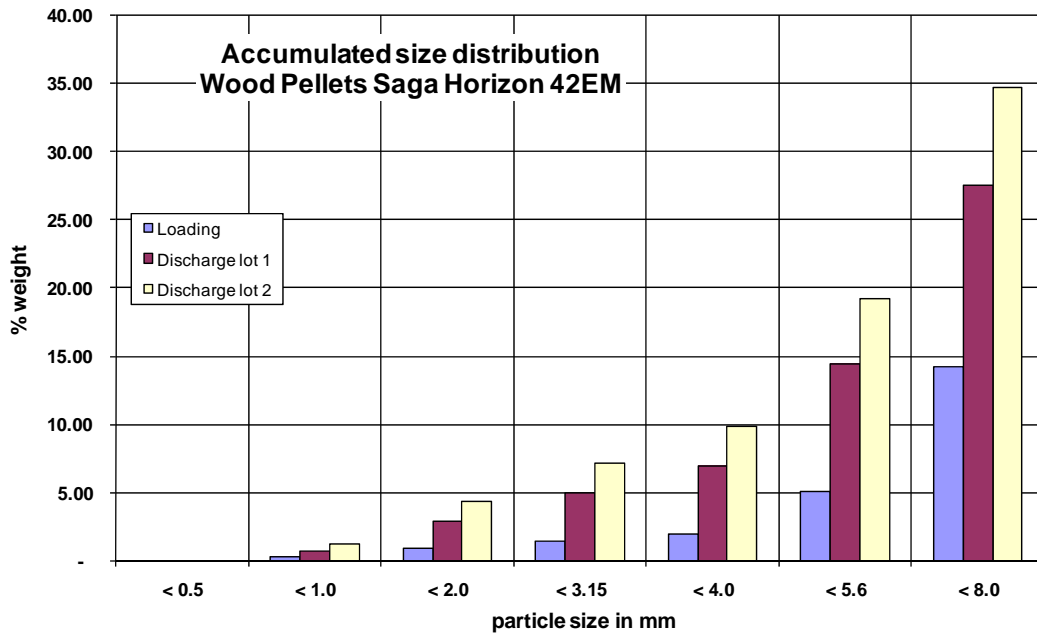
Graph 4.2.5

The difference in the fines content between lot # 1 and 2 is difficult to explain. To a degree it may have something to do with the source of the material such as the top or the bottom layer of the storage silos or the manufacturing quality of the pellets. The speed of the conveyor belt is constant and should not be a consideration. The fact that we only have a composite from the two holds together does not allow a closer analysis.

The fractional size distribution of the **raw material** used for the production of the pellets was analyzed and is summarized in the following Table 4.2.6 and Graph 4.2.7.

Table 4.2.6 Fractional size distribution of raw material			
Fraction (mm)	Weight (g)	Weight (%)	Acc. Weight (%)
3.15	0.2	0.2	99.8
2.5	0.9	0.9	98.9
2.0	2.6	2.7	96.2
1.4	10.0	10.4	85.9
1.0	18.4	19.0	66.9
0.85	7.3	7.6	59.3
0.71	13.7	14.1	45.2
0.5	15.3	15.8	29.3
0.25	17.6	18.2	11.2
< 0.25	10.8	11.2	0.0
Total	96.6	100.0	

This profile is typical of what we have seen in other analysis for pellets from BC and is likely a reflection of the characteristics of the size reduction equipment used during the feedstock preparation.

**Fractional distribution
of raw material used in Wood Pellets**
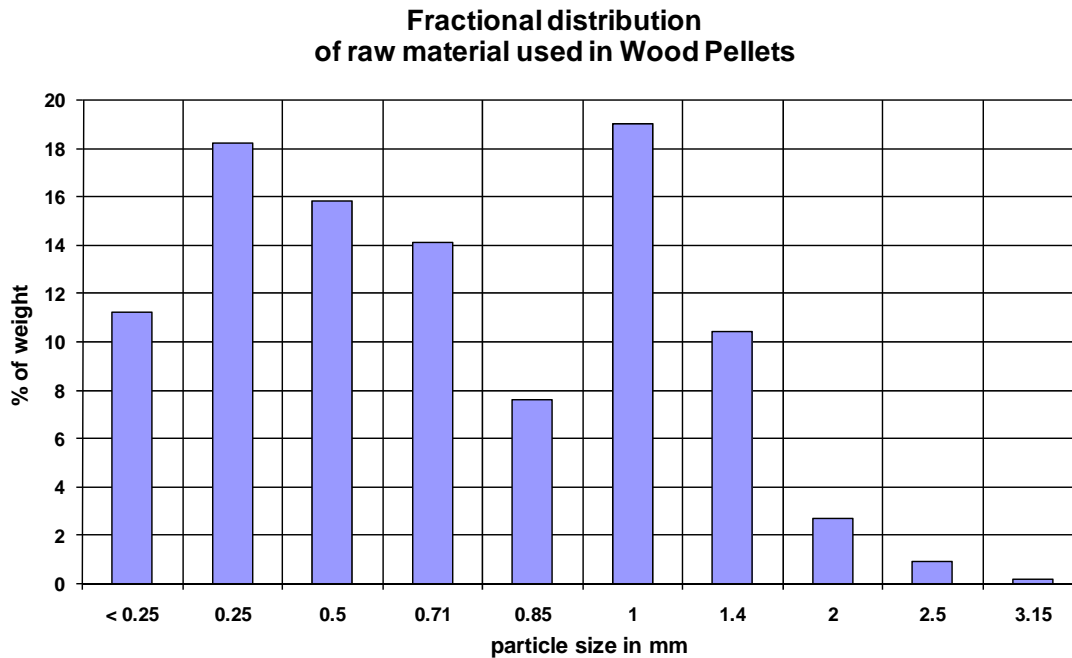
Graph 4.2.7

4. 3 Wood Pellets Durability

The durability analysis (CEN/TS 15210-1) is done after the fines have been removed. Table 4.2 indicates practically no change in durability in the composite sample taken before the shiploader and the samples taken after discharge. In view of the high dust content at discharge and the relatively gentle handling during the discharge it is reasonable to assume the fines have been generated primarily in one step when the pellets go through the shiploader.

Special attention was paid during the discharge in Helsingborg to get a feeling for if the degradation is happening at discharge or if the product is already degraded when arriving. The following can be concluded:

- The sampling of pellets upon loading in Vancouver was done on the conveyor belt after the silo storage but before the shiploader at Fibreco. In view of the degradation when passing through the shiploader, this may not be the most representative sampling point from a client perspective.
- The speed of the product when leaving the belt is high (approximately 4 m/sec) and is further accelerated by gravity before landing in the cargo hold. The drop height in the beginning of the loading cycle is as much as 10 meter or more and as low as 5 meters during top trimming, still at full speed. The pressure from the high speed flow is felt if standing next to the flow or partly in the flow during loading.

- The cargo is subject to compaction during ocean transportation due to high frequency vibrations in the hull in combination with low frequency swaying movement due to the waves at sea. Some degradation is likely happening as a result of friction in the cargo
- The sampling of pellets upon discharge in Helsingborg was done on the conveyor belt after the discharge hopper before going in to the bulk storage at the power plant
- The discharge in Helsingborg is done with a clam squeezing each scope gently and lifting 32 metric tonne of pellets at a time and dropping it in to the hopper. The drop height from the clam to the hopper is between 1 and 2 meters and most often around 1 meter since the hopper is almost always choked with product slowly moving downwards to the conveyor beneath. The product is slowly flowing from the bottom of the hopper on to the belt without any drop height. The entire handling during discharge must be described as very gentle

4.4 Fines, Moisture and Bulk Weight Relation

Assuming the moisture content and the amount of fines was distributed evenly in the volume loaded in hatch # 6 and 9 in Vancouver, it appears as if the % of fines has a greater impact on the bulk density (going from 712 to 751 kg/m^3) than the moisture content in cargo hatch # 9. The moisture content is increasing with only 0.2 % (from 5.6 to 5.8 %) while the fines content increases with 5.9 % (from 0.4 to 6.7 %). The fines will occupy more of the voids between pellets and add to the weight without adding to the volume.

4.5 Stowage Factor for Wood Pellets During Ocean Voyage

The compaction of the pellets in hold # 9 measured as the difference in height between the top of the hatch coaming and the average height of the pellets in the hatch, often referred to as the slack, is caused as a result of settling of the pellets during vibrations and swaying motion of the ocean vessel. The bulk density of the pellets, including the fines after passing through the shiploader, was established by lab test to be 751 kg/m^3.

The compaction during a voyage can be estimated as follows:

Bulk weight (est.) of the pellets in hatch # 9 = 3,800,000 kg (3,800 tonne)
Hatch dimension (from Table 5.0.2)
      Height = 16.54 m
      Width = 25.3 m
      Length = 13.2 m
Final slack in cargo hatch (headspace)   = 1.25 m average across the hatch
Initial slack in cargo hatch (headspace)   = 0.15 m average across the hatch
Bulk density (lab test)   = 751 kg/m^3

Calculated bulk density = 3,800,000/(25.3*13.2*(16.54-1.25)) = 744 kg/m^3
This result is reasonably close to the bulk density from the lab test. There are many reasons why the two numbers differ such as;
      - inaccuracy in the estimated bulk weight

- inaccuracy in the estimated initial and final slack
- the compaction may not be as complete as in the lab test which is using forced vibration

Compaction = 25.3*13.2*(1.25-0.15)/25.3*13.2*16.54 = 0.0665 (6.7 %)

Stowage Factor for wood pellets may be given in cubic feet per metric tonne as follows;
<u>Loading</u>
25.3*13.2*(16.54-0.15)*35.31/3,800 = 50.86 cuft/tonne
<u>Discharge</u>
25.3*13.2*(16.54-1.25)*35.31/3,800 = 47.45 cuft/tonne

4.6 Discussion
A number of significant issues needs to be addressed related to the physical characteristics of wood pellets;

Fines Content
There is reason to believe that the overwhelming majority of the fines are generated during the impact immediately after exiting the shiploader. However, the sampling was done before the shiploader and only after discharge in Sweden which means that we do not have a sample immediately after the shiploader. For verification purposes sampling was done on a subsequent vessel (MV Saga Jandaia 27EM loading on April 22, 2007 in Vancouver). The result (16) clearly indicates a substantial generation of fines when the pellets are passing through the shiploader. Since the durability of the pellets is essentially intact before and after this step it appears as if the degradation is catastrophic, meaning that the pellets are either pulverized or survive the step intact. This may indicate most of the degradation is generated by impact rather than by friction.

The generally accepted level of fines in bulk pellets in Europe is < 1 % at factory gate and < 3 % delivered although some contracts are tighter. For bag product the acceptable level is generally < 0.5 %. High bulk density is generally considered as a sign of high quality of the pellets. However, a high bulk density number may be misleading if the fines content is high.

Risk Factors Related to High Fines Content
Besides the increased risk for explosions due to dust, the high level of fines exclude the product from entering the bag market after completion of ocean voyage without a robust screening process with substantial loss of volume. Another concern is the rapid increase in surface area for the material as a result of a high level of fines. Increased surface area will escalate the off-gassing as well as the self-heating. Another concern is the potential for stratification of pellets or dust with different permeability promoting localized heating. Increased fines content is also changing the angle of repose which may have consequences in other applications.

Stowage Factor
It should be noted that wood pulp typically has a Stowage Factor 43-45 cuft/tonne for 8 bale bundling. A typical average length of pellets in bulk is ¾ inch. The bulk density and

thereby the Stowage Factor improves (17) if the length of the pellets approaches a spherical shape as is illustrated in Graph 4.5.1. Theoretically it appears as if the Stowage Factor for pellets could be improved 8-10 % provided the length of the pellets could be shortened and the stowage density could be improved during loading by means of a smother surface of the pellets and a different shape to avoid the rough end-surface. The rough end surface is likely also the main source of the fines generated from friction. Such improvement could potentially mean a significant cost saving in terms of lower shipping rate (17) per tonne.

## 5. Analysis of Thermal Data in Cargo Hatch # 9
When analyzing the thermal conditions and dynamics in the cargo hatch it is important to define the initial conditions and the envelop of the cargo hatch. The cargo hold was subject to the regular Cleanliness Inspection and certified as ready before loading started in the morning on January 26, 2007. The Hatch Sealing Inspection was conducted upon completion of loading in the evening at around 17.00, subsequent to inspection of the rubber seal located under the pontoon hatch cover.

The general arrangement of Saga Horizon is illustrated in the following Schematic 5.0.1 with the side view showing the location of the cargo hatches. Hatch # 6 and 9 were loaded with pellets and the investigation documented in this report was conducted in hatch # 9. The two gantry cranes are parked in the aft position covering cargo hatches 8, 9 and 10 during voyage.

Table 5.0.2 (*see section 4.5 for more information)			
Parameter		**Measure**	**Value**
Pellet bulk density (loading)		kg/m^3	712*
Pellet bulk density (discharge)		kg/m^3	751*
Pellet specific density		kg/m^3	1,200
Ambient air density		kg/m^3@1 atm (101.325 kPa), 0°C (NTP)	1.293
Ambient air pressure		kPa	variable
Ambient air temperature		^{o}K	variable
Cargo hatch	height	m	16.54
	width	m	25.30
	length	m	13.20
	gross volume	m^3	5,523.7
Stairway	Estimated volume	m^3	230
Headspace	height (loading)	m	0.15
	height (discharge)	m	1.25
	width	m	25.30
	length	m	13.20
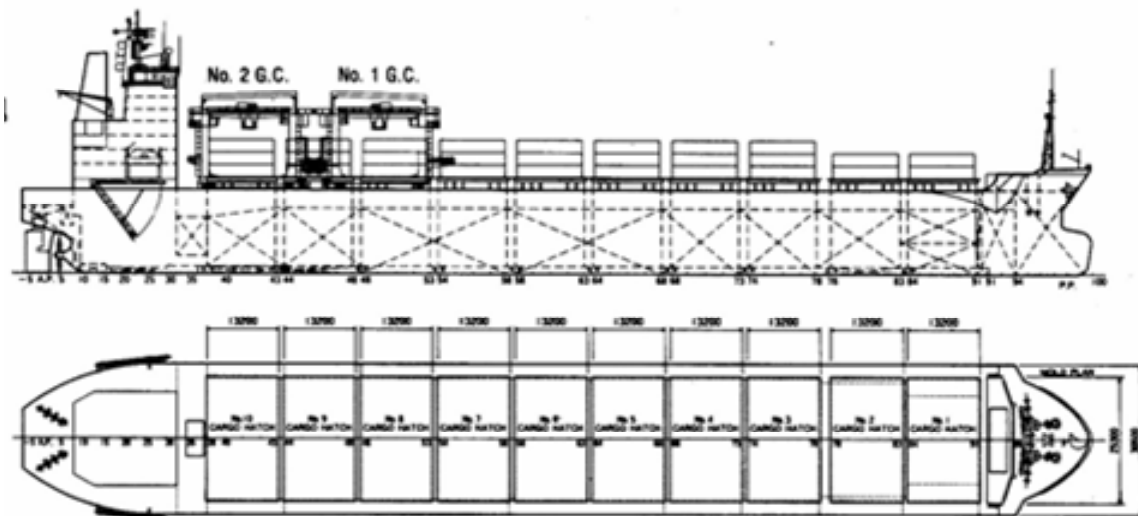
Schematic 5.0.1
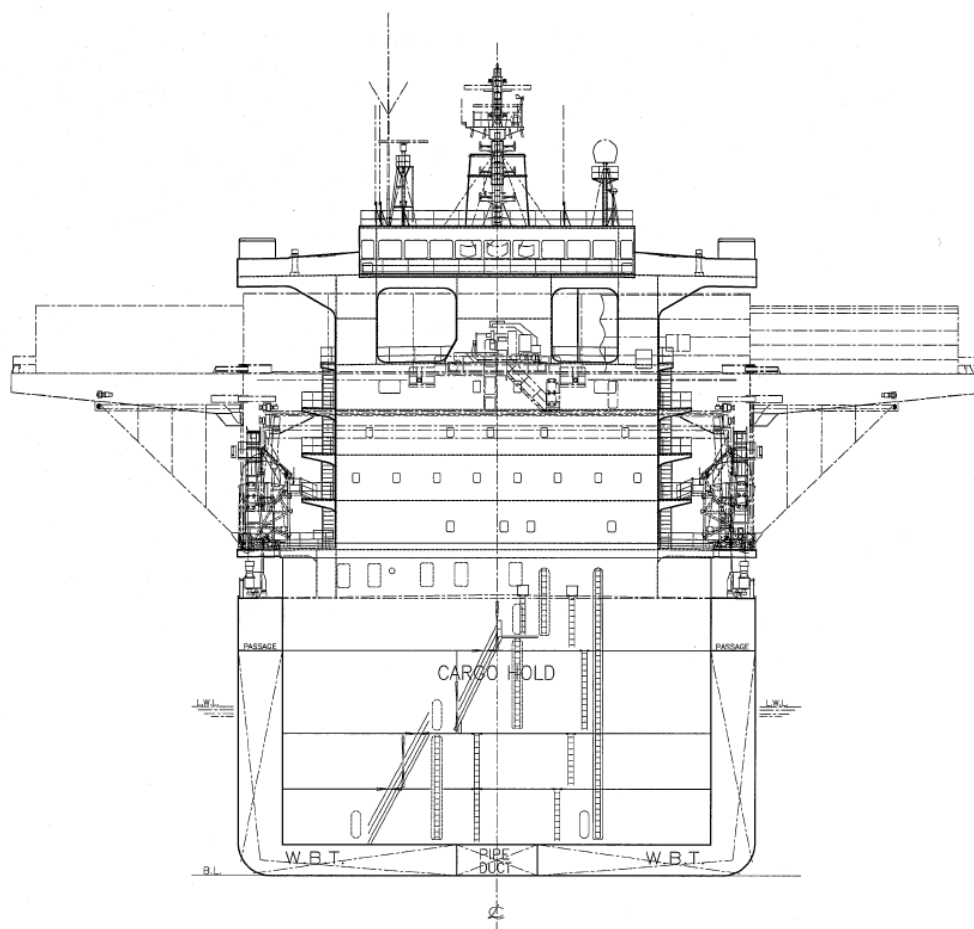
Schematic 5.0.3

The Cleanliness Inspection also includes a check that all access doors between the stairway and the cargo space are closed. After the accident onboard Saga Spray in Helsingborg on November 16, 2006 the access doors are no longer taped in order to allow for easier opening of the doors during the discharge operations in case the doors needs to be opened from inside the stairway for ventilation purposes. The gaskets around the access doors between the stairway and the cargo space are normally not inspected during Cleanliness Inspection. Advice from the shipping company and onboard personnel verifies that there is no known communication channel between the cargo space and the stairway but it was also verified by the onboard personnel that the gaskets are not gas-tight. The access hatch between the stairway and the outside deck has a gasket which for all intents and purposes eliminates any substantial leakage from the stairway space to the ambient air (see Picture 3.3.3).

Schematic 5.0.3 illustrates the cross profile of the ocean vessel with the double skin hull consisting of ballast tanks and fuel tanks clearly visible as well as the stairway with entrance ladder starting from the outside deck at the top and going down to the bottom (called tank top). The passage way is located on top of the side tanks with the outside wall of the passage way facing the outside skin of the vessel.

Heat is transferred to and from the pellets through the bottom, side walls and the hatch cover. There are three types of transfer functions – Conduction, Convection and Radiation. Under prevailing sailing conditions the thermal heat transfer between the pellets in the cargo hold and the ocean water can be estimated according to Schematic 5.04. For simplicity we assume;

- since all sides of the cargo hold is facing steel the heat transfer function may be disregarded in all directions
- heat is balanced (is in steady state due to the relatively long time involved) between the ocean water and the ballast tanks
- heat is balanced (is in steady state due to the relatively long time involved) between the ambient air as well as the air within the hatch cover and in the underdeck causeway
- prevailing transfer mechanism is by means of conduction since the intermediate media is stationary (water in the ballast tanks and the air in the inside the hatch cover)
- conduction through the bulkheads between hatches has much lower heat transfer coefficient (k) since the adjacent space is filled with air

Heat transfer by conduction is defined as follows;

$$\frac{Q}{A} = -k\frac{dT}{dx} = -k\frac{T1 - T2}{dx}$$ (Fourier's equation for conduction)

k = heat transfer coefficient (W/mK$^{\text{o}}$)
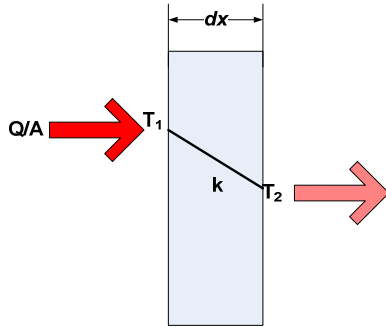
The heat transfer in the headspace is very complex since it consists of both conduction between the pellets and the air, thermal convection and ventilation through the leakage as is discussed in section 6.5. heat transfer by <u>convection</u> is defined as follows;

$$\frac{Q}{A} = h(Ts - Tf) = \text{(Newton's equation for convection)}$$

h = heat transfer coefficient (W/m²K°), not known for the surface layer of pellets

Since the headspace is comparatively small in comparison with the thermal inertia in the pellet volume and surface temperature of the pellets (T_{h1}) and the temperature in the cement hole recessed in to the hatch cover (T_{h2}) is very close (less than 0.5 °C throughout the voyage) we simplify by approximating the heat transfer to conduction for the purpose of estimating the relative thermal impact of the ambient air temperature and the ocean water on the thermal conditions in the pellets.

Table 5.0.5 is summarizing the rough estimate of the relative impact of the heat transfer envelop on one hand between the pellets and the ocean water and on the other hand the transfer envelop between the pellets and the ambient air.
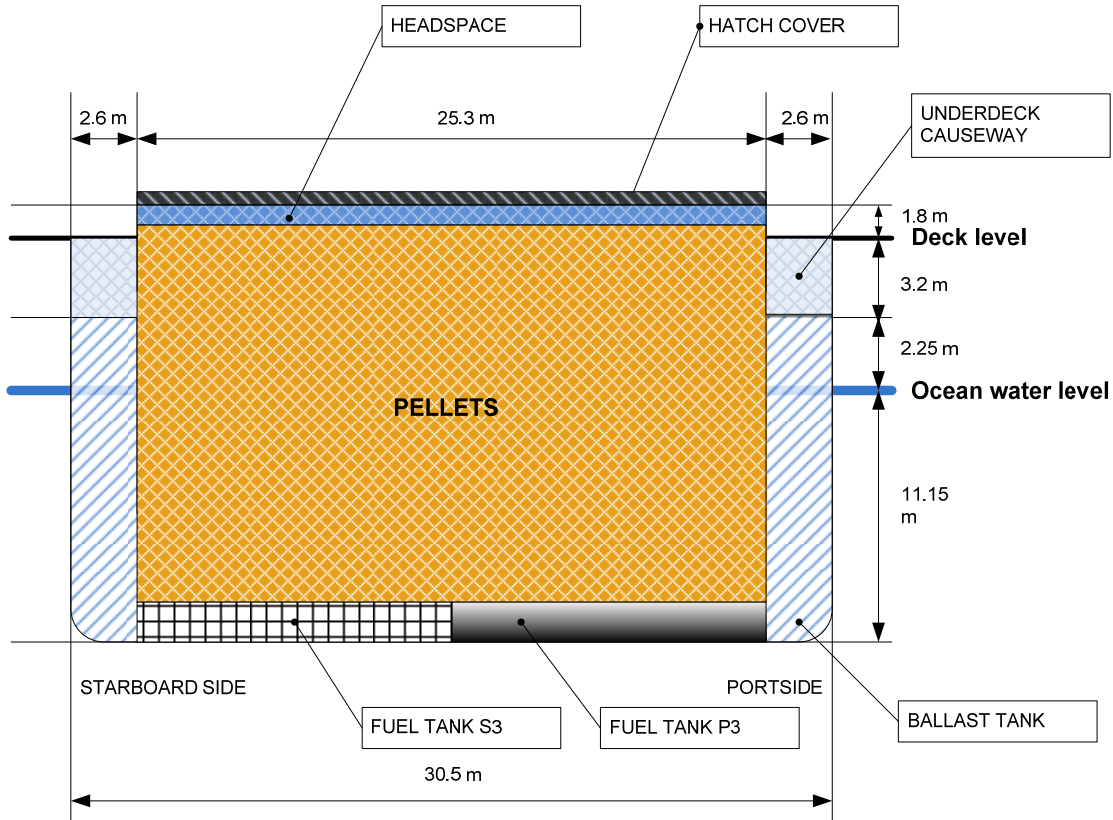
Schematic 5.0.4

Table 5.05				
Cross section	Length in meter			Conduction Coefficient (W/mKᵒ)
	Water	Air	Oil	outside steel wall [19]
Portside wall	11.15	-	-	0.610
	-	5.45	-	0.026
Starboard side wall	11.15	-	-	0.610
	-	5.45	-	0.026
Bottom	15.25	-	-	0.610
			15.25	0.130
Hatch cover	-	25.3	-	0.026
Total	37.55	36.2	15.25	

Both side ballast tanks and fuel tank S3 where empty during the voyage. Fuel tank P3 (portside) was filled with fuel oil at the time of loading but the oil was consumed throughout the voyage and empty sometime during the voyage. The oil in the fuel tanks is heated to + 25 to 30 ^{o}C by steam coils to keep the viscocity within range. It is not clear though whether this heating is continuous or depending on the rate of depletion of the oil in the tank. A rough order of magnitude ratio between the heat transfer through conduction to water versus air will give us an indication of which media (water or air) will dominate the impact of the thermal conditions in the pellets. The ratio may be estimated as follows;

$$\text{Water/Air} \propto 37.55*0.61/(36.2*0.026) \sim 24$$

Water is dominating by a factor 24 if we disregard the effect of the heated fuel tank P3.

The following sections present the temperature data collected during the voyage in the 5 locations throughout the cargo and in the headspace of the cargo hold. The ocean vessel was entering the Panama Canal on February 17, 2007 and the diagrams clearly indicate the impact of the tropical water temperatures. Schematic 3.4.3 indicates the placement of the temperature sensors in the cargo hatch. The blue line is the ocean temperature and the black line is the air temperature. The ocean temperature is somewhat higher than the air temperature which is typical for winter time conditions

5.1 Aft Starboard Corner Temperature Profile

The green line (T_{31}) in Graph 5.1.1 illustrates the temperature at the bottom of the hold which is tracking the ocean water (T_{ocean}) temperature while the temperature at the 5 (red line T_{21}) and 10 (orange line T_{11}) meter level are relatively independent of the T_{ocean}. The center of the cargo (T_{21}) in this corner appears to be accumulating heat while the upper section (T_{11}) appears to adjust to the ambient conditions.
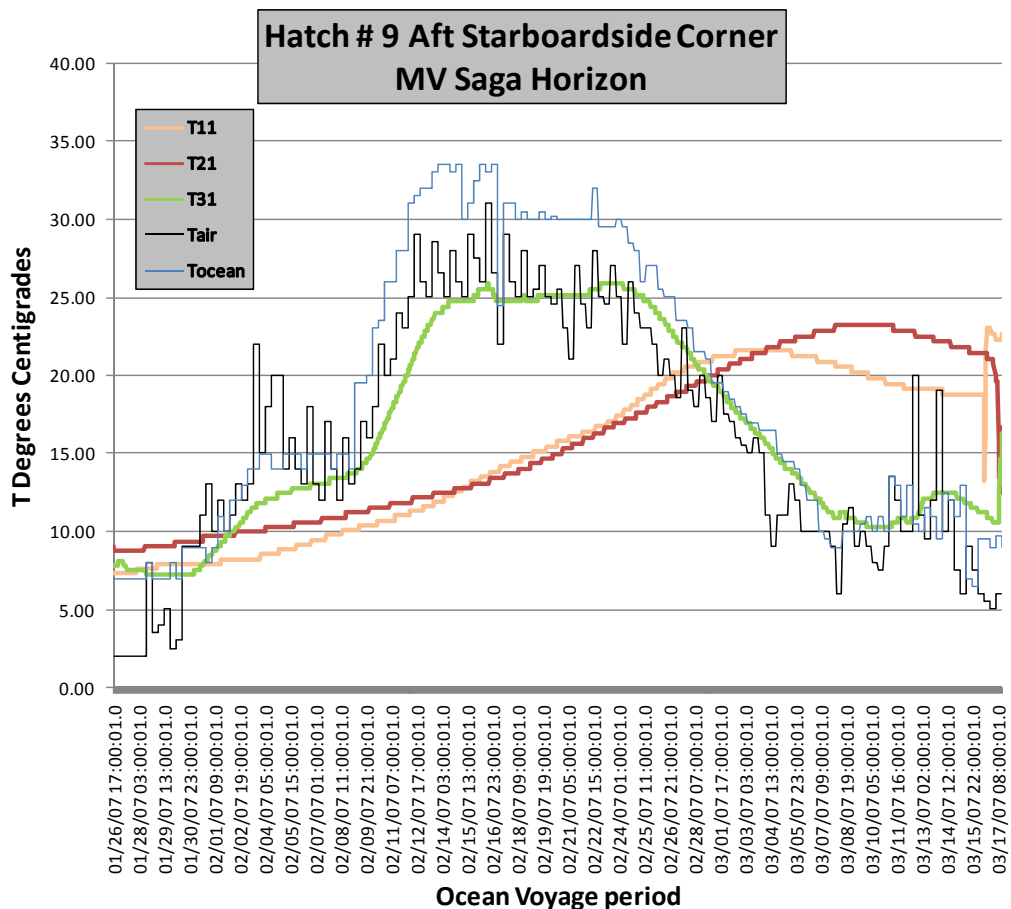
Graph 5.1.1

5.2 Aft Portside Corner Temperature Profile

The only difference between the following Graph 5.2.1 and Graph 5.1.1 is that the temperatures are approximately 4 ^{o}C higher, otherwise the dynamics is very similar. There is no apparent reason for this difference other than perhaps effects from the ballast tanks providing a thermal source

Hatch # 9 Aft Portside Corner MV Saga Horizon
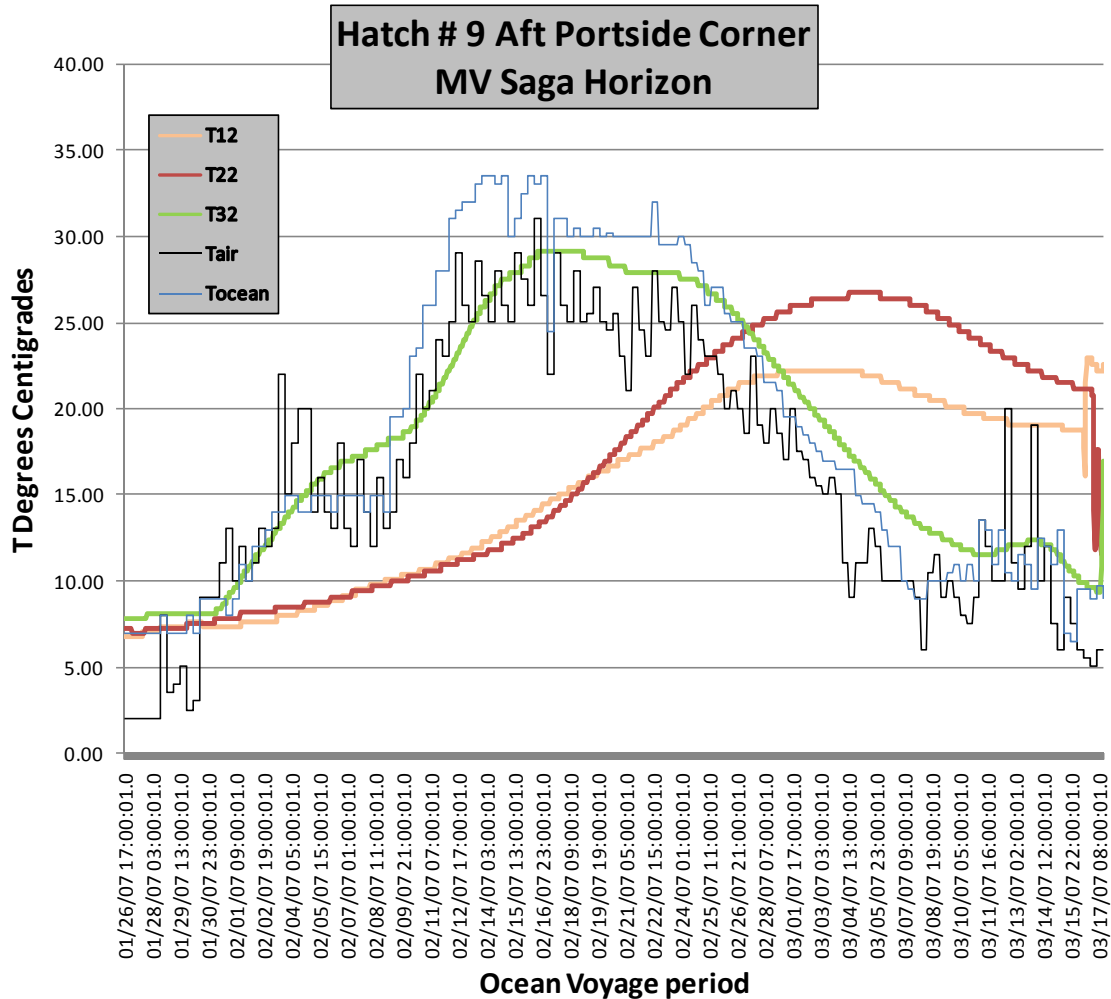
Graph 5.2.1

5.3 Forward Portside Corner Temperature Profile

Sensor T_{13} in Graph 5.3.1 at the 10 meter level was lost during the discharge operation. The other two sensors (T_{23} at the 5 meter level and T_{33} at the bottom) are neither tracking the T_{air} nor the T_{ocean} temperatures which is consistent with Graph 5.2.1. It is possible that the heat from fuel tank P3, located directly underneath this corner is the cause of the decoupling of the thermal tracking between the pellets and the water. This is the only temperature in the cargo hatch not tracking the water temperature.

Hatch # 9 Forward Portside Corner MV Saga Horizon

Legend:
- T13
- T23
- T33
- Tair
- Tocean

Y-axis: T Degrees Centigrades (0.00 to 40.00)

X-axis: Ocean Voyage period (01/26/07 17:00:01.0 to 03/17/07 08:00:01.0)
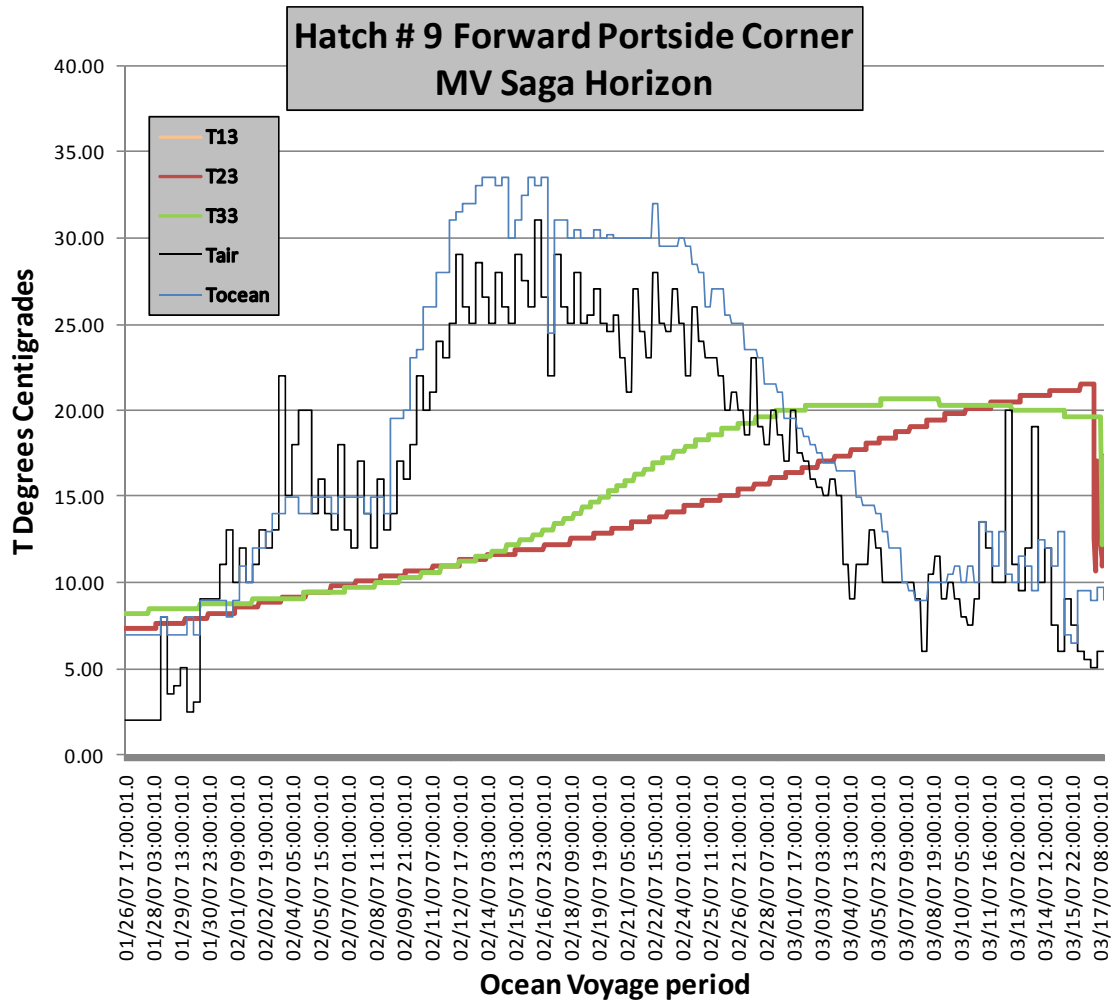
Graph 5.3.1

5.4 Forward Starboard side Corner Temperature Profile

The only difference between Graph 5.4.1and Graphs 5.2.1 is the substantially closer tracking by T_{14} of the ambient air T_{air} and ocean T_{ocean} temperatures. There is no apparent explanation for this except perhaps that this corner is on the south side when the vessel going in the easterly direction which means somewhat more heat exposure from the sun which primarily hits the pontoon hatch cover which may transfer heat to the upper level of the pellets. Both T_{11} and T_{14} on the Starboardside have more sun exposure than T_{12} on the Port side, particularly T_{14} considering the limited shadow from the gantry cranes when they are in the retracted position during ocean voyage as can be surmised from the picture on the front page of this Report of the vessel traveling in the easterly direction.
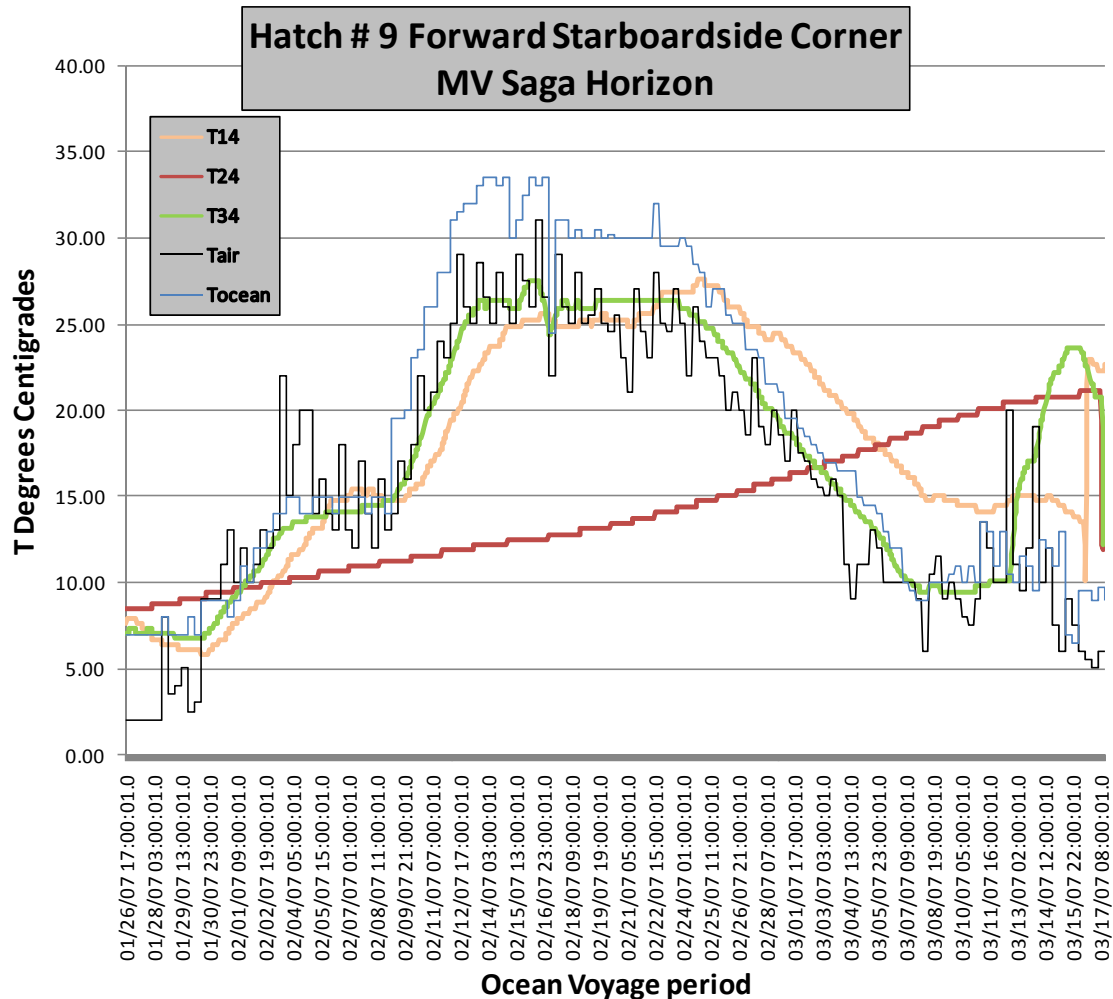
Graph 5.4.1

5.5 Hatch Center Temperature Profile

This graph is perhaps the most surprising since the conventional thinking is that the high center of a pile of pellets or biomass would always have the highest temperature. The sensor T_{35} indicates the highest temperature at the bottom, even higher than the ocean temperature T_{ocean}, which may indicate heat influx from the pipe duct running between the two skins of the vessel immediately under the center of the cargo hatch. There may also be some heat contribution from self heating although T_{15} at the 10 meter level indicate surprisingly low temperature in the event significant self-heating was taking place.
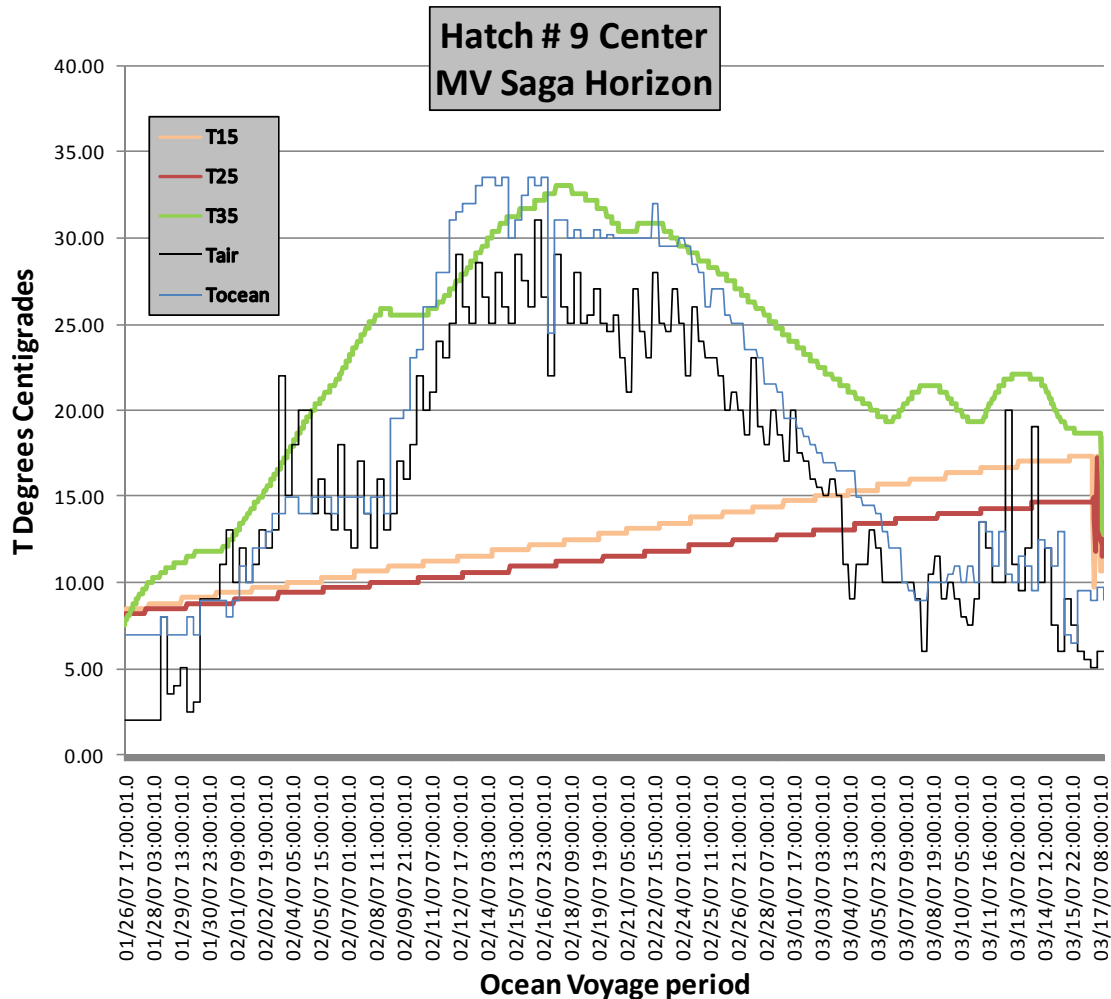
Graph 5.5.1

5.6 Center & Headspace Temperature Profile

The temperature sensors located on top of the pellets (T_{Rh1}) and in the cement hole of the pontoon (T_{Rh2}) in the headspace are primarily recording the impact of ambient air temperature T_{air} and the impact of exposure of the pontoon to the heat from the sun. As can be seen in Graph 5.6.1 both the T_{Rh1} and T_{Rh2} are tracking the air temperature very closely, with T_{Rh2} shooting over at occasions due to the enclosed position of the cement hole. In contrast, T_{15} at the 10 meter level is surprisingly low as already pointed out.
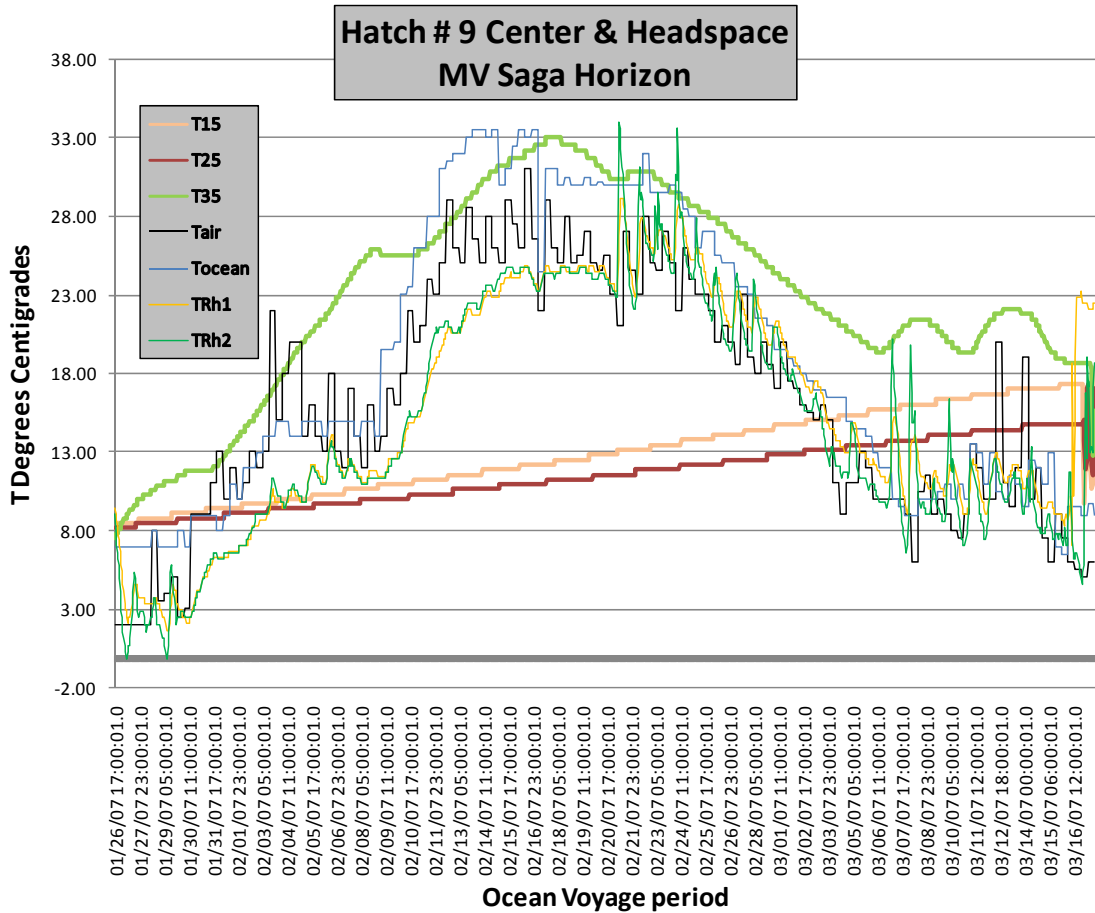
Graph 5.6.1

5.7 Discussion

The temp of the pellets in a cargo hold in a double skin vessel of type Saga Horizon is primarily affected by the ocean water temperature and thus somewhat dependent on the loaded draft (freeboard) of the vessel. Dependence on air temperature increases the more freeboard the vessel have

1. Variations of the temperature within a hold may depend on the exposure to the heat of the sun as well as ambient heat sinks such as ballast water in side tanks
2. The temperature at loading was only + 7 to 8 $^{\circ}$C for the shipment investigated. It is not clear from this investigation what the thermal dynamics will be if the starting temperature is substantially higher and the reactivity of the pellets is more pronounced.

6. Analysis of Gas Conditions in Cargo Hatch # 9

The gas conditions in the cargo hatch were measured throughout the ocean voyage with the intent to develop an understanding of the dynamics between oxygen CO and CO_2 as a function of temperature in the cargo hatch. The instrument used onboard the vessel was a multi-gas meter type ATX-620 from Industrial Scientific with the sensor arrangement as per Appendix E, section E.3.

As it turns out, there is a substantial communication of gas between the cargo hatch and the stairway as well as between the cargo hatch and the ambient air. The Report is making an attempt to quantify these intra-relationships in the following sections.

6.1 Impact of Atmospheric Conditions
The ocean vessel passed through several climatic and weather conditions during the voyage from Vancouver through the Panama Canal to Helsingborg. The variables include barometric pressure, relative humidity, ambient air temperature and ocean temperature. Even if the cargo hold was closed during a voyage there was communication (leakage) of air and gasses between the hold and the surrounding atmosphere. The "breathing" between the hatch and the surrounding ambient atmosphere as well as the leakage between the cargo hatch and the stairway is caused by;
- barometric pressure variations
- thermal expansion of the gases (primarily air)
- thermal convection inside the cargo hold and stairway
- changes in partial gas pressures as a result of chemical reactions in the pellets

It is important to estimate the amount of gas communication between the total containment surrounding the pellets under deck and the outside in order to understand how much the gas concentration is impacted and also to understand to what extent moisture from the ambient air may penetrate the pellets.

6.2 Leakage between Ambient Air and Headspace in Cargo Hatch
The first step when evaluating the leakage between the headspace and the ambient air is to determine how much gas is contained under deck at the time the cargo hatch and stairway are closed immediately after the loading. The second step is to estimate the amount of breathing as well as the direction of the breathing. To establish the gas balance we use the Gas Law by calculating the moles content in the under deck containment at each instance when measurements are taken and from there we construct a volumetric estimate of the air/gas flow which in turn is a measure of the dilution of the gas concentration in the containment.

It is assumed the pressure inside and outside the containment is equal since it is an open containment from a pressure standpoint communicating with the ambient conditions. To determine the gas flow in and out of the containment the thermal condition outside and inside needs to be established. The outside is represented by the ambient air pressure and temperature. The inside is more complex with a vertically and horizontally dispersed thermal profile. An average of all temperature sensor readings, including the headspace (16 in all with T_{13} sensor lost) are used in the calculations and is believed to be fairly representative. See Appendix C for calculation of the average temperature in the pellet pile.

As the ambient air temperature and pressure changes and the temperature in the containment changes, the gas is migrating in or out of the containment and can be quantified by the volume of moles. The migration rate is calculated based on the hourly data samples as increments of gas even though the flow is continuous between data points. An increase in the instantaneous moles count means an outflow of gas and a

decrease in the instantaneous moles count means an inflow of gas. Graph 6.5.1 shows the direction of the gas flow at every instance and Graph 6.5.2 illustrates the accumulated gas flow in each direction as well as the total accumulated bidirectional gas flow which essentially is a measure of the dilution of the gas in the containment.

In order to determine the initial gas (air) in the total containment as defined in Schematic 3.2.1, the void in the pellets needs to be calculated and subtracted. The headspace and the stairway are here included in order to determine the Total Space within which the gas is acting. Table 5.0.2 summarizes the values used in the calculations.

6.3 Calculation of the Void in the Wood Pellets
Total hatch volume = 5,523.7 m^3
Subtracted headspace volume at loading = 0.15*25.3*13.2 = 50.1 m^3
Volume of cargo in hatch at loading = 5,523.7 – 50.1 = 5,473.6 m^3

Due to the degradation of the pellets when going through the shiploader, the bulk density (751 kg/m^3) established by the lab at the time of the discharge is considered more representative. This corresponds to a specific density of the solids in the cargo hatch of around 1,332 kg/m^3.

Weight of pellets in cargo hatch = 5,473.6 * 751 = 4,110,674 kg
Solid volume of pellets = 4,110,674 / 1,332 = 3,086.1 m^3
Void in pellets = 5,473.6 – 3,086.1 = 2,387.5 m^3 (43.6 % of pellet volume)

Experimental determination of the void was done by Svedberg by means of evacuation of air from a cylinder (Picture 6.3.1) filled with wood pellets from the ocean vessel and subsequently refilled with air from an airtight syringe.

The void in the pellets were determined to be 50.7 % which is somewhat higher than the method established by determination of the bulk density by lab method as documented in Table 5.02 and calculations as documented above in this section. In principle, this method is more accurate since it also accounts for the porosity in the pellet material. However, it is uncertain how representative the relatively small sample is for the entire volume. For the purpose of this report we use a void estimate of 50.7 % (49.3 % solid volume). Based on this data the total gas volume underdeck may be calculated as follows:

16.54x25.3x13.2-0.493x(16.54x25.3x13.2-0.15x25.3x13.2) + 230 = 3,055 m^3

39
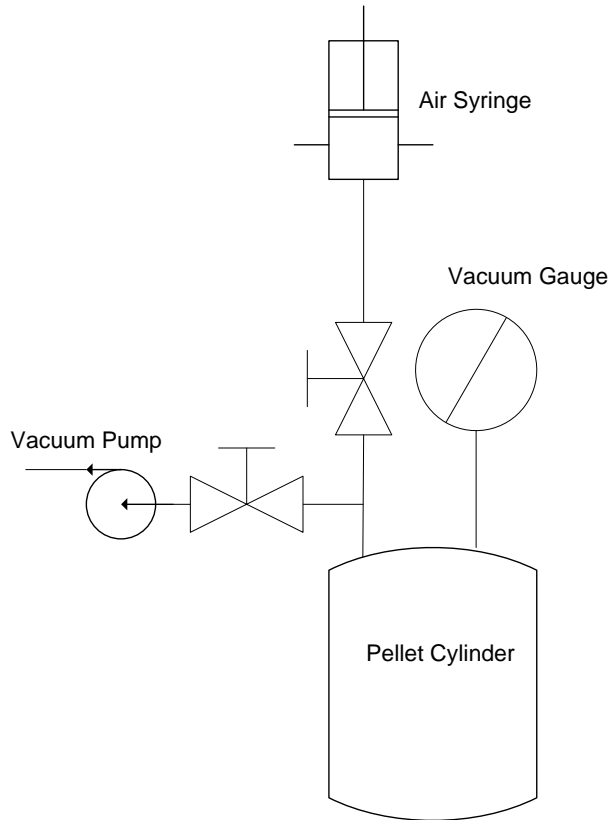
Picture 6.3.1

6.4 Calculation of Total Gas Containment Under-deck
Void in pellets = 2,387.5 m^3
Headspace volume at loading = 50.1 m^3
Total stairway volume = 230 m^3
Total Gas Containment under-deck = 2,387.5 + 50.1 + 230 = 2,667.6 m^3

6.5 Calculation of Dynamics in Total Gas Containment Underdeck
Application of the Ideal Gas Law allows calculation of the volume of gas in the total containment as follows;

Ideal Gas Law $\quad VP = nRT$ [formula 6.5.1]

$V = nRT/P$

where $R = 0.0821$ Liter atm mol^{-1} K^{-1}
$T = 273.15$ ^{o}K@ 0°C
$P = 1$ atm
V = volume in Liter
n = number of moles

$V = 1(mole)*0.0821*273.15/1 = 22.43$ L
1 Liter of gas contains 1/22.43 mole @ 0°C and 1 atm

At other temperatures and pressures the volume of gas per mole may be calculated as follows;

$$V_{mole} = 1(mole)*0.0821*T_P/P_P \qquad \text{[formula 6.5.2]}$$
$$V_{mole} = 1*0.0821*T_P/P_P$$
$$\text{where} \quad T_P = \text{prevailing temperature in } ^oK$$
$$P_P = \text{prevailing pressure in kPa}$$

Calculation of the dynamics in the gas under deck is illustrated in Appendix C and provides a measure of the amount of inflow as well as outflow of gas there is between the total gas containment under deck and the ambient air. The results of the calculations of instantaneous gas exchange are illustrated in Graph 6.5.1 below and indicate a relatively small but frequent flow.
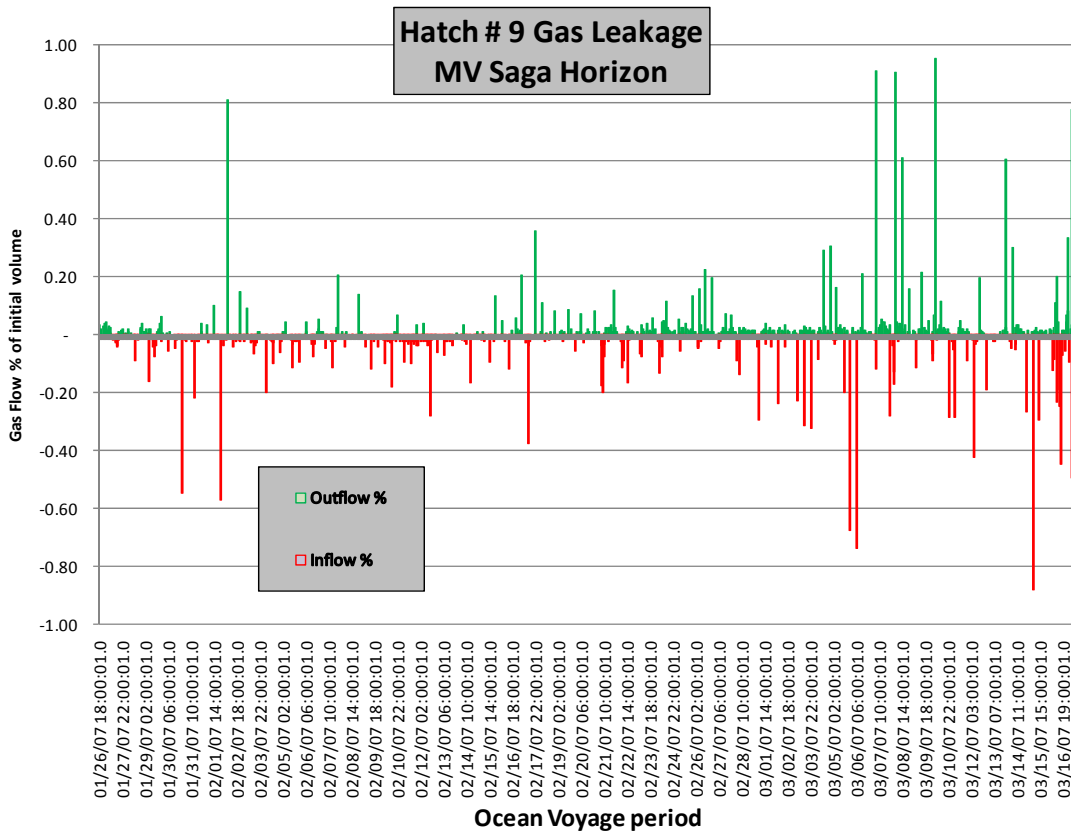
Graph 6.5.1

Quantification of the gas flow in moles of gas can be translated in to % of original gas volume at the time of loading in the total containment as indicated in the Graph 6.5.2 below. The cumulative dilution appears to approach 40 % of the initial volume contained under deck.

Graph 6.5.2
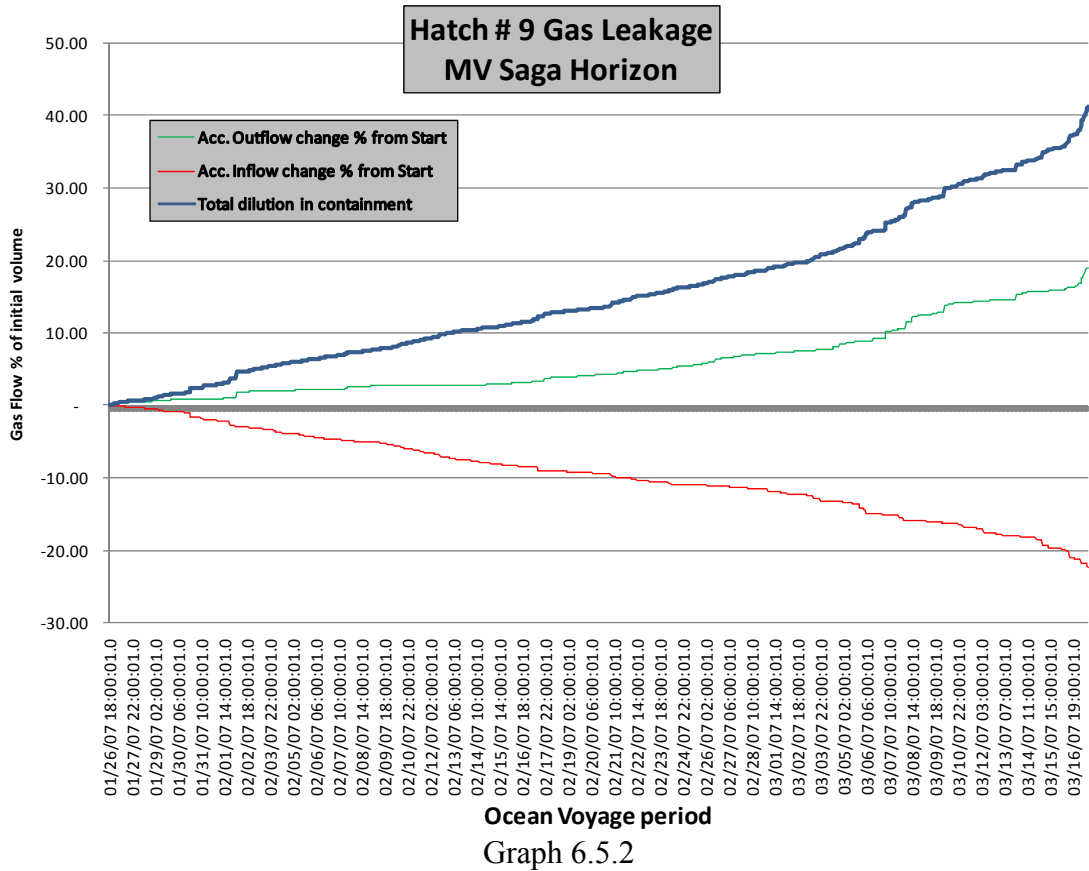
Besides the gas expansion induced by the pressure and thermal dynamics there is migration of gas as a result of the coupling (leakage) between the internal convection in the cargo hold and the movement of air (wind) outside on deck, even during time of thermal balance between the containment and the ambient condition.

6.6 Trace Gas

In order to determine the cause of the oxygen depletion in the cargo hatch, the leakage from the hold to the outside was quantified by means of trace gas injection. The depletion is a combination of oxidation and leakage. An exact volume of sulfurhexafluoride (SF_6) was injected as a trace gas immediately upon closing of hatch covers after completion of the loading. The injection was done at Sampling Panel A through the tube connected to the sampling points G_4 (bottom) in the cargo hatch. The assumption was made that the trace gas would diffuse evenly in the cargo hold. Measurement of the concentration of the trace gas was done immediately before opening the hatch cover at discharge.

Appendix B is illustrating the calculation of the initial trace gas concentration which was 882 ppm. The trace gas concentration measured with the FTIR immediately before discharge was 33 ppm at discharge immediately before the hatch cover was opened. This means that only about 3.7 % of the trace gas remained in the under deck containment.

Graph 6.5.2 indicates a dilution of 40 % of the underdeck containment based on barometric breathing alone. The low level of trace gas left indicate a much higher degree of ventilation taking place based on the estimation in Appendix B.3 which indicates a total dilution corresponding to approximately 3.3 times the total underdeck containment. These numbers should however be used with caution since little is known about the pattern of convection within the cargo hatch keeping in mind the complex combination of barometric breathing and thermal convection by means of leakage in the cargo hatch.

6.7 Gas Conditions Underdeck
The recorded data for the gas emissions during the voyage in the cargo hatch as well as in the stairway are considered to be too unreliable for closer evaluation with the exception of the oxygen. The sensors may have been affected by a combination of contamination (saturation due to the high concentration of certain gases such as CO), cross sensitivity between gases, calibration of the onboard instrument at a too low range etc. The evaluation is therefore limited to primarily the FTIR analysis of the gas sampled in the stairway immediately before the discharge of the pellets. The following concentrations were recorded by the FTIR;

Table 6.7.1					
Gas species	G_5 ppmv	G_6 ppmv	G_7 ppmv	G_8 ppmv	Mean ppmv
CO	11,485	11,444	11,527	11,511	11,492
CO_2	5,761	5,708	5,742	5,743	5,732
CH_4	185	183	184	183	184
Butane eqv	610	600	609	609	607
Oxygen %	4.9	4.9	7.5	4.8	5.5

The concentration of CO was expected to reach the range of 1,000 ppmv towards the end of the voyage. Already after only 3 days at sea the instrument registered over 900 ppmv in the upper section (sampling point G_2) of the pellets. The calibration curve for the onboard ATX-620 instrument is non-linear and was calibrated with a reference gas for 100 ppmv of CO at the time of the loading of the vessel. With no way of calibrating the instrument onboard at a higher range and 3 measurements per 24 hours the instrument appears to have become dysfunctional for CO measurements very quickly.

The CO_2 was measured by means of non-dispersive infrared absorption in the ATX-620 instrument and was calibrated with a zero-gas (20.9 % oxygen and 79.1 % nitrogen) at the time of the loading of the vessel. The concentration of CO_2 was expected to reach the range of less than 0.5 % (5,000 ppmv) towards the end of the voyage. The calibration curve for the onboard ATX-620 instrument is non-linear and was calibrated with a zero reference gas (20.9 % O_2 and the balance N_2) at the time of the loading of the vessel. The records from the sampling appear stochastic and unreliable and therefore only the FTIR data immediately before discharge of the pellets is used for the CO_2 evaluation.

6.8 Oxygen Conditions in the Stairway

The continuous gas measurements onboard the vessel with the ATX-620 instrument show a clear and rapidly declining content of oxygen on all levels in both the cargo space and the stairway. Graphs 6.8.1 shows the oxygen level in the headspace of the cargo hatch and the stairway and Graph 6.8.2 shows the oxygen concentration at the bottom of the cargo hatch and stairway.

The interesting aspect is the concentration differential between the cargo space and the stairway. Graph 6.8.3 shows a 4 % difference in oxygen content between the headspace (G_1) and the top of the stairway (G_5). A similar trend is observed at the bottom of the cargo hatch (G_4) and the bottom of the stairway (G_8) in Graph 6.8.4 although not as pronounced.

A steady-state of approximately 10% oxygen level was reach after approximately 3 weeks at sea. The initial difference between the oxygen level in the staircase and the hold can be interpreted such that about one week lag time exists between the two spaces, indicated as the horizontal distance between two equal concentrations at the beginning of the voyage. This also represents the time needed for a sealed staircase to be naturally ventilated to a safe level after that the cargo hold has been emptied.

Graph 6.8.1

Hatch # 9 Oxygen Concentration
MV Saga Horizon

Graph 6.8.2

Hatch # 9 Oxygen Migration
Stairway headspace (G5) towards Hatch headspace (G1)
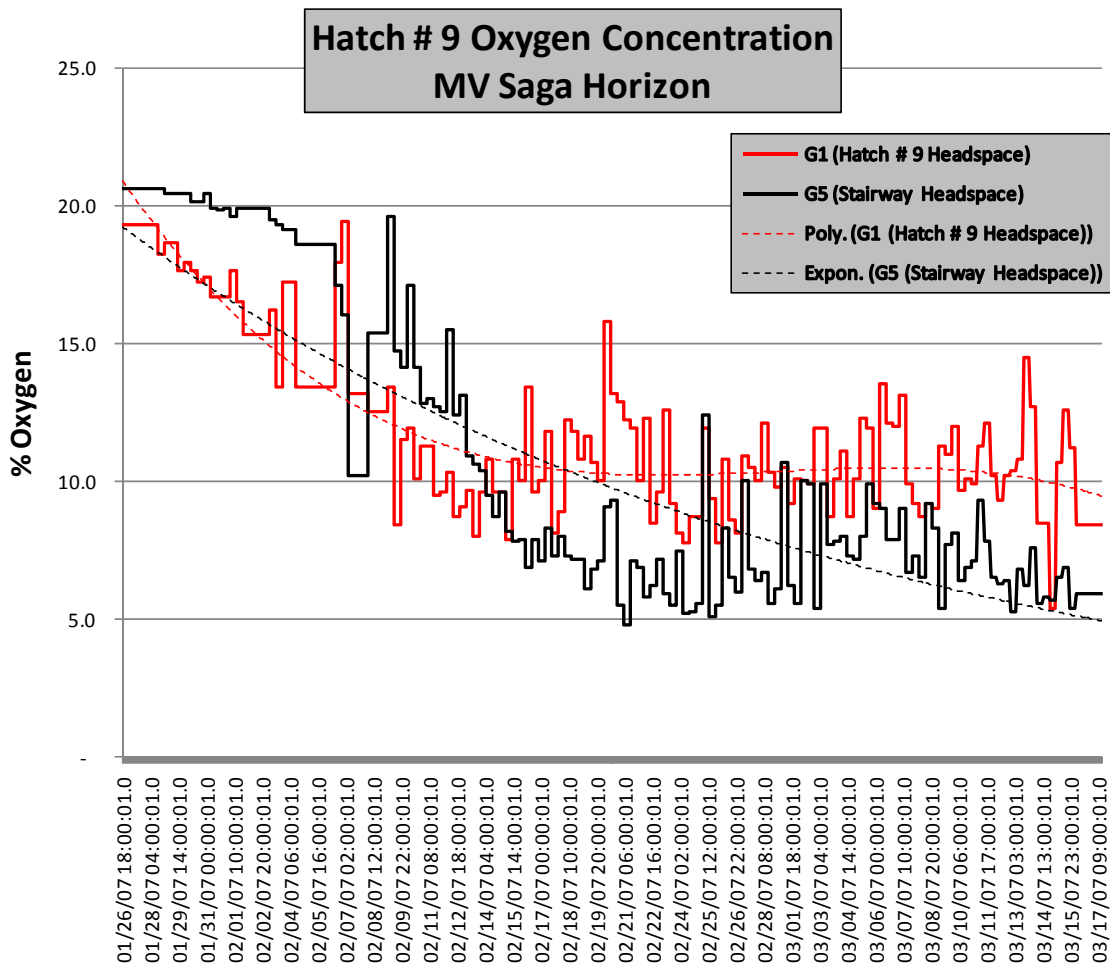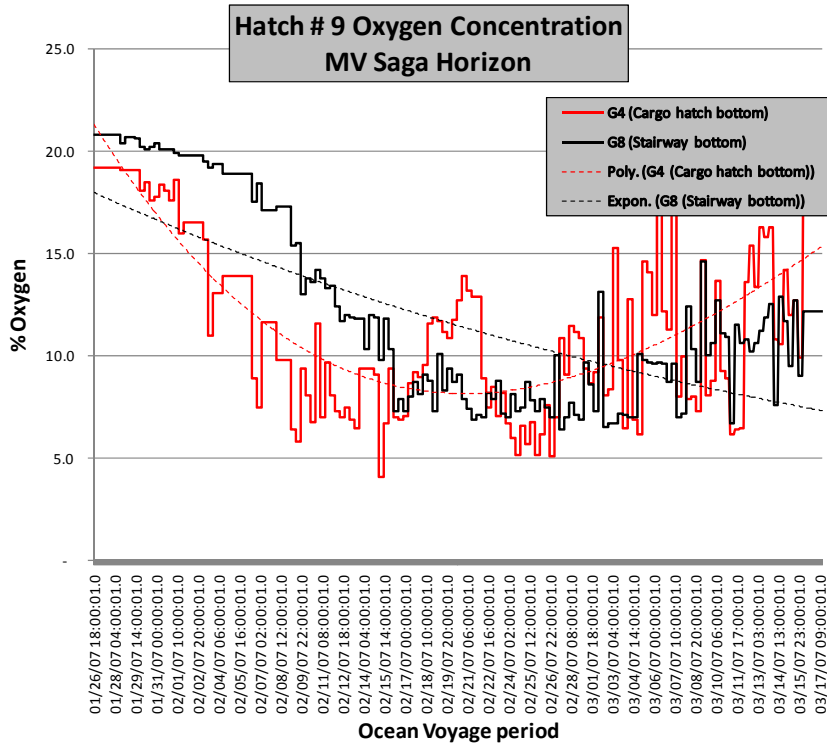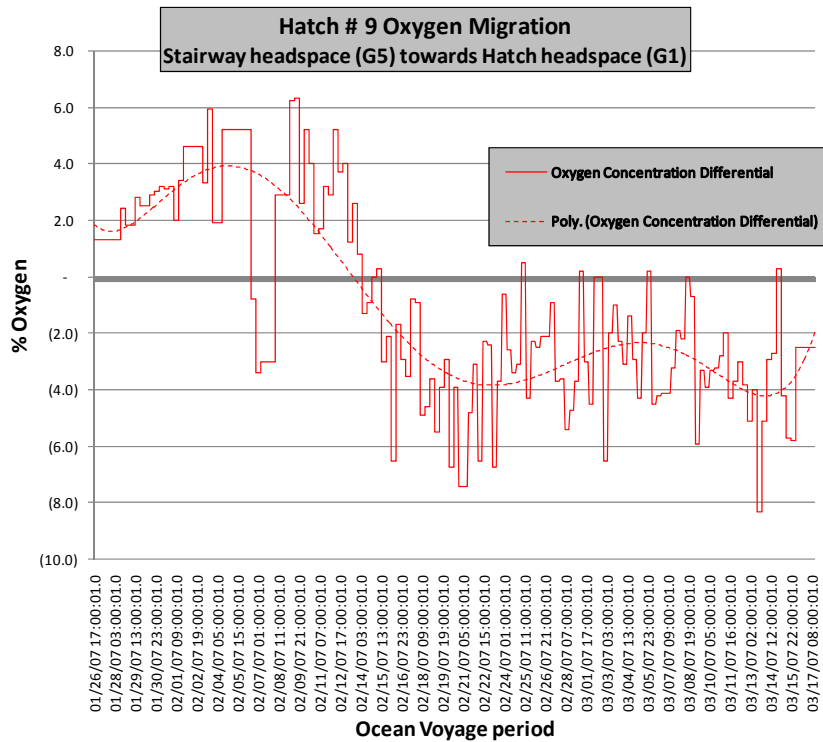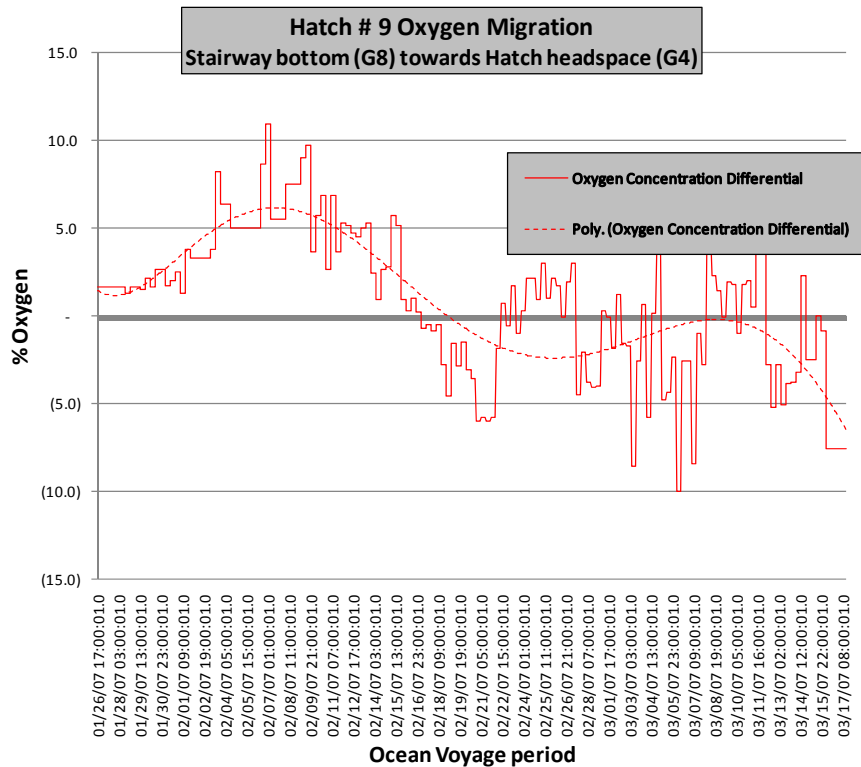
Graph 6.8.3

Graph 6.8.4

The cargo space and the stairway are physically separated although the separation is not gas-tight since some leakage can be expected through the rubber seals of the three access doors from the three platforms in the stairway. Oxygen depletion in an empty space is often an indication of chemical reaction such as rusting. Inspection of the stairway at the time of the installation of gas tubes did not uncover any rust spots or degraded paint anywhere in that space. Due to the close tracking of the oxygen depletion in the two spaces it is assumed there is communication between the two.

6.9 Carbonmonoxide (CO) Conditions in the Stairway and Ventilation
While the ship was unloading in Helsingborg, the decay of the CO in point G8 was monitored over 2 hours. The sample air was pumped to the mobile FTIR unit beside the ship. Initially the staircase door was closed and almost no decay could be seen, the first flat part of the log-linear plot in Graph 6.9.1 based on FTIR data. The staircase cover was then removed and a decay corresponding to a ventilation rate of 0.23 air volumes per hour was measured. The log-linear behavior of the decay indicates that mixing ventilation exists and that first-order kinetics can be applied to the calculations. This ventilation rate represents all natural ventilation without mechanical assistance. The results show that, in order for the CO concentration at the bottom level to reach the Swedish acceptable 8-hour occupational exposure limit of 35 ppm, 26 hours of ventilation is required.

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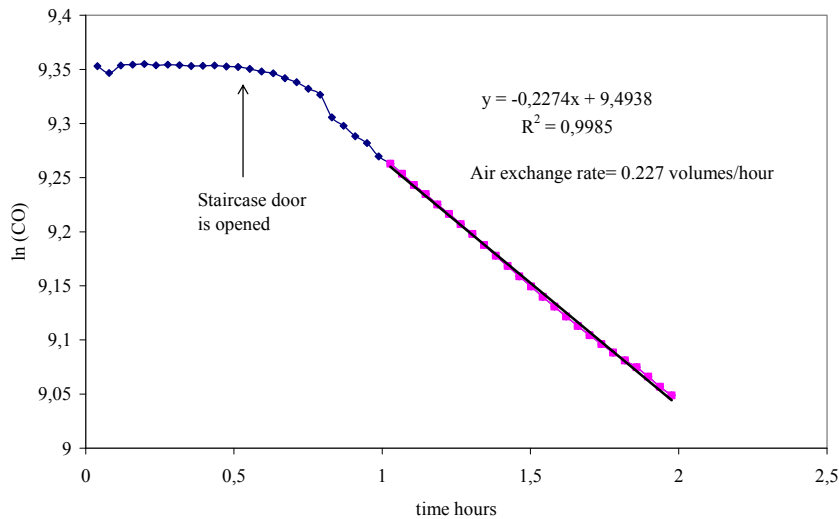
Graph 6.9.1

6.10 Ambient Air Moisture Considerations

As can be seen in Picture4.6.1 there is a thin veil of moist wood pellets at the very top in the hatch. Experience from the past with other shipments to Europe is that this layer may be substantially thicker, in some cases up to 10 cm and with clear drip lines (see Picture 6.10.1). Similar layer have been observed also in rail cars arriving at the loading terminal.

Picture 6.10.1

It has been thought that the phenomenon has been caused by moisture coming from the pellets or from outside but no clear understanding has been developed. Based on the findings during the EWDOT Project the following has been proven;

- there is a substantial exchange of gas between the cargo space and the ambient air as discussed in section 6.5
- the relative humidity in the ambient air is quite high during part of the ocean voyage while the humidity (water vapor) in the cargo space is low

- the temperature fluctuations within the cargo hatch in the top layer of the wood pellets are relatively small compared to the fluctuations of the temperature in the ambient air
- the water vapor content of the ambient air leaking in to the cargo space (as per the red curve in Graph 6.5.2) for cargo hatch # 9 onboard Saga Horizon was generally high throughout the voyage (see Graph 6.10.4 below), often twice as high as the cooler gases in the cargo hatch and higher than what can be sustained in vapor form without precipitating water droplets (dew).

It is known that warmer air can contain more water in vapor form than colder air. The amount of water vapor held is measured as Specific Humidity (S_h) and the maximum value is reached when precipitation (dew) is beginning to develop and is called the Saturation Specific Humidity (SS_h). Both S_h and SS_h are specified in gram H_2O_{vapor}/kg air. The ratio S_h/SS_h is called Relative Humidity (R_h) and is specified in percent. Graph 6.10.2 below is illustrating the SS_h at various levels of R_h as a function of temperature.
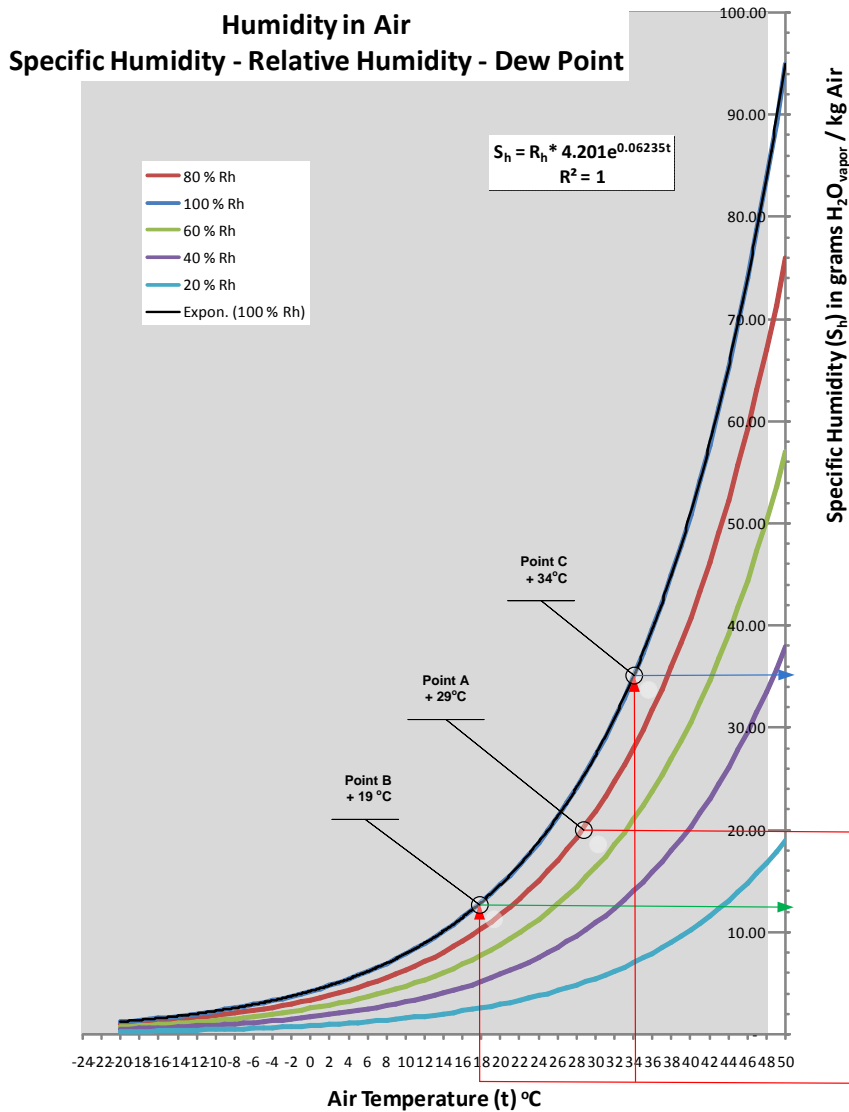
Graph 6.10.2

As the relative humidity decreases, so does the SS_h and the dew point temperature. The pointers in the Graph illustrates what happens with the water vapor (humidity) if air with a relative humidity of 80 % at a temperature of $+ 28.5^oC$ (point A in Graph 6.10.2), corresponding to a Specific Humidity 20 gram/kg air, ingress in to a space with a temperature of $+18^oC$ (see point B), corresponding to Specific Humidity of 13 gram/kg air (green arrow). The receiving air volume becomes saturated and is shedding water vapor as dew in the amount of 6 gram/kg air. In fact, the saturation point is reached even sooner if the receiving space already has a level of air including water vapor. Another scenario illustrated in the Graph is assuming ingress of air in to a space with a temperature of $+ 34^oC$ (see point C), corresponding to Specific Humidity of 35 gram/kg air (blue arrow). In this case the receiving space can hold more water vapor than comes through the ingress from the somewhat cooler air and the dew point is never reached unless the receiving space already has water vapor in which case dew may be generated if the saturation point is reached. The following formulas define the process of dew precipitation.

$S_h/SS_h = R_h*100$ (%)

$S_h = R_h*4.201*e^{0.06235t}$ (gram H_2O_{vapor}/kg air)

$SS_h = (100/100)*4.201*e^{0.06235t}$ (dew point)   (gram H_2O_{vapor}/kg air)

S_h(hatch) + S_h(air ingress) > SS_h@ R_h=100%   (dew point condition)

$t = \ln(SS_h/0.06235)$ (dew point temperature)   (^oC)

The humidity sensors Rh_1 and Rh_2 are both located in the center of the headspace, relatively far from the points of leakage and none of those two sensors are recording temperatures close to the dew point temperatures at any time during the voyage. It should be noted that humidity sensors are not reacting to dew (condensed water), only to water vapor. The moist air leaking in to the cargo hatch is likely reaching saturation resulting in dew before affecting the centrally located sensors and appears as a veil (thin moist layer) at the top of the pellets. In addition, the moisture sensors are logging only hourly averages and the air leaking in to the cargo hatch is likely turbulent and mixing with dry air convecting from within the pellets which tend to mask bursts of potentially saturated air passing by the sensors.

It should be pointed out that the data available from the EWDOT Project does not allow an accurate evaluation of the quantitative precipitation of dew. The discussion is merely intended to explain the phenomenon of moisture accumulation in the headspace. Graph 6.10.3 is illustrating the frequency of dew point instances in the cargo hatch based on R_h in the air during ingress as illustrated in Graph 6.5.1.
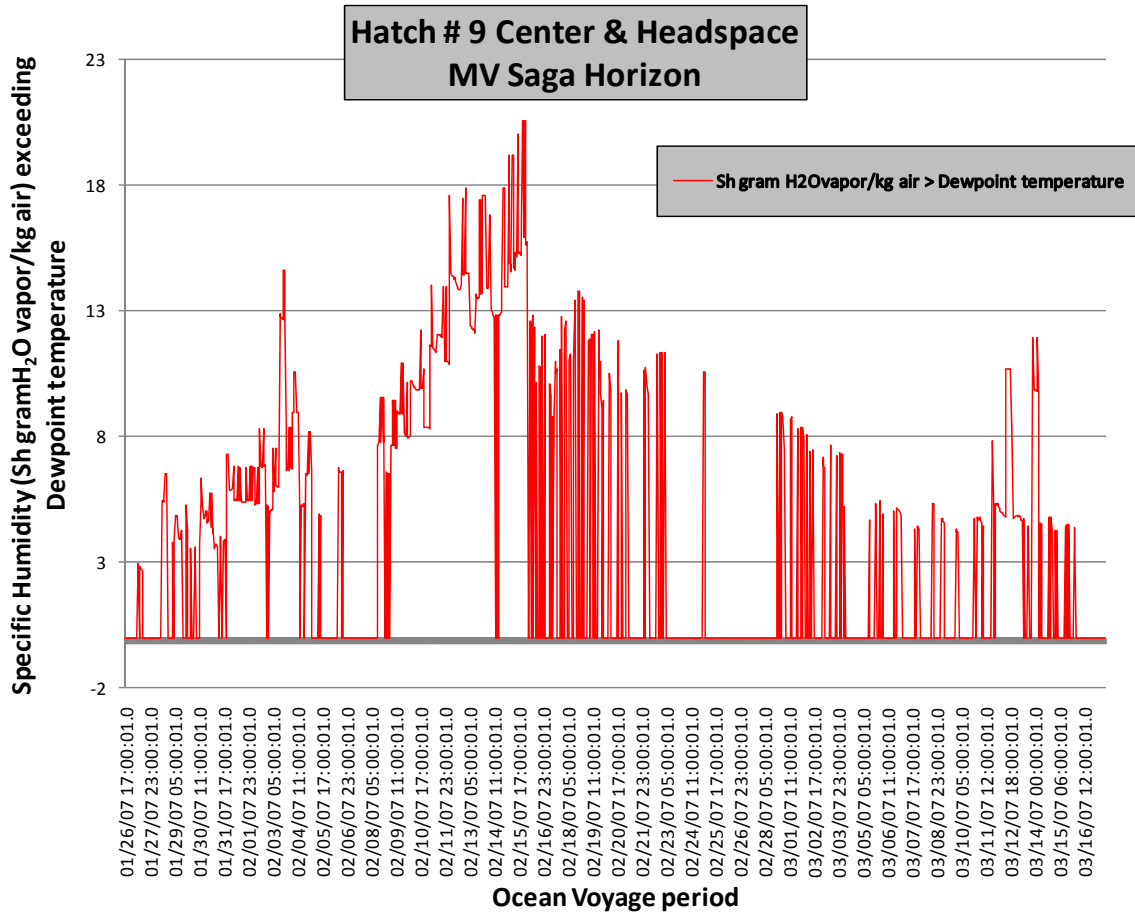
Graph 6.10.3

Based on the barometric breathing alone as illustrated in the above Graph 6.10.3 the accumulated amount of dew (S_h @ R_h=100%) can be calculated as 4,696 gram H_2O vapor/kg air during ambient air inflow conditions. Adding about 50 % of the additional leakage due to convection, the total amount of dew during the voyage is likely in the range of 7,000 gram H_2O_{vapor}/kg air. The average headspace air volume estimated as 25.3m*13.2m*0.6m = 200 m^3. The weight of air is approximately 1.293 kg/m^3@NTP. Total precipitated dew can be estimated as

$$200m^3*1.293kg/m^3*7,000 \text{ gram/kg} = 1,806,000 \text{ gram} \sim 1,800 \text{ kg}$$

The pellets penetrated by the dew will dissolve to a varying degree. The top layer may absorb almost all the dew until the dissolved pellets are saturated with water after which the moisture is creeping further deeper down in to the cargo. The saturation point for the pellets and the depth of the penetration are not known but it is estimated that a moisture content above 15 % cause a gradual swelling and will over time partially dissolve the pellets. It is know from the pelletizing process that a pellet with more than 12 % will not hold together over time. A rough calculation of the resulting moisture content in the 5 cm top layer of the pellets gives us an indication of the level of degradation of the mechanical integrity of the pellets due to exposure to dew.

751 kg/m^3*5.8 % = 43.56 kg H$_2$O/m^3 (water content in pellets)
25.3 m*13.2 m*0.05m = 16.7 m^3 (selected top 5 cm layer)
1,800 kg/16.7 m^3 = 107.8 kg H$_2$O/m^3 (dew)
x %*(751 + 107.8) = 43.56 + 107.8
x ~ 18 %

The estimated 18 % moisture content in the top 5 cm of the pellets (see Picture 3.4.1) will cause softening of the surface of the pellets across the cargo hold as indicated by the veil in Picture 6.10.1. This softening is impacting the durability of the pellets during handling. It should be noted however that the above calculations are only indicatory.

Assuming an even distribution of the dew across the surface of the cargo yields an estimate of the wetting of the pellets as follows;

The correlation between the relative humidity in the ambient air and the relative humidity as recorded by the two humidity sensors are not very strong which is consistent with discussion above. It is further consistent with the absence of correlation between the average temperature in the pellets and the ambient air temperature. The water vapor in the incoming air is precipitated as dew in the top layer of the pellets before penetrating the humidity sensors.
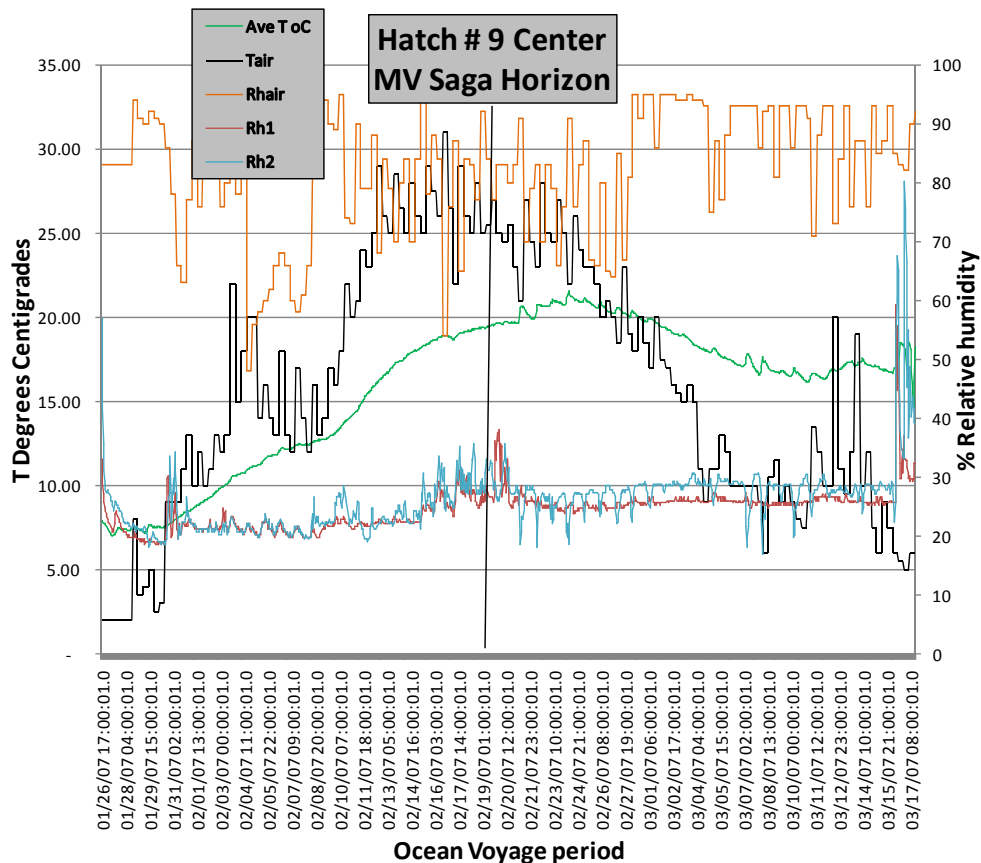
Graph 6.10.4

6.11 Discussion

The impact of ambient air conditions during ocean voyages on the cargo has not been described in the past and is an important consideration with a product such as wood pellets which in it's present form is hydrophobic and prone to chemical and physical decomposition. Collection of some of the data in the EWDOT Project was intended to explain some of the phenomenon observed during ocean transportation and provide direction for more detailed research.

Leakage between Ambient Air and Headspace in Cargo Hatch
The accuracy in the evacuation determination according to Svedberg depends to some extent upon how representative the sample is of the total volume in the cargo hatch. The accuracy in the geometric determination described in section depends to some extent upon the accuracy in the lab test of bulk density and the accuracy in the subtracted volumetric estimation of the headspace.

Trace Gas
The method of using a trace gas in this project was intended to provide a method of quantifying the leakage between the cargo underdeck space and the ambient atmosphere and if possible to segregate the effects of forced barometric breathing from convection. It appears as if this objective was met, at least in terms of the ratio between the two phenomena.

Leakage between Cargo Hatch and Stairway
It is obvious by all accounts that gas is leaking between the cargo space and the stairway. However the apparent higher concentration in the stairway is somewhat difficult to explain. The systematic differential in the concentration could have been caused by leakage in the tubing to the instrumentation.

Gas Conditions in Cargo Hatch
It appears as if electrochemical sensors may not have been the best choice in the unexpectedly high gas concentrations. It is recommended for future research to use for example an FTIR instrument in a loop, preferably with automatic logging, in similar projects. Another approach would be if onboard researchers are available in which case sampling of gas by syringe and analysis using a micro-chromatograph may be an alternative.

Moisture Condensation in Headspace of Cargo Hatch
Condensation of water vapor in the top layer of the pellets has been a mysterious problem for years and has in some cases caused rejection of hundreds of tonne of pellets in the discharge port. The modeling develop in this report provides and explanation and predict the potential for avoiding condensation to occur by fairly simple methods of monitoring temperatures and humidity in combination with controlled ventilation.

Similar phenomenon of a moist veil at the top of the pellets has been observed in storage silos and inside the rail cars loaded in the interior of British Columbia destined to the

much cooler Pacific Coast loading terminals, particularly during summertime. The relatively warm weather in the interior holding a relatively medium level of relative humidity is precipitating dew when the cooler air is penetrating the inside of the rail cars during night and when reaching the coast.

7. Proposed Future Research

Several areas requiring further research have been identified throughout the EWDOT Project. Most of this research would be suitable for undergraduate, graduate as well as more comprehensive post-doctoral research in a university environment in close collaboration with the industry. Projects of this nature are very difficult to conduct strictly in a laboratory environment and represent an excellent opportunity to expose students to real world issues before entering the workforce.

Another industrial scale on-board project similar to the EWDOT Project would be of value if conducted during another season and under other climatic conditions. For example, loading under hot conditions and following the thermal dynamics when entering tropical conditions would be very valuable in view of past experience with large shipments arriving in European ports with significant damage on the pellets from water condensation in the headspace. This mechanism is not totally understood. Such project could be structured very similar to the EWDOT Project which would have additional benefits in terms of verification of many of the concepts developed as a result of EWDOT such as the barometric breathing, effusion between communicating spaces etc.

Research is under way at University of British Columbia (UBC) which will follow the feedstock material from the source, through the manufacturing all the way to delivery in bulk to end user. The cargo hatch onboard an ocean vessel is in many ways very similar to a large scale reactor. The same is true for large scale storage silos. The research completed under the EWDOT Project will augment the information currently gained from the controlled reactor experiments with wood pellets at UBC which are intended not only to define the off-gassing but also to create an understanding of the physico-chemical processes going on in the pellets and how to control these processes.

Appendix F. is listing some of the potential research projects which have been discussed in the context of the EWDOT Project.

8. Conclusion

The results from the EWDOT Research Project can be summarized as follows;

- emission of primarily carbonmonoxide (CO) is substantial and much higher than expected
- depletion of oxygen (O_2) is also much more severe than expected
- established operational procedures when accessing cargo space and communicating spaces such as stairways after the spaces have been sealed for only a few days has to be strictly enforced in order to avoid accidents
- self-ventilation of stairways before entry is not sufficient due to very low circulation through the hatch access door. Gas conditions in such spaces have to

be tested both for oxygen and carbonmonoxide. Oxygen metering alone is not sufficient to establish safe conditions for entry and nor is carbonmonoxide metering due to the limitation of time for a vessel when in port, it is essential to have forced ventilation in such spaces prior to entry during discharge, preferably from the bottom up since the CO is similar in weight to air and CO_2 is considerably heavier than air and may accumulate at the bottom without too much upward movement without forced circulation. An alternative to consider is to have continuous forced ventilation of stairway spaces during time at sea when the cargo hatch is sealed and leaking gas in to the stairway space. The slow decay rate of the toxic levels in the staircase, even after opening the staircase cover, is a verification of the importance of using a mechanical ventilation system to rapidly reach safe entry conditions. Since the passage way to the staircase is narrow and quite obstructed (Picture 3.3.2), a strong recommendation is that the process of ventilating the staircases is done by an automatic remote control system where the O_2 and carbon CO are monitored. The practice used today on the investigated ships was to position a fan close to the manhole and lowering a flexible ventilation duct through the manhole. On the one ship were we observed this task being carried out, it was clear that the crew was unaccustomed to the procedures and had difficulty to carry out their task, due to inappropriate, heavy and bulky equipment and very tight working space. The time needed to clear the toxic gases throughout the entire staircase volume was unknown to the crew. The oxygen measurements were carried out by the crew by lowering a meter to the top floor level. Ventilation of the bottom levels could not be done until the top level was cleared. Pockets with toxic concentrations may still exist and be released in a previously cleared work space. This again points to the need of a well-designed mechanical ventilation system that clears the entire space safely. A mechanical ventilation system should not need to run throughout the voyage but could be started during unloading, When it is time to enter the staircases, they are already safe, without loss of time

- communication of gas between the cargo hatch and the related stairway is much higher than expected
- as established by other recent research focused on other wood based commodities such as pulp logs and wood chips the CO concentration may be quite low but the CO_2 concentration may be extremely high (3 – 15 %) in combination with almost complete oxygen depletion. This presents another scenario for accidents which again confirms the requirement for simultaneous measurements of CO and O_2 concentrations before entry
- further investigation needs to be conducted to establish why the electrochemical gas meter did not provide correct readings of concentrations. Could it be due to leakage in the tubing for sampling or could it be due to contamination of sensors by high concentrations of gases?
- thermal dynamics in the cargo hatch is primarily dependent upon the ocean water temperature and not the air temperature as previously thought
- breakdown of the surface layer of the pellets in the cargo hatch as a result of moisture absorption is caused by ingress of moist air in to the headspace from ambient air. This Report is proposing a model for quantifying such impact. The

tighter the hatch cover the less ingress of moist air from outside caused by convection. Barometric breathing is not possible to avoid

- the high fines content at discharge is likely caused by shiploader in the loading port

-

Appendix A.

A.1 Chemical Analysis Specification for Wood Pellets

The following Table A.1 is summarizing the wood pellets parameters analyzed.

The same laboratory was conducting the analysis of the samples collected from the loading and the discharge in order to eliminate variations from differences in lab routines and instrumentation.

Table A.1					
#	Parameter	Measure	As received	Dry basis	Analysis Standard
7	Total Moisture	% of weight	X		CEN/TS 14774-1
8	Particle or pellets size	% of weight	X		CEN/TS 15149-1,2
9	Mechanical durability	% of weight	X		CEN/TS 15210-1
10	Bulk density	kg/m^3	X		CEN/TS 15103
11	Specific density	kg/m^3	X		CEN/TS 15405
12	CHN composition	% of weight		X	CEN/TS 15104
13	Total Ash	% of weight		X	CEN/TS 14775
14	Fines	% of weight	X		CEN/TS 14961
15	Fractional size distribution of material in pellets	% of weight		X	CEN/TS (under development)
16	Gross calorific value	GJ/tonne	X	X	CEN/TS 14918
17	Net calorific value @ constant pressure	GJ/tonne	X	X	
18	Net calorific value @ constant pressure, ash free	GJ/tonne		X	

Request for Analysis Reports should be directed to Premium Pellet Ltd as the manufacturer of the pellets.

Appendix B.

B.1 Application of Trace Gas
A chemically stable trace gas was injected in to the cargo hold immediately upon completion of loading (see section F.6). The gas had the following characteristics;

       Sulfurhexafluoride SF_6
       CAS = 2551-62-4
       Class 2.2 UN1080
       Purity = 99.9 %
       ACGIH TLV = 1000 ppmv in air
       Inert
       Colorless
       Odorless
       Non-combustible
       In-solable in water in pure form
       Molecular (formula) weight = 32 + 6*19 = 146 amu
       Well separated spectral line
       Manufacturer; Praxair Canada Inc.

B.2 Calculation of Initial Trace Gas Concentration
SF_6 = 17.24 kg injected (17,240 g)
Moles = 17,240/146 = 118.0822
$V_{SF6} = n*0.0821*T_{PC}/P_{PP}$
T_{PC} = +281.10 °K
P_{PP} = 1.0116 atm

       V_{SF6} = 118.0822*0.0821*281.10/1.0116
          = 2,693.89 Litre (SF_6)

Concentration of SF_6 in the total containment under deck immediately upon injection;

       (2,693.89/3,055,000)*100 = 0.088179 % = 882 ppm SF_6 in total containment
          where 3,055,000 m^3 is the total gas containment under deck (see section 6.4)

Picture B.2.1 below illustrate the cylinder with SF6 at Sampling Panel A where the gas injection was done through the tubing to Gas Sampling Point G_4 at the bottom of the cargo hatch. As the cylinder was emptied the gas pressure decreased and the liquid gas gradually converted to gas which consumes heat and caused ice to form on the outside of the cylinder.

Picture B.2.1

B.3 Estimation of Air Exchanges

In an attempt to establish the air exchange rates in the hatch during the voyage of Saga Horizon, a tracer gas, 17.24 kg sulfur hexafluoride (SF_6) was distributed through sampling point G4 into the cargo after loading. Assuming that SF_6 spreads evenly in the hatch and staircase (total volume 3,055 m^3 based on void volume determined by vacuum method), an initial concentration of 882 ppm is calculated. A residual concentration of 33 ppm was recorded at the time of unloading. Provided that there is good mixing of the air,

the tracer gas decays exponentially over time, Graph B.3.1. The air-exchange rate (N) is given as:

N= $(\ln C_0 - \ln C_t)/t$

where; C_o is the concentration at the time =0, C_t is the concentration at time = t, and t is the time between C_t and C_o.

Assuming an exponential decay, the air exchange rate in the cargo hatch was 0.00274 air volumes per hour. The total time of the voyage was 50 days or 1200 hours. The total air volume ventilated during the voyage is given by the product of the air exchange rate, air volume and time (0.00274 x 3,055m^3 x 1200h) = 10,044 m^3 or ~3.3 air exchanges during the voyage.

If, and to what degree SF$_6$ binds to the wood structure, dissolves in the water or lipid phase, still needs to be confirmed by laboratory studies. Pending those results it is assumed that SF$_6$ disappeared through a ventilation process. The ventilation rate also affects the concentration of CO. However, since CO is generated continuously and the ventilation rate quite low, CO is allowed to build up to high concentration levels.
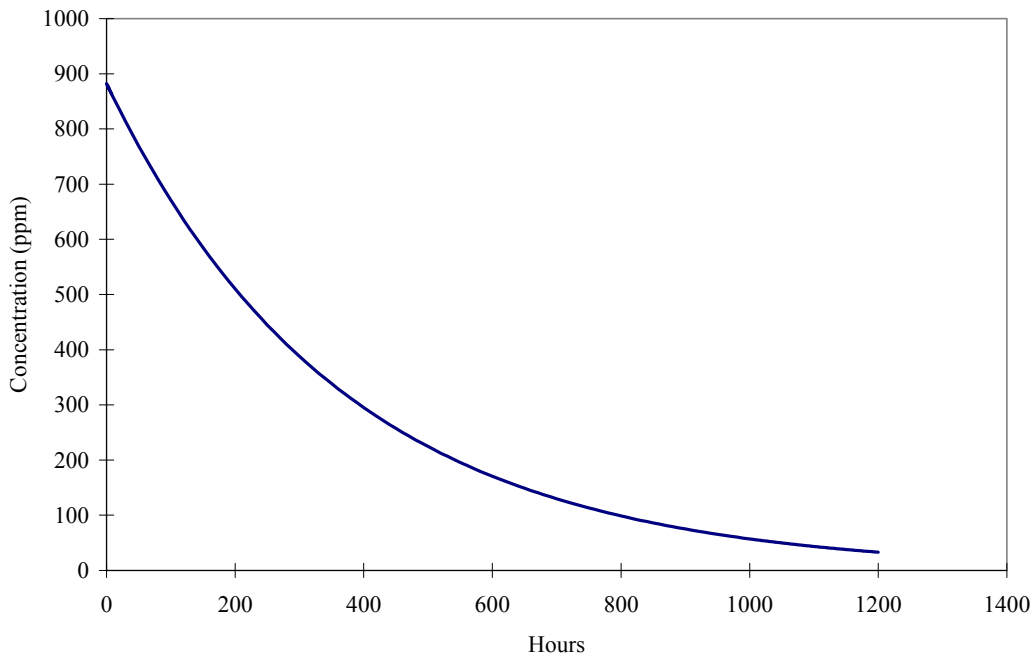
Graph B.3.1

Appendix C.

Calculation of Mean Temperature in Underdeck Containment

Table C.1 illustrates the calculation of the average temperature in the pellets pile immediately upon closing the hatch covers after completion of the loading (January 26, 2007 @ 17.00 o'clock). For illustration purposes the temperature for February 17, 2007 just before the vessel entered the Panama Canal has been included as a contrast.

Table C.1			
Temperature sensor	^{o}C Jan 26, @ 17.00 o'clock	^{o}C Febr 17, @ 05.00 o'clock	^{o}C Febr 17, @ 06.00 o'clock
T11	7.36	13.82	13.92
T21	9.04	13.38	13.38
T31	7.86	24.75	24.74
T12	6.75	14.44	14.44
T22	7.29	13.74	13.74
T32	7.83	29.09	29.09
T13	NA	NA	NA
T23	7.33	12.22	12.22
T33	8.16	13.08	13.08
T14	7.63	25.60	25.21
T24	8.52	12.82	12.82
T34	7.04	24.82	24.44
T15	8.23	12.22	12.22
T25	8.17	10.92	10.92
T35	7.57	32.61	32.61
T_{Rh1}	9.42	23.24	23.24
T_{Rh2}	9.03	23.24	23.24
Average temperature T_{PC} ^{o}C	7.95	18.07	18.71

The following Table C.2 illustrates the principle used in the calculations of the breathing of gas in and out of the containment.

The number of moles in the gas in the total containment as well as the incremental change as the prevailing conditions change are included. The volume for Total Containment underdeck used in the calculations is 3,380.4 m^3 = 3,380,400 Litre (see section 6.4).

The cumulative change is the summary of all the incremental changes occurring from the time of the loading to the time of discharge of the pellets.

The results from the calculations are illustrated in Graph 6.5.1 of this Report.

Table C.2			
	Jan 26, @ 17.00 o'clock	Febr 17, @ 05.00 o'clock	Febr 17, @ 06.00 o'clock
Starting T_{PC} ^oC	+7.95	-	-
Starting T_{PC} ^oK	+281.10	-	-
Starting Air Pressure kPa	102.50	-	-
Starting Air Pressure atm	1.0116	-	-
Starting $V_{mole}=1*0.0821*T_{PC}/P_P$ (Litre per mole of gas)	22.81	-	-
Moles in containment $(3,031,500*V_{mole})$	132,902		
Prevailing Conditions			
Prevailing T_{PC} ^oC	-	+18.07	+18.71
Prevailing T_{PC} ^oK	-	+291.90	+291.85
Prevailing Air temperature T_{AIR} ^oC	-	+26.5	+22.0
Prevailing Air temperature T_{AIR} ^oK	-	+299.65	+295.15
Prevailing Air Pressure P_P kPa		100.93	101.12
Prevailing Air Pressure P_P atm		0.9961	0.9980
Prevailing volume $V_{mole}=1*0.0821*T_{PC}/P_P$ (Litre per mole of gas)	-	24.06	24.01
Moles in containment $(3,031,500*V_{mole})$		129,474.8	129,740.0
Incremental change in moles	-	-	265.2
Incremental change in %	-	-	0.205
Incremental change in moles from Start in moles	-	-7,064.7	-6,799.5
Cumulative change from Start in %		-5.17	-4.97

Appendix D.

Temperature Measurement Equipment

The following data logging devices were used for onboard data collection during the ocean voyage. The devices are self-contained with internal memory and power supply and do not need any outside connection during data collection. The devices are activated via a computer program and interrogated by cable connection to a computer running supporting software. For more details see http://www.onsetcomp.com/

D.1 Temperature Data Logger

The Onset was selected since it is a certified intrinsically safe device. The concentration of hydrocarbons in the cargo hold in combination with an active energy source such as a battery in a self-contained device unit may approach explosive conditions if not designed for intrinsically safe conditions. The ONSET data loggers are self contained with their own battery and memory for data storage.

Schematic D.1.

TBIB-40+75-IS
StowAway-IS

StowAway®-IS Temperature Data Logger

Part # TBIB-40+75-IS

IS Rating: Class I, II, Division 1, Groups A-G

Key Specifications

The StowAway-IS Temperature Data Logger's small size, wide temperature range and splash-proof design are ideal for industrial environments. The unit can be trigger started using the Coupler or a magnet and may be conveniently launched and read out with an Optic Base Station and StowAway IS Coupler. The Optic Shuttle may also be used for readout at remote deployment sites.*

• Measurement Range: -40° to 75°C (-40° to 167°F)

• Accuracy: ±0.46° at 20°C (±0.83° at 68°F)

• Environmental Rating: tested to NEMA 6 (IP67)

• Alarm Indication: LED blinks if temperature exceeds limits

• Capacity: 32,520 measurements total

• Battery Life: up to 5 years continuous use; non-replaceable

The optical readout elements were protected by a sock crimped on to the device in order to avoid damage or abrasion during loading of pellets. The following picture illustrates the operational conditioning of the device.
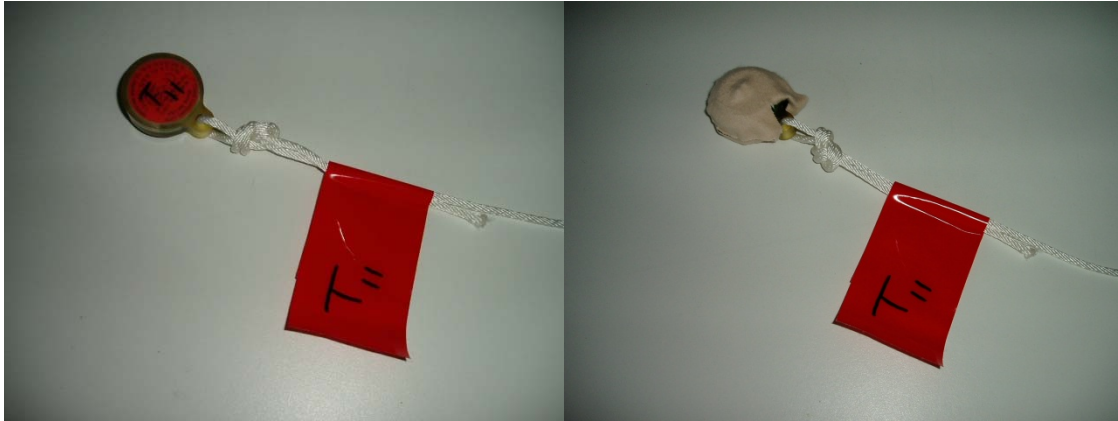
Picture D.1.1. Onset TBIB data logger with retrieval string and marking
(with protective sock in picture on right hand side)

D.2 Relative Humidity Data Logger

The Onset HOBO H8 combined R_h and Temp data logger was selected since it is a certified intrinsically safe device although it is not water proof and has to mounted up-side down on a bracket to avoid condensation on the sensor surface. The concentration of hydrocarbons in the cargo hold in combination with an active energy source such as a battery in a self-contained device unit may approach explosive conditions if not designed for intrinsically safe conditions. The ONSET data loggers are self contained with their own battery and memory for data storage.

        Schematic D.2.

H08-032-IS
HOBO Pro RH/Temp

HOBO H8 Pro Temperature/RH-IS Data Logger

Part # H08-032-IS

IS Rating: Class I, II, Division 1, Groups A-G

Key Specifications

Designed for use in outdoor applications, this IS model offers precision measurements of temperature and

relative humidity. The unit's temperature measurement range is -30° to 50°C (-22° to 122°F) with accuracy of ±0.2° at 21°C (±0.33° at 70°F) in high-resolution mode; ±0.4° at 21°C (±0.7° at 70°F) in standard-resolution mode. RH accuracy is ±3%.

D.3 Data Logger Setup

Each data loggers has an individual code which earmarks the data which is later retrieved to a specific physical location in the cargo hold. The tag number and a digital code in the firmware of the device. These two numbers identified the logger and the position in the cargo hold. The data from each logger is also given a data file index in order to simplify the filing of the data during date retrieval and subsequent data processing. Table D.3.1 illustrates how the loggers and identifiers are related.

Rh = Relative humidity in %
Ah = Absolute humidity in %
Dew = Dew point in gram/m^3
Depl. = deployment

Table D.3.1 Data Logger Setup						
Logger Tag Number	Digital Code	Parameter	Sampling Frequency	Sampling Method	Initiation Time	Data File Index
T_{11}		t °C	1 per hour	Averaging		/T11
T_{12}		t °C	1 per hour	Averaging		/T12
T_{13}		t °C	1 per hour	Averaging		/T13
T_{14}		t °C	1 per hour	Averaging		/T14
T_{15}		t °C	1 per hour	Averaging		/T15
T_{21}		t °C	1 per hour	Averaging		/T21
T_{22}		t °C	1 per hour	Averaging		/T22
T_{23}		t °C	1 per hour	Averaging		/T23
T_{24}		t °C	1 per hour	Averaging		/T24
T_{25}		t °C	1 per hour	Averaging		/T25
T_{31}		t °C	1 per hour	Averaging		/T31
T_{32}		t °C	1 per hour	Averaging		/T32
T_{33}		t °C	1 per hour	Averaging		/T33
T_{34}		t °C	1 per hour	Averaging		/T34
T_{35}		t °C	1 per hour	Averaging		/T35
Rh_1		t °C	1 per hour	Averaging		/Rh1
Rh_2		t °C	1 per hour	Averaging		/Rh2

The data loggers were interrogated individually from a PC for data accumulated during the voyage immediately after completed discharge of cargo.

The temperature is logged once every hour in order to capture the 24 hours cycle throughout the entire voyage since the ambient temperature is going through substantial changes from day to night conditions, superimposed on significant changes in ambient

water temperature throughout a voyage. A voyage may last up to 8 weeks which results in the following size of data file;

Voyage data 7 days x 24 h x 8 weeks = 1,344 data points
Loading data max 48 h = 48 data points
Discharge retrieval time 48 h = 48 data points
Total data points = 1,344 + 48 + 48 = 1,440

Appendix E.

Gas Sampling and Analysis Equipment

Tubing will be installed onboard the ocean vessel for sampling gasses emitted from the wood pellets at various levels in the cargo hold. Also, tubing will be installed in the stairway (Australian ladder) related to the cargo hold in order to sample the gas content upon arrival in the discharge port to determine the gas leakage from the cargo hatch to the stairway.

E.1 Gas Sampling Head, Tubing and Sampling Panels
Flexible tubing shall be sufficiently rigid to avoid collapse under relatively high pressure from weight of the cargo. Tubing made of nylon is used since it is relatively inert with a very low absorption characteristic for hydro-carbons. The tubing has ¼ inch Inner Diameter (ID) and 3/8 inch Outer Diameter (OD).

The gas access point is protected by a Sampling Head assembly in order to avoid debris entering the sampling tubing (see Schematic E.1.1 below).
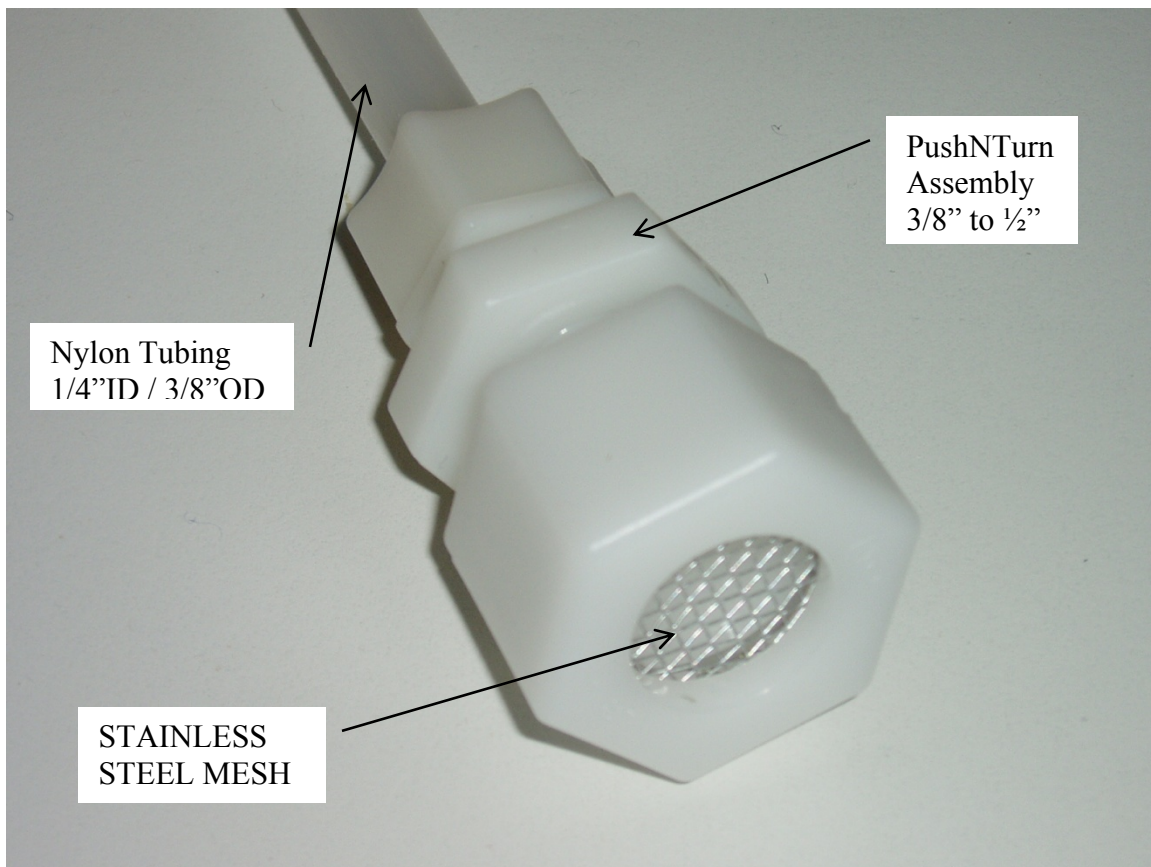

Picture E.1.1. Sampling Head

E.2 Cargo Hatch Tubing

The tubing from the four Sampling Heads in the cargo hatch was routed through the outlet port for the onboard air-conditioning system in the upper section of the cargo hatch to Sampling Panel A located on the outside of the flange in the under deck causeway of the vessel.

The four tubes leading to the cargo hatch were terminated at Sampling Panel A. and sealed by the plugs on the Panel. The In-line dust filter was located in the middle of the panel. The connector to the right shall be connected to the Gas Meter or the FTIR.
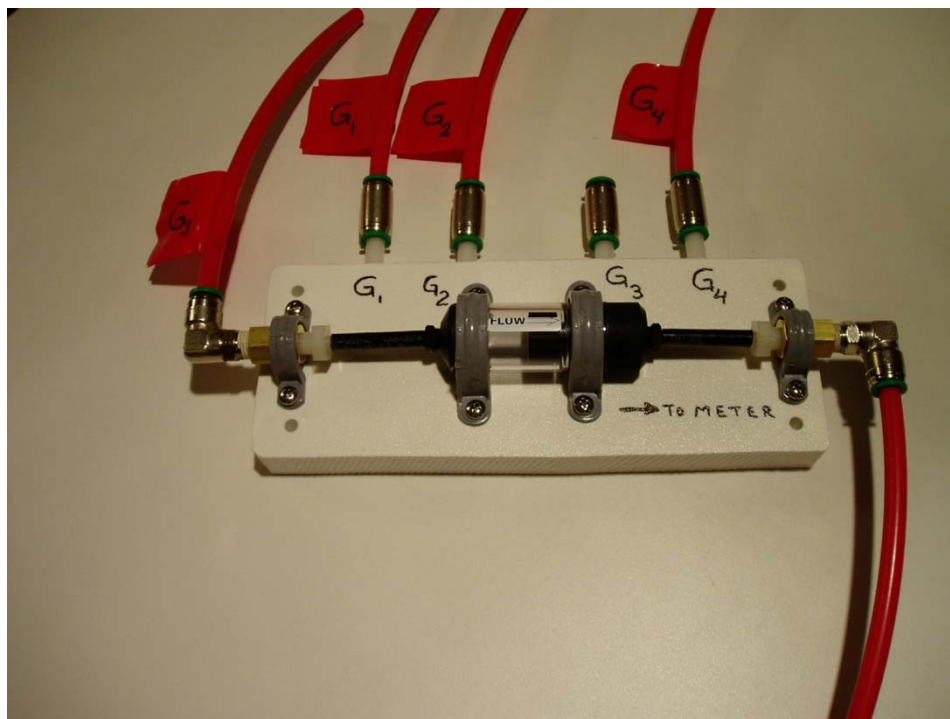
Picture E.2.1 Sampling Panel A in sampling mode for G_3

The underdeck causeway is always ventilated and can be accessed through the Access Hatch on deck located between cargo hold # 10 and the superstructure of the vessel or, alternatively through the doorway from the starboard side of the vessel if need be during gas sampling operations.

A common connector tube leads for Sampling Panel A, on top of the cable ladder in the under deck causeway ceiling and up under the vertical access ladder leading to the Access Hatch between # 10 cargo hatch and the superstructure of the vessel.

A Sampling Connector is located immediately under the Access Hatch cover which has to be lifted off the access hatch for sampling. The tubing coming from the FTIR ashore will connect to this Sampling Connector.

E.3 Gas Measurement During Ocean Voyage

A handheld gas meter model ATX620 (18102772-0411) manufactured by Industrial Scientific was used onboard the ocean vessel for measuring gas emissions during the ocean voyage as follows:

Gas	Chemical Formula	CAS	Range	Nominal Resolution	T90[1] sec	TLV[2]
Carbon Monoxide	CO	630-08-0	0 – 15,000 ppmv	1 ppm	48	50 ppmv
Carbon Dioxide	CO_2	7783-06-4	0 – 6 % of volume	1 ppm	98	
Oxygen	O_2	7782-44-7	0 – 30 % of volume	0.1 %	10	
Combustibles			0 – 100 % LEL vol.	1 %	35	

Table E.3.1

[1] T90 is the time in seconds required to reach 90 % of the steady state measure.
[2] TLV = Threshold Limit Value.

The meter is illustrated below and has the following characteristics:

ATX620 Multi-Gas Specifications

LEL, CH_4, O_2, H_2S, CO, CO_2, SO_2, NO_2, Cl_2   **1-4 Gases**

Case:
Type 304 Stainless Steel (case top) and high impact composite (battery housing)

Dimensions:
8.2" x 3.7" x 3.2" (208mm x 94mm x 81mm)

Weight:
3.4 lbs (1.5 kg)

Sensors:
Combustible Gases - Catalytic Diffusion (PPM leak check mode)
Carbon Dioxide and Methane - Non-Dispersive Infrared Absorption (normal operating mode)
Oxygen and Toxic Gases - Electrochemical

Measuring Ranges:
Combustible Gases/General Hydrocarbons - 50 ppm to 100% LEL
Methane - 0 to 100% of volume
Carbon Dioxide - 0 to 6% of volume
Oxygen - 0 to 30% of volume in 0.1% increments
Carbon Monoxide - 0 to 10,000 PPM in 1 PPM increments
Hydrogen Sulfide - 0 to 999 PPM in 1 PPM increments
Chlorine, Nitrogen Dioxide, Sulfur Dioxide - 0.2 to 99.9 PPM in

Power Source (Run time):
Rechargeable Ni-Cad Battery Pack (12 hours typical)
Replaceable Cell Alkaline Battery Pack (13 hours typical)

Temperature Range:
-4°F to 122°F (-20°C to 50°C)

Humidity Range:
0 to 99% RH (non-condensing)

Approvals:
UL and CSA - Class I, Groups C and D
MSHA - Intrinsically safe for Methane/Air mixtures only
CENELEC and Australia - EEx ia d IIB T4

Enlarge >>

Details:
Specifications
Features & Benefits
Ordering Information
Major Accessories

PDFs
Literature
Features & Benefits
Manual

For additional information see www.indsci.com

The instrument has four separate gas channels and sensors as follows;

1. Electrochemical sensor for measuring O_2
2. Electrochemical sensor for measuring CO
3. Electrochemical sensor for measuring Explosive gases (LEL)
4. Infrared sensor for measuring CO_2

The primary purpose with the onboard gas measurement was to establish a record of the dynamics of the off-gassing of the selected gasses throughout the various conditions prevailing during the ocean voyage. The meter included an aspiration pump set to automatically engage when the meter was activated. The pump was passing 0.5 Liter per minute of gas by the sensor window of the meter. The pump had an internal filter.

The gas meter was used during the voyage to sample gas from all Sampling Heads in the cargo hold as well as in the stairway. The risk of sensor contamination due to ingress of condensed moisture, which may occur immediately on top of the pellets, was minimized by the bracket raising Sampling Point G_1 from the top of the pellets in the cargo hold (see Picture 3.4.1 illustrating the combined support bracket for sampling Head G_1 and Rh_1 meter). The gas meter sensing element had to be protected from water or non-continuous condensing atmosphere which is why the Sampling Head G_1 was protected under the bracket.

In order to obtain a representative volume gas from a Sampling Point, a certain volume of gas had to be evacuated from the sampling line before the actual value is recorded from the meter. The following formula illustrates how the evacuation time was calculated:

Evacuation volume $\quad\quad\quad = \pi*(d/2)^2*L/ps$
where d = tube diameter in mm
L = tube length in meter
ps = pumping capacity in Liter per minute

The minimum sampling time before reading is the sum of the evacuation time and T90 for a pumping capacity of 0.5 Liter per minute for the ATX620 Gas Meter. Table E.3.2 illustrate the minimum time involved for each Sampling Point.

Table E.3.2 Sampling Time						
	Sampling Capacity = 0.50 Liter per minute			Sampling Capacity = 1.0 Liter per minute		
	ET minutes	T90 CO2 seconds	ET + T90 minutes	ET minutes	T90 seconds	ET + T90 minutes
G1	2.60	98	4.23	1.30	98	2.93
G2	2.88	98	4.52	1.44	98	3.08
G3	3.17	98	4.80	1.58	98	3.22
G4	3.39	98	5.03	1.70	98	3.33
G5	0.11	98	1.75	0.06	98	1.69
G6	0.45	98	2.09	0.23	98	1.86
G7	0.85	98	2.48	0.42	98	2.06
G8	1.13	98	2.76	0.57	98	2.20

CO	48
CO2	98
O2	10
LEL	35

ET = Air Evacuation Time
T90 = 90 % Threshold Time
ET + T90 = Total Minimum Sampling Time

E.4 Procedure at Sampling

Approximately 0.5 hours should be allocated per sampling session onboard the vessel. The time for sampling is selected to co-inside with work shift arrangements onboard.

Meter should be running for at least 5 minutes before measurements are taken to allow warmup of sensors. Exposure to saltwater should be avoided.

The Meter has an internal replaceable filter to protect against contamination of sensor elements. Three spare filters are left onboard the vessel.

Sampling Panel A with tubing connected to the cargo hold is equipped with a high volume filter for protection against dust and water to be sucked in from the cargo. This filter can be taken apart and cleaned if necessary as per instruction below.

E.5 Gas Analysis During Discharge of Ocean Vessel

A Fourier Transform InfraRed Spectrometer ((FTIR) instrument (ABB Bomem MB104, made in Canada) will be used for measuring the gas samples in the discharge port. The FTIR technology selected is based on a direct-reading flow-through instrument for characterizing the absorption spectra of the gas passing through in a continuous flow by use of a pump. The absorption of the energy in an infrared (IR) beam passing through the flow of gas is related to the type and concentration of the components of the gas passing through the instrument. The absorption is registered by a sensor and converted to a spectrum by the instrument.

A transportable arrangement of the instrument in a car located alongside the vessel will be used (Picture E.5.1 Instrumentation used by Chalmers University of Technology).

Picture E.5.1 FTIR transportable instrument

Picture E.5.2 FTIR display

Appendix F.

Proposed Research as a Result of the EWDOT Project

F.1 Proposed Research
As a direct result of the EWDOT Project the following research projects have been identified.

Table		
	Definition	Proposed approach
1	The Permissible Exposure Limit (PEL) for CO in combination with oxygen depletion does not seem to have been established	Arrange for research project to be done by medical expertise
2	The specific density of dust from wood pellets has never been established	Arrange for integration to research program at UBC/CHBE
3	The surface area of dust from wood pellets have never been established and how it relates to the rate of off-gassing	Arrange for integration to research program at UBC/CHBE
4	The thermo-dynamics and measurements of off-gassing starting with a high temperature during loading needs to be done to compare the results with the EWDOT Project. Is the dependence on external thermal conditions directly proportional or is there a run-away condition	Conduct a repeat of the EWDOT Project for ocean vessel loading in July or August. Measurements should be done with automatic recording on-board the vessel and should include also a select group of hydro-carbons. It is not clear what the thermo-dynamics would be when passing through tropical waters if the starting temperature would be for example + 30 ^{o}C.
5	The EWDOT research suggest there might be conditions under which special precautions must be taken to secure safe voyage such as characteristics of the pellets during loading, atmospheric characteristics, ocean temperatures etc.	If research as per item 4 above are undertaken, the upper side of the thermal envelop will be known and facilitate a detailed multi-variable guideline for safe voyage
6	At higher temperature in the pellets there are reasons to suspect increased microbial growth followed by additional thermal activity	Make an inventory of microbes present in the raw material as well as in the

		pellets along the transportation path
7	The lab experiments done at UBC/CHBE are done in hermetically sealed conditions which do not replicate the live conditions on-board an ocean vessel	Design experiments which replicate the conditions more accurately and run tests, including measurements of oxygen level
8	The data collected from the thermo-dynamic conditions in the cargo hatch are somewhat complex to fully understand.	Develop a computer model to dynamically illustrate the temperature variations over time in a three-dimensional diagram
9	The hypothesis regarding the effusion of gases between the cargo hatch and the stairway needs to be verified	A lab experiment should be designed to emulate the condition onboard an ocean vessel
10	The heat transfer mechanism in a wood pellets pile in relation to external heat sources is not fully understood	Investigate the thermal transfer characteristics of wood pellets in the lab and build a computer model including the transfer of heat from an external source. This model could be further developed to be applicable to land based silos for predicting critical temperature ranges
11	The IMO code relating to ventilation onboard ocean vessels is currently not adequate to prevent serious accidents	Review IMO code and propose to IMO necessary modifications. This review should also include entry procedures for enclosed spaces
12	The degradation of the wood pellets during loading is quite severe and it appears as if the majority of the fines is generated when the pellets go passes through the shiploader	The impact on the pellets caused by the shiploader in Vancouver needs to be analyzed. A force impact calculation can easily be done and should be followed up with lab experiments to establish a guideline for maximum allowable impact on conventional wood pellets
13	High concentration of dust is generated along the	The risk for explosions and

	path of the pellets during loading. The dust concentration inside the storage silos are unknown	fire should be evaluated. An explosivity analysis ought to be done by a professional laboratory
14	It appears as if most gas meters based on electro-chemical detector technology used for personal protection has a measurement range of up to 1,000 ppmv and are typically calibrated at 100 ppmv for CO. Most are used only for alarm at low level such as 25 ppmv. Since the response curve for the detector in non-linear and frequent exposure to for example CO and hydrocarbons at high concentration the detector element may cause contamination of the detector, these meters are not suitable for measurement in the higher ranges without frequent calibration and "burn-off" time. With CO concentrations reaching in to the thousands of ppmv there is the risk of grossly misleading measurements unless the meter is well maintained and caution is taken to avoid exposing the meter to extreme gas concentrations	Consult gas instrument manufacturers to discuss the issue and try to develop some guidelines for use and maintenance of meters.
15	Optimizing the shape of pellets and the surface characteristics by means decreasing the friction during bulk-flow may increase bulk density and improve the Stowage Factor and result in substantial cost savings	Establish a bulk-flow friction co-efficient for regular wood pellets of different length. Explore the feasibility of producing a pellet with a aspect ratio closer to the value 1.

F.2 Recommendation

In the event another similar to EWDOT is conducted (see item 4 above) there are some recommendations for how to improve the project as follows;

1. separate sampling and analysis of each cargo hold at loading
2. sampling and analysis of fines content before and after shiploader as well as before and after discharge
3. use continuous automated sampling of gases and data logging on-board. Do not use electro-chemical gas sensors. Re-circulating FTIR may be one solution
4. hourly logging of atmospheric and ocean data would improve the accuracy of the analysis. This could be done by a fairly in-expensive weather station with logging capability
5. installation of sampling point in separate "pinhole" between cargo hatch and stairway with the objective to verify the concept of effusion between the two spaces

Appendix G.

Literature References

1) S. Sokhansanj et al, Heat and Moisture Transfer and Quality Changes in Containerized Alfalfa Cubes During Transport, ASAE, Vol 46(2) 2003, ISSN 0001-2351.

2) U. Svedberg, Fourier Transform Infrared Spectroscopy in Industrial Hygiene Applications, Assessment of Emissions from Exposure in Wood Processing Industries, Comprehensive Summaries of Uppsala Dissertations from the Faculty of Medicine 1344, Uppsala 2004, ISBN 91-554-5941-2.

3) Kompletterande information ang. risker med pellets, Helsingborgs Hamn 2006-11-18.

4) Urban Svedberg, Hans-Erik Högberg, Johan Högberg, Bo Galle Emission of Hexanal and Carbon Monoxide from Storage of Wood Pellets, a Potential Occupational and Domestic Health Hazard Ann. Occupational. Hygiene., Vol. 48, No. 4, pp. 339*349, 2004.

5) Urban Svedberg, Jerker Samuelsson, Staffan Melin, Lethal levels of carbon monoxide found in cargo holds with wood pellets. 9th International Symposium on Maritime Health, Esbjerg, Denmark, June 3-6, 2007.

6) ISO, Toxicity testing of fire effluents - Part 1. 1989, International Standard Organization.

7) Grieve, P.W., Measuring ventilation using tracer-gases. 1991, Naerum: Bruel & Kjaer. 33.

8) Arbetarskyddsstyrelsen, Hygieniska gränsvärden och åtgärder mot luftföroreningar. Vol. 2005:17. 2005.

9) ACGIH, TLVs and BEIs. Threshold Limit Values for Chemical Substances and Physical Agents. Biological Exposure Limits. 2007, Cincinnati: ACGIH.

10) NAS/COT, Iterim Acute Exposure Guideline Levels (AEGLs) Carbon Monoxide, 2005, National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances.

11) Arbetarskyddsstyrelsen, Hygieniska gränsvärden och åtgärder mot luftföroreningar. Vol. 2005:17. 2005.

12) Code of Safe Practice for Solid Bulk Cargoes (BC Code), IMO-260E, 2005, ISBN-10:92-801-4201-1.

13) SOLAS IMO-110E, 2001, ISBN 92-801-5100-2.

14) Code of Practice for the Safe Loading and Unloading of Bulk Carriers, IMO-266E, 1998, ISBN 92-801-1458-1.

15) Peterson, J.E. and R.D. Stewart, Predicting the carboxyhemoglobin levels resulting from carbon monoxide exposures. Journal of Applied Physiology, 1975. 39(4): p. 633-8.

16) Off-gassing Research, UBC/CHBE, September 2007 (unpublished)

17) Staffan Melin. Impact of Stowage Factor on Ocean Freight Rate, BC Pellet Fuel Manufacturers Association, Sept 29, 2005.

18) Hawley's Condensed Chemical Dictionary, Richard J. Lewis Sr., Van Nostrand Reinhold, 1997, ISBN 0-442-02324-3.
19) Handbook of Chemistry and Physics 87th Edition 2006-2007, David Lide, CRC,