live export

Development of a heat stress risk management model

Project LIVE.116
Final Report prepared for MLA and Livecorp by:

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LIVE.116

Development of a Heat Stress Risk Management Model

Final Report

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Table of Contents

List of Figures

List of Tables

Executive Summary

This final report documents the data analysis, mathematical modeling and software development of 'HS', a program to estimate the risk of mortality due to heat stress in livestock decks on voyages from Australia to the Middle East. The report now includes the risk management model for open decks which is also fully implemented in the software. The software has been expanded and revised following industry workshops and is now released as "HS Version 2.1".

The risk assessment method takes account of weather at destination and en route, animal acclimatisation, coat and condition and the ventilation characteristics of the ships.

Very little solid information is available to assist the assessment of animal mortality limits. The available data have been used to extrapolate to other animals using scaling based on dimensional analysis and knowledge of heat transfer behaviour. The weather data are also uncertain to some extent and we have decreased the observing ships' wet bulb data probability distributions by 1°C to allow for known data deficiencies which cannot be fully corrected. With adjustments so made, it is felt that the risk predictions for voyages are neither overly conservative nor overly optimistic. This is confirmed by a new validation based on analysis of voyage 20 of the Al Shuwaikh. Certainly, high risk voyages will be identified and prevented in the future. There will always be some grey areas in estimating lower level risks around the level of the target risk limit.

Further animal house work and voyage weather and animal observations will allow the input data to be improved with time, possibly resulting in adjustments to the model. It is suggested that the model, the software and the outcomes be reviewed annually following the northern summer.

There is little recorded information on the temporal variation of wind in discharge ports. For this reason, the proposed method for control of heat stress risk on open decks is different to that for closed decks. For open decks we recommend that:

- Open decks on new ships should be ventilated and assessed as for closed decks
- Existing ships with mechanical PAT on open decks of less than 150m/hr should undertake engineering investigations to identify all reasonably practical measures for improving PAT.
- Open decks not assessed as for closed decks shall be operated according to protocols designed to minimize still air risks (operational guidelines are given).

1 Introduction

1.1 Background

High mortality incidents in livestock export to the Middle East over the 2002 northern summer have highlighted systemic weaknesses in the standards and procedures previously applied to animal welfare and mortality risk reduction on such voyages. There has been a need to bring practices into line with the current risk management knowledge which has been documented particularly over the last two years.

From work for LiveCorp/MLA by Dr Richard Norris of AgWA, it is known that the three principal causes of mortality in sheep and goats are inanition (failure to eat), feedlot related salmonellosis and heat stroke. Inanition causes weaknesses which predispose the animal to other diseases (including salmonellosis) and is characterised by a trickle of mortality which, if anything, builds slightly towards the end of long haul voyages. Feedlot related salmonellosis is evidenced by scour, and mortalities generally peak within the first 5 days of a voyage and subside to inanition type levels later in the voyage, when the two diseases are often likely to be in combination anyway. When either of these problems is very severe, the combination of the two may push the mortality rate above the 2% reporting threshold.

Heat stroke, and the precursor heat stress, occurs as sudden deck-wide epidemics when the environmental conditions are such that animals cannot reject sufficient heat to maintain core body temperature at normal levels in the face of the ongoing generation of internal body (metabolic) heat. Before a major epidemic becomes apparent, increasing environmental heat will drive up mortality rates as those sheep weakened by salmonellosis or other diseases succumb before the general population. Oddly, some degree of inanition may assist survival in a heat wave by decreasing the animals' internal heat generation. This is not yet certain.

For cattle, the principal causes of mortality are trauma, respiratory disease and heat stroke. Trauma is minimised through animal housing design and handling procedures. Respiratory disease prevention is the subject of a current LiveCorp/MLA study led by Dr Simon More. Heat stroke and heat stress in cattle follow epidemiological patterns similar to those for sheep, albeit with onset over a wide range of conditions for different livestock types and lines.

Studies coordinated by LiveCorp and MLA and managed principally by Dr Conrad Stacey of Maunsell Australia and Dr Simon More of AusVet Animal Health Services have elucidated and documented the science relating to the heat stress, ventilation and salmonellosis issues relevant to livestock export by sea.

1.2 Scope and Objectives

This project focussed on the risk of stress and mortality caused by heat. The risk of heat stress relates to parameters in three broad categories:

- Weather
- Animal physiology
- Ship ventilation

The interaction of the principal parameters is well known from precursor projects. This project aims to include secondary effects and to formulate a risk assessment method which is as soundly based as possible given available data. Simplicity of application and understanding is also important and so we have not made the method more complex than can be justified by both the knowledge of risk factor interactions and the confidence level in relevant parameters.

The principal outputs of the project are, for sheep and cattle voyages to the Middle East:

- A clear and transparent method of risk evaluation
- Documented risk parameters
- A simple software tool to assist exporters with heat stress risk assessment

1.3 Project Progress

Project LIVE.116 is now complete except for the software maintenance period. HS Software has been revised to Version 2.1.

1.4 A Quick Look at Outcomes

The purpose of the risk estimate software is to automate the calculation process involving table look-ups and repetitive calculations for many combinations of input variables. To assist in understanding the outcomes, Figure 1.1, Figure 1.2 and Figure 1.3 show the closed deck data in a different form. They give allowable stocking density as a fraction of the LEAP maxima for three common classes of animal.

Since very few cattle decks have a pen air turnover (PAT) of 100m/hr or less, Figure 1.1 effectively shows that the current fleet can transport northern Australia *Bos indicus* animals with relative safety all year round. This accords with industry experience. Figure 1.2 shows that, unlike *Bos indicus*, *Bos taurus* animals will require light stocking for much of the year and should really not be delivered in August. Figure 1.3, for 40kg Merinos, looks similar to Figure 1.1 for 300kg *Bos indicus*, however it has more serious implications as many sheep decks have a PAT less than 100m/hr.

Where the stocking fraction tends towards zero, there is clear indication that the animal could be in trouble even when alone in the ambient conditions. The equivalent result for an open deck assessment is the required crosswind trending towards infinity.

Figure 1.1 Allowable Stocking Fraction for 300kg *Bos indicus*, fat score 3, acclimatised to 15°C wet bulb

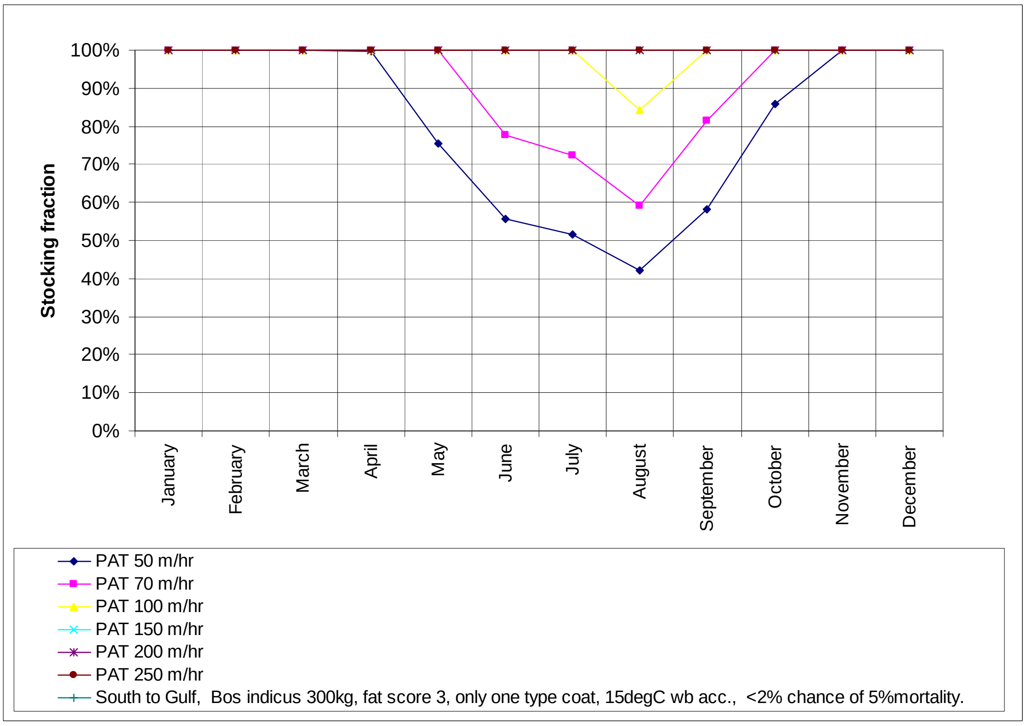


Figure 1.2 Allowable Stocking Fraction for 300kg *Bos taurus*, fat score 3, acclimatised to 15°C wet bulb, mid season coat

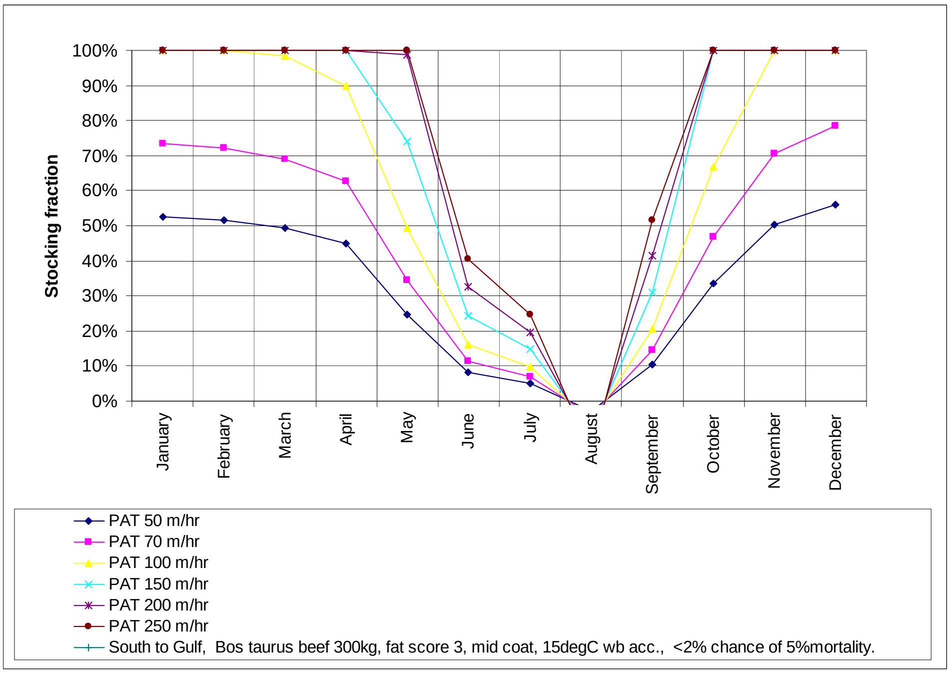
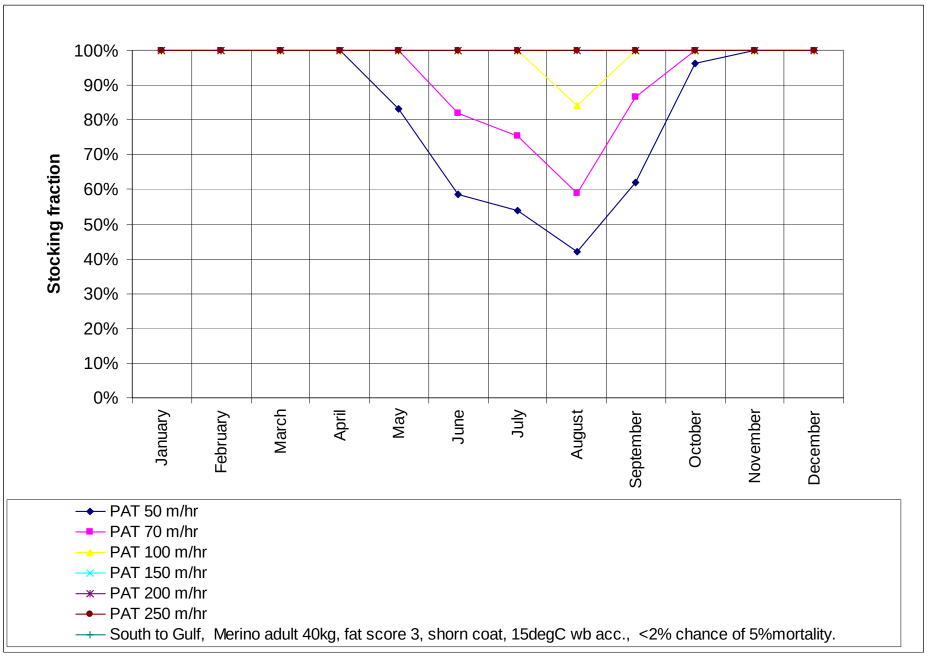


Figure 1.3 Allowable Stocking Fraction for 40kg Adult Merinos, fat score 3, acclimatised to 15°C wet bulb, shorn



1.5 Recommendations for Further Work

Following the principal risk influences, further work could focus on weather, animal parameters or ship ventilation.

1.5.1 Weather

It is considered that the best use has already been made of available data. A serious weather monitoring program would take decades to build statistically useful data to supplant the data already available. However, monitoring Gulf and Red Sea weather has a distinct advantage in being able to corroborate shipboard measurements whenever an incident is being investigated. For example; satellite based weather data could assist in assessing heat stress effects on the Cormo Express voyage turned away from Saudi Arabia.

1.5.2 Animal Parameters

While the animal heat stress thresholds (HST) and mortality limits (ML) are uncertain, the trends of there parameters with the risk influences of weight, breed, coat, acclimatisation and fat score are less clear.

It may well be that, for example, lambs could be loaded more densely than suggested, with the heaviest wethers requiring still more space. We believe that the targets for hot house research work (in order of priority) are:

- Influence of weight on the HST of sheep
- Influence of weight on the HST of cattle
- HST of crossbred vs. Merino sheep
- Influence of *Bos indicus* infusion on HST
- Influence of acclimatisation on the HST of sheep and cattle
- Influence of fat score on the HST of sheep and cattle
- Metabolic heat production data (can be done together with the other experiments if the facility is appropriately set up).

1.5.3 Vessel Ventilation

HS Version 2.1 has no allowance for air jetting or variation of ventilation along a deck. More importantly, the vessel ventilation data in HS Version 2.1 remain largely unaudited. We recommend that all vessels on the trade be subject to ventilation surveys to verify or amend PAT data which are central to risk assessment.

Jetting assessment is more problematic. We now take the view that the air flows to give the necessary pen air turnover will be sufficient to give effective jetting (and general circulation) over animal areas. Lack of jetting will be correlated with low PAT. If the input risk data are (appropriately) taken as relevant to pens with jetting, then the method may only be criticised for not applying a 'de-rating' to areas with no jetting and only a general drift velocity. Such a de-rating could be included later if required as provision has been made in the software data structure.

2 Weather

The key weather influences on the live export trade, notably the detailed seasonal variations of wet bulb temperature climatologies, are described in the following sections. Section 2.1 focuses on the weather experienced in the nine key Middle Eastern ports of disembarkation. Section 2.2 looks at the voyage weather covering the oceanic areas ranging from the Persian Gulf and Gulf of Oman, the Red Sea and Gulf of Aden, the Arabian Sea and the Indian Ocean. Section 2.4 provides an overview of the wet bulb climatology of the Australian ports of departure.

2.1 Middle East Weather

2.1.1 Data Sources and Quality

Temperature and humidity data from the last six years (1997 to 2002 inclusive) were obtained from the national meteorological service of each country's official meteorological observing stations close to eight major ports in the Persian Gulf and Red Sea. The ports selected are destination ports for the live cattle, sheep and goat trade out of Australia. The data were collated and mean daily wet bulb temperatures calculated from the original dry bulb temperature and dew point data. The data originate from the international airport-based observation stations closest to the ports of offloading. Although these data are considered accurate in their own right, the stations are all slightly inland and hence a degree of caution needs to be exercised in applying these data to the port locations. It is probable that coastal wet bulb values are equal to or slightly higher than indicated by the probability distributions presented in this report. With the highest wet bulb temperatures at both sites being associated with gentle onshore air movement, it is likely that distributions are fairly accurate at the high wet bulb temperature end. Until such time as high quality temperature and humidity data can be sourced from within the ports themselves, the airport-based information is the best available. The instrumentation at the airports selected should be subject to regular maintenance and calibration in order to meet the rigid requirements for accuracy and reliability stipulated by the International Civil Aviation Organisation (ICAO) and the World Meteorological Organisation (WMO). Hence the data are regarded as being of high quality. Inspection of the data during the analysis did not reveal any systematic bias or any of several errors that can be detected from standard data analysis techniques. The only data outliers found were for very dry conditions and these were considered to be meteorologically possible given the location of the observation stations.

2.1.2 General Temperature Observations

Northern Winter

The six month period from November to April marks the coolest six months of the year for the Middle East ports used for the livestock trade from Australia. As is the case for most desert climates, these ports can and do experience periods of quite cool weather. However, they do not reach the extremes of cold experienced in more northern climates and across southern Australia during the southern winter. This is due to the moderating effects of the Persian Gulf, Red Sea and Gulfs of Aqaba and Oman. The sea temperatures in these seas do not drop as rapidly as do the temperatures over land, which have been known to drop as low as –9C inland from Kuwait. In general the sea surface temperatures stay in the mid to high 20s.

Temperatures, humidities and wet bulb temperatures drop rapidly during the months of October and November from their summer maxima then tend to stabilize from December through until March when they start to rise again. Short-lived hot spells are possible during the months of November and April, particularly at the southern most ports and Jeddah. Dust storms are also relatively common during these months.

Although still very dry by Australian standards, a few weather systems during this season bring short-lived periods of rain. This is more so in the northern ports of Aqaba, Adabiya and Kuwait. Most ports would experience fewer than 10 wet days (days on which more than 0.2mm of rain is reported) for the entire winter period.

Northern Summer

The heat and humidity levels rapidly build across all Middle East ports during the period from May through to June. First affected are the southern most ports of Muscat and Fujairah where the sun rapidly climbs to almost overhead during May. The heat and humidity extend northwards with central Gulf ports from Dubai to Doha, Bahrain and Dhahran becoming consistently hot and humid from June onwards. Jeddah, on the Red Sea, also enters its' very hot season in June. The true peak of heat and humidity sets in for the northern most ports of Kuwait in the Gulf and Aqaba in the Red Sea (Gulf of Aqaba) towards the end of June into early July. The high heat and humidity levels continue through until the end of September, except for the southern Persian Gulf ports where the high humidity levels linger into October. October is a transition month with shorter spells of hot and humid weather becoming interspersed with cooler and drier conditions. In general, lower humidities tend to be experienced when there are stronger winds, particularly from the NNW (the “Shamal as it is known in the Persian Gulf) or when there are lighter offshore winds from the nearby desert. The latter are often associated with stronger winds, as the sea breeze will tend to overpower any lighter offshore breeze.

Detailed descriptions of the climatology for each discharge port are given in Appendix A.

2.2 Voyage Weather

While the weather in the Middle East was understood to dominate the heat stress risk for much of the year, it was important to verify that understanding with hard data, and to check the importance of conditions en route to heat stress risk during the northern winter. Both of these were done using data from the Voluntary Observing Ships programme.

Marine data, including weather observations from voluntary observing ships, drifting and moored buoys, for the last decade for the Red Sea, Persian Gulf, Arabian Sea and Indian Ocean were purchased from the USA’s National Climatic Data Center in order to better quantify the climatic regimes encountered during the voyage from Australian ports to ports in the Red Sea and Persian Gulf. This is the most comprehensive marine data set available anywhere in the world. Although the marine data does undergo quality control processing within the US National Climate Data Center, analysis of the data revealed that there were still data included in this dataset that was considered to be potentially erroneous, particularly at the high end of the wet bulb temperature distribution. To identify and completely remove all of these incorrect data is a large task and one outside the scope of this project. However, to compensate at least partially for these incorrect data, monthly Normal wet bulb temperature distributions were manually derived in the highest oceanic sector for each of the four Middle East routes.

The oceanic regions were subdivided into approximately 30 separate zones for ease of analysis. The Persian Gulf was divided into 4 zones representing the northern, central and southern regions of the Gulf plus the Gulf of Oman. The Red Sea was subdivided into four latitudinal zones in an attempt to better quantify the north – south wet bulb gradients within this elongated sea with some extra detail around the Straits of Mandeb that separates the Red Sea from the Gulf of Aden. The open oceanic zones were generally five degree latitude and 10 degree longitude boxes, increasing to ten degree square latitude / longitude boxes south of 10^{o}S where the wet bulb regime was considered more benign.

The north of the Persian Gulf exhibits the greatest seasonal variations in wet bulb distribution of all the regions included in this study. The combination of shallow waters to the north of the Gulf combined with its northern most location is the reason for this large wet bulb range. During half of the year the wet bulb rarely approaches 26^{o}C. However, during the months of June to September the mean wet bulb temperature exceeds 26^{o}C and peaks around 33^{o}C in late July to early August. The central and southern parts of the Persian Gulf are also subject to strong seasonal variations, although not as large as in the north. Once again it is the four months from June to September inclusive when the mean wet bulb temperature exceeds 26^{o}C. The highest wet bulb temperatures are recorded in August when the mean rises to 29^{o}C and maximum values are known to exceed 33^{o}C. These values, recorded over the western approaches to the Straits of Hormuz, are the highest of any region included in this study.

The eastern approaches to the Straits of Hormuz have a longer period of elevated wet bulb temperature – with the period when the mean wet bulb temperature exceeds 26^{o}C lasting from May through until towards the end of September, when the wet bulb temperature drops rapidly. The highest mean wet bulb is reached relatively early in the summer in June and July when the wet bulb averages 28.7^{o}C. The strengthening SW monsoon through the Arabian Sea helps to drop the wet bulb slightly in this region in August and particularly in September.

The Red Sea is also subject to a marked seasonal variation in wet bulb temperatures but its greater depth limits the degree to which the wet bulb temperatures rise in the hottest months. North of 28^{o}N the wet bulb temperature exceeds 26^{o}C on relatively few occasions – and these are primarily confined to the months from July to early September, although infrequent reports of high wet bulb values have occurred in June and October. The Red Sea's humidity levels rise a little south to 25^{o}N, although the mean wet bulb temperature even in August between 25^{o}N and 28^{o}N peaks below 26^{o}C with a value of 25.6^{o}C. In the latitude band between 20^{o}N and 25^{o}N the Red Sea takes longer to warm than the corresponding latitude band in the Persian Gulf. The mean wet bulb temperature does not reach 26^{o}C until July and peaks with a value 0f 27.4^{o}C in August. The extreme values are also lower in the Red Sea when compared to the Persian Gulf with the August 98th percentile reaching 31^{o}C. The hottest region in the Red Sea and approaches is the shallower waters in the northern approaches to the Straits of Mandeb, particularly near the Farasan Islands to Hanish Islands region at the southern end of the Red Sea. The stronger NNW flow common further north also weakens in this region during the summer months. In this region the mean wet bulb temperature exceeds 26^{o}C from May through until October inclusive with the four months from June to September inclusive having a very similar wet bulb temperature profile. July is the most humid month with the mean wet bulb temperature peaking at 28.4^{o}C. The 98th percentile for both July and August peaks at 32^{o}C in this region.

The Gulf of Aden region is interesting in the fact that its humidity peaks earlier than all other parts of the Middle East Oceans – reaching a mean value of 27.7°C in June with the 98th percentile reaching 31°C. Wet bulb temperatures remain above 26°C on average from May through until September but the extent of the rise is limited by the development of the low level Somali jet that affects the waters in the entrance to the Gulf of Aden. There is a late secondary peak in humidity in this region in September when the Somali jet dies away before the seasonal cooling sets in during October.

The open oceanic waters of the Indian Ocean are characterised by generally lower mean wet bulb temperatures than experienced in the Persian Gulf and the Red Sea, as well as the Gulfs of Oman and Aden. However, there are times of the year when there can be sizeable areas with raised wet bulb temperatures. The region between 15°N and 10°N from 50°E to 70°E experiences a period from May to June when the mean wet bulb temperature exceeds 26°C – peaking at 26.7°C in June. The 98th percentile reaches 30°C in June. This is the time of northward transit of the sun and it coincides with prolonged periods of light wind conditions. The May to June period is also very humid over the approaches to the Gulf of Oman, although wet bulb temperatures are generally not quite as high as in the regions immediately to the south and west. The region between 5°N and 10°N between 70°E and 80°E to the west of the southern tip of India also warrants a mention. This region experiences mean wet bulb temperatures above 26°C early in the season – during April and May – as the sun traverses overhead and reaches 29°C on 2% of occasions.

The near equatorial region – from 5°N to 5°S is characterised by a relatively uniform wet bulb temperature distribution – mostly around 25°C to 26°C. There is a slight peak in the period from April to June as the southeast trade winds tend to be weaker at this time of the year and the SW monsoon is yet to develop. It is notable that although there is a strong tendency for most wet bulb temperature to fall within the 25 to 26°C range there are quite a few periods of time when the wet bulb temperature reaches 28°C. Although they are scattered throughout the year there is a preference for them to occur in June. They tend to coincide with periods of time when the SE trade winds are weak and there are large areas of light winds lasting several days. The voyage of the Becrux encountered one such period of elevated wet bulb temperature – reaching 28°C in Late June 2002. It is possible to avoid these areas on most occasions by changing the route to stay over regions where the wind is stronger, although this is not a practice currently followed.

South of 5°S there are periods of time between March and May when the mean wet bulb temperature is elevated close to 26°C. In April the wet bulb temperature reaches 28°C on 10% of occasions and there are occurrences in other months of the year when the temperatures reach 28°C.

South of 10°S there is not great concern about oceanic wet bulb temperatures. Trade winds keep the ocean surface well mixed and as a result wet bulb temperatures rarely exceed 26°C.

2.2.1 Data Source and Quality

Data for the voyage analysis were purchased from the 'National Climatic Data Center' (a US government body), covering the ocean areas of interest for the last 10 years.

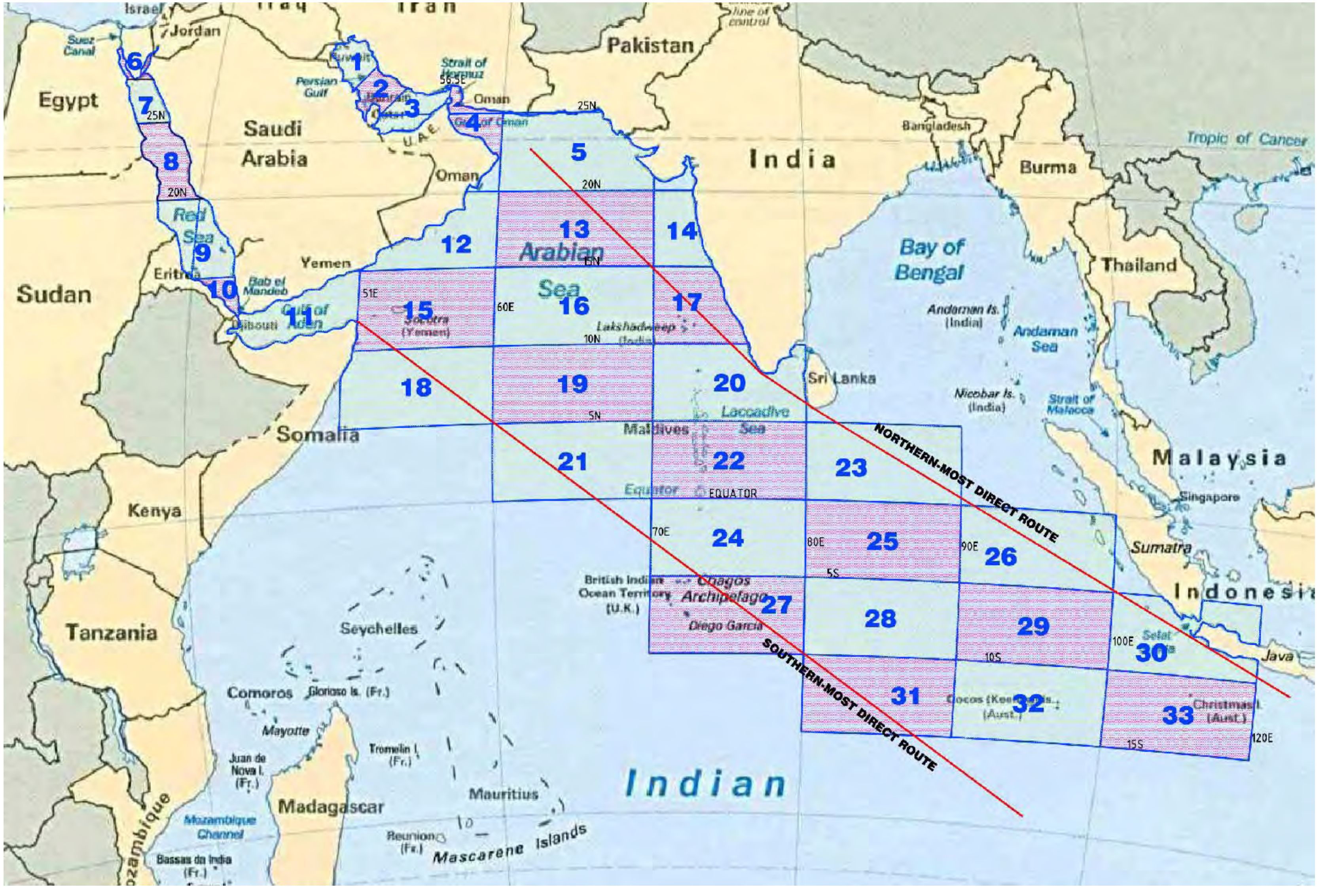
The data originate from a wide variety of sources including naval vessels, merchant vessels and fixed and drifting buoys set up by one of several countries interested in the data. As a result, the quality of the data and recording varies widely. Attempts have been made by NCDC to remove obviously spurious data, however some remain. The intention, in gathering a vast number of data points, is that the effect of bad data on the overall statistics will be negligible.

The most likely error in reporting wet bulb temperature is that the wet bulb itself becomes dry or does not have air freely circulating around it. Both problems increase the reported wet bulb temperature. It was felt, after analysis, that the oceanic data had a significant fraction of 'over-estimated' wet bulb values, making a difference to the statistics at the high temperature end of the range. For each of the ocean zones, this has been manually accounted for when fitting Normal distributions to the data. When doing this in Gulf and Red Sea areas, acknowledgement was also made of the statistics of the more reliable data from adjacent ports. This calibration against the shore data led to a blanket reduction in the mean by 1^{o}C being applied to all ship sourced wet bulb statistics. Thus, the data in Table 2.1 may appear to be 1^{o}C too cool if compared only to the NCDC data, however they are now consistent with the shore based records.

2.3 Use of Voyage and Destination Weather

Section 2.2.1 gives the rationale (related to data quality) by which the available data were used to give cumulative probabilities of wet bulb appropriate to each zone of ocean, for each month of the year. In order to handle the vast volume of data (200Mb) in the NCDC data set, and to avoid meaningless statistics covering a large fraction of the globe at one time, the relevant ocean areas were divided into zones of roughly constant climatology. Figure 2.1 shows the ocean zones applied. There are 4 zones covering Gulf waters and 5 zones covering the Red Sea. This is sufficient to capture the climate variation from south to north for each of these bodies of water. The remainder of 33 zones each cover a 5^o range in latitude and 10^o range in longitude, and together cover all ocean north of latitude 15^{o}S relevant to shipping routes from Australia to the Middle East.

Figure 2.1 Indian Ocean Weather Zones Map



Each of the zones had sufficient data (>1000 points/month) to generate a realistic probability distribution of wet bulb temperature within the zone for each month. The least populous zones were 10°S to 15°S where conditions are milder. Those zones clearly do not control the heat stress risk of voyages to the Middle East and so the sparsity of data is not an issue. Appendix A tabulates the wet bulb temperature probability distributions derived from the NCDC data set. As discussed in Section 2.2.1, these data were combined into voyage maxima for each month along each of 4 routes; northern Australia to the Gulf, northern Australia to the Red Sea, southern Australia to the Gulf and southern Australia to the Red Sea. Normal distributions were adjusted to fit the worst case probabilities for each route and month (48 cases) applying meteorological judgement in allowing for the known data deficiencies. In fitting Normal distributions to the wet bulb data, attention was only paid to the top 50% of the distribution. This may give an error at lower temperatures however low temperatures are not relevant to heat stress. The resulting 48 pairs of mean and standard deviation are given in Table 2.1. Note that, in order to improve agreement with shore based data, and acknowledging known data deficiencies, the risk estimation currently applies a 1°C shift to all means. This adjustment is already included in Table 2.1.

Table 2.1 Idealized "Normal" Wet Bulb Probability Distributions (mean ± standard deviation)

Month	North to Red Sea	South to Red Sea	North to Gulf	South to Gulf
January	24.2 ± 1.30	24.0 ± 1.30	24.1 ± 1.40	24.0 ± 1.40
February	24.4 ± 1.40	24.2 ± 1.30	24.4 ± 1.40	24.2 ± 1.35
March	24.6 ± 1.35	24.5 ± 1.40	24.6 ± 1.35	24.5 ± 1.30
April	25.0 ± 1.45	24.9 ± 1.30	24.9 ± 1.50	24.9 ± 1.30
May	26.3 ± 1.30	26.2 ± 1.40	25.9 ± 1.70	25.9 ± 1.70
June	27.1 ± 1.30	27.1 ± 1.30	27.4 ± 1.70	27.4 ± 1.70
July	27.4 ± 1.55	27.4 ± 1.55	28.1 ± 1.50	28.1 ± 1.50
August	27.3 ± 1.55	27.3 ± 1.55	28.2 ± 1.65	28.2 ± 1.80
September	27.1 ± 1.40	27.1 ± 1.40	27.2 ± 1.80	27.2 ± 1.70
October	25.8 ± 1.50	25.8 ± 1.50	24.7 ± 1.90	24.7 ± 1.90
November	24.0 ± 1.35	24.0 ± 1.35	24.1 ± 1.45	24.1 ± 1.45
December	24.0 ± 1.25	24.0 ± 1.25	24.1 ± 1.25	24.0 ± 1.25

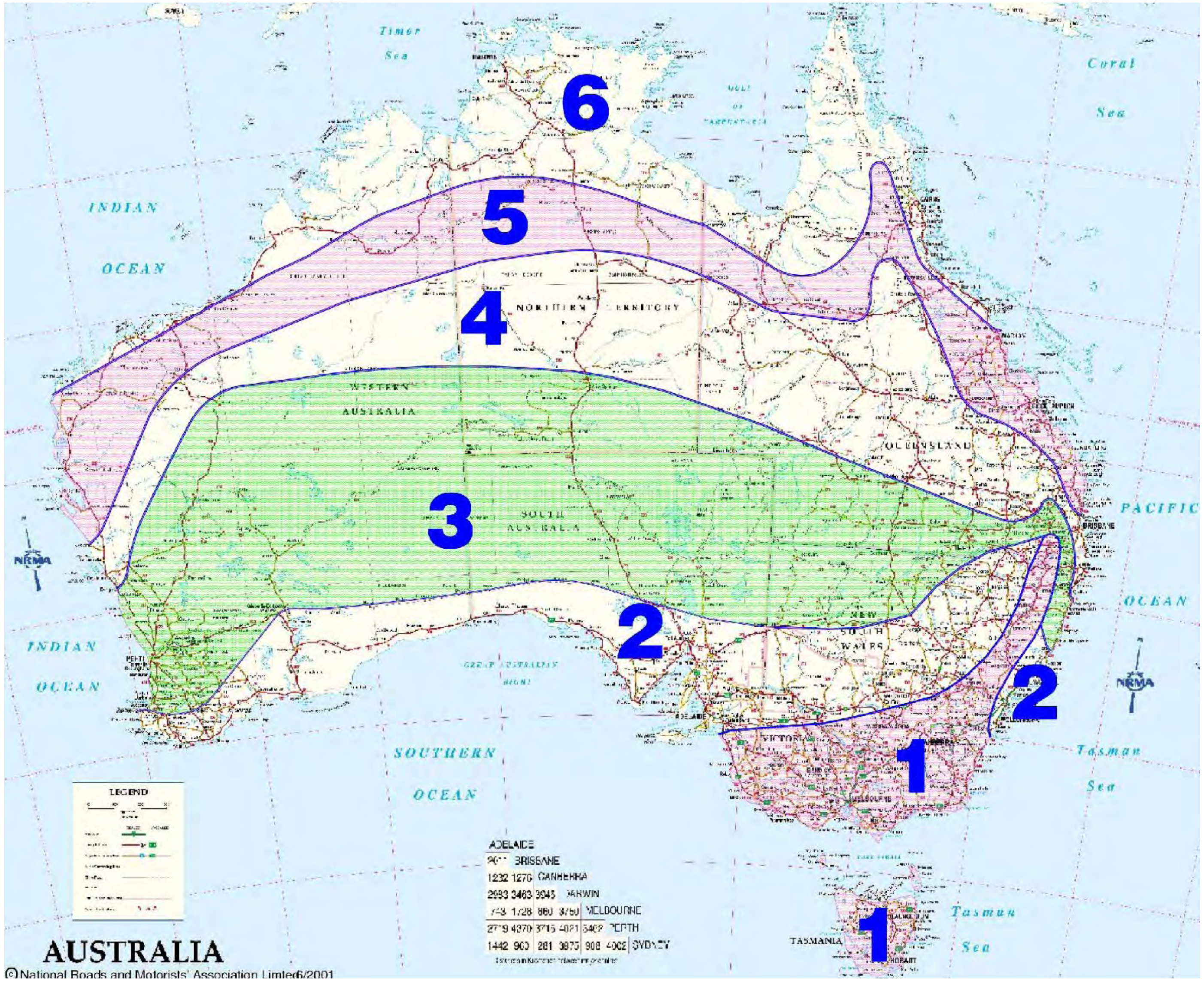
2.4 Departure Ports

Wet bulb data for all significant departure ports have been sourced and analysed. The detailed port information given below has now been largely superseded by a change in the modelling of acclimatisation which followed from discussions at the Milestone 2 meeting in Canberra. The acclimatisation factor, which is discussed in detail in Section 3.3.2, is now based on 'acclimatisation zones'. Across any one acclimatisation zone, the wet bulb variation through the year is reasonably consistent. These zones were selected using summary wet bulb data not only from the ports but from a total of 97 weather stations across Australia. Figure 2.2 shows the draft acclimatisation zone map with the weather sites marked. The numbers next to each site show the approximate average wet bulb temperatures for January (top number) and July (bottom number). Figure 2.3 is the zone map included in the software.

The zone boundaries were placed using the data shown in Figure 2.2, together with a meteorological interpretation of regional climate variations.

Figure 2.2 Australian Acclimatisation Zone Map with Average January (top number) and July (bottom number) Wet Bulb Temperatures at Various Sites

Figure 2.3 Australian Weather Zones Map



Where the animals are transported from the property of origin to the ship and spend only a day or two near the port, it is clear that the acclimatisation zone entered should be appropriate to the property of origin. Similarly, if the animals have spent considerable time at the port (say 15 days or more) they may be considered as being acclimatised to the port conditions and the zone entered into the software should be that of the port. To cover the grey area in between these two, we suggest the following approach.

- If the animals spend less than 4 days between the property of origin and sailing, the zone is taken at the property of origin.
- If the animals spend 15 days or more in the zone of the port, then the appropriate zone is that covering the port.
- If the animals spend between 4 and 14 days in the port zone, the zone number entered should be the average of the zone numbers for the property of origin and the port (rounded down to the nearest integer if required).

Arguments could be mounted for a different approach for special cases. For example, cattle sourced in zone 3, spelled for 8 days in zone 1 and held for 4 days near the zone 2 port would have uncertain acclimatisation. The number chosen is a matter for judgment on each occasion.

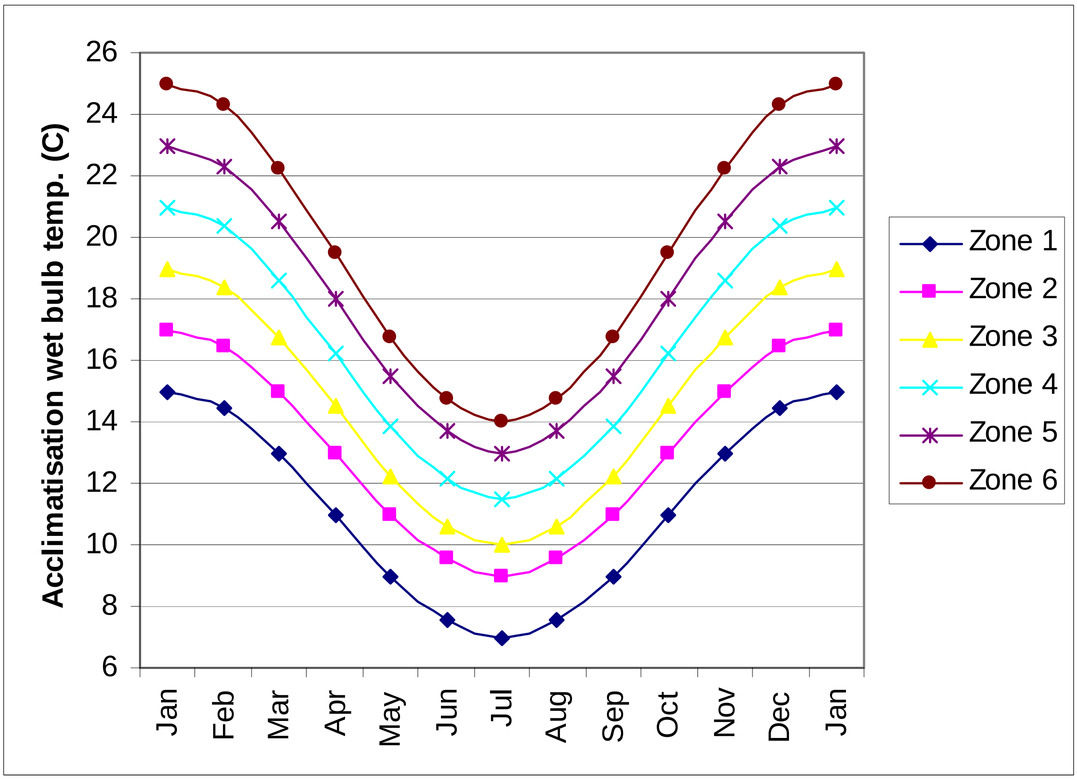
Table 2.2 gives the adopted wet bulb temperatures for acclimatisation for each month and zone. The same data are shown graphically in Figure 2.4

Table 2.2 Acclimatisation Wet Bulb Temperatures by Zone and Month

	ZONE					
	1	**2**	**3**	**4**	**5**	**6**
Jan	**15**	**17**	**19**	**21**	**23**	**25**
Feb	14.5	16.5	18.4	20.4	22.3	24.3
Mar	13	15	16.8	18.6	20.5	22.3
Apr	11	13	14.5	16.3	18	19.5
May	9	11	12.3	13.9	15.5	16.8
Jun	7.5	9.5	10.6	12.1	13.7	14.7
Jul	**7**	**9**	**10**	**11.5**	**13**	**14**
Aug	7.5	9.5	10.6	12.1	13.7	14.7
Sep	9	11	12.3	13.9	15.5	16.8
Oct	11	13	14.5	16.3	18	19.5
Nov	13	15	16.8	18.6	20.5	22.3
Dec	14.5	16.5	18.4	20.4	22.3	24.3

When a ship is close to sailing and the actual acclimatising wet bulb temperature is known, that figure may be used in place of statistically expected numbers above. HS Software has an override facility on the acclimatisation zone method.

Figure 2.4 Acclimatisation Wet Bulb Temperatures by Zone and Month



3 Animal Parameters

The overall model for heat stress risk is reliant on a sound understanding of four components relating to animal heat tolerance, including:

- An evaluation of the heat stress threshold (HST) and mortality limit (ML) in sheep and cattle from available experimental and observational data for different breeds.
- An assessment of the principal modifiers of HST and ML including acclimatisation, weight/age, body condition and wool/coat length.
- Thermal modelling and scaling parameters to allow interpolation and extrapolation of recorded data to cover the range of animal parameters, and to correlate the available data into a single coherent set.
- The statistical variability of heat tolerance within animal populations.

Detailed information on source data is presented in Appendix B.

3.1 Appropriate Terminology and Definitions

The issues of terminology and definition have been discussed at length in several forums recently. There is often confusion and sometimes disagreement about the definition and use of measures relating to heat stress in animals. We have undertaken a detailed review of relevant literature to capture current international thinking and ensure that the terminology does not conflict with international best-practice in this area. Detailed background on this is given in Appendix B.

Although the concepts of 'thermoneutral zone' and 'upper critical temperature' appear to be universally accepted, definition of these particular concepts remains somewhat problematic.

The upper critical temperature (UCT) is a common term in the literature, used to describe the dry bulb temperature at the upper boundary of the thermoneutral zone. Unfortunately UCT as defined cannot exist unless heat stress is closely related to dry bulb temperature. In the project proposal we suggested an Upper Critical wet bulb Temperature (UCwbT) to recognise that heat stress is more closely related to wet bulb temperature. A recent industry meeting in Canberra agreed that UCwbT was too much of a mouthful and, by consensus, adopted the term Heat Stress Threshold (HST). On balance and suitable to the requirements of industry and this model, we believe that HST should be defined as '*the maximum ambient wet bulb temperature at which heat balance of the deep body temperature can be controlled using available mechanisms of heat loss'.*

That is; when the local air wet bulb temperature reaches any animal's HST, the animal is on the verge of becoming stressed. As implied above, incipient stress in this sense means the first uncontrolled rise in core body temperature. We take this as being 0.5^{o}C above what the core temperature would otherwise have been.

The same meeting in Canberra agreed 'Mortality Threshold' as the descriptor of the wet bulb temperature at which an animal will die. In this context, 'threshold' is perhaps inappropriate as it implies that the animal has started dying and might finish dying at another temperature. We prefer 'Mortality Limit' or ML as the limiting wet bulb temperature above which the animal is dead.

3.2 Evaluating the Heat Stress Threshold and Mortality Limit

A review has been made of data on the HST and ML of cattle and sheep during live export. A range of information sources were used, including:

- Published information (from scientific literature)
- Experimental information (particularly LiveCorp-funded R&D projects SBMR.002, LIVE.209 and LIVE.212)
- Voyage investigation (Voyage 1 of the *MV Becrux*)

Evaluation of these parameters is in two stages. First, the parameters specific to each case have to be assessed from the given data. Then, the understanding of all the modifying influences (weight, acclimatisation, coat and condition) is used to link the assessed 'raw' parameters into a cohesive framework, allowing the HST and ML to be estimated for any new animal with its own combination of modifying factors.

Because there may be deficiencies associated with each data source, it is important to simultaneously consider all of these results in the evaluations of HST and ML in sheep and in cattle. For studies with populous data sets, a form of multi-variate regression would normally be applied to estimate the factors. This is simply not possible with the present limited data set and so the fitting of factors to raw data has been done manually.

The process by which this was done is indicated by Table 3.1, Table 3.2 and Table 3.3. In Table 3.1, for cattle, there are 6 primary data observations for *Bos taurus* cattle and 3 for *Bos indicus* cattle. Underneath each of these entries are inferred data rows with 'standard' animals. The heat stress threshold and mortality limit for each standard animal is scaled from the observed data using the appropriate factors from Table 3.3. The factors were adjusted to give similar results for the standard animal when calculated from each observation. If the system had included factors fully describing animal differences, it might be hoped that all standard animal entries would have the same HST and ML. Of course that is not so, and discrepancies remain. The values currently adopted for HST and ML of the standard animal are given in Table 3.4.

Table 3.1 Original and Inferred Cattle Parameters

DATA SET		ACCLIMATISATION WB TEMP	WEIGHT (KG)	COAT	FAT SCORE	Facc	Fweight	Fcoat	Fcond	HST	ML	HST diff	ML diff	MLdiff / HSTdiff	REFERENCE
	***BOS TAURUS* TABLE**														
1	Becrux soft southern cattle	12	350	winter	5	1.057	1.05	1.1	1.2	26.0	30.0	14.0	10.0	0.71	Ausvet report. ML looks OK.
	Inferred base, 350kg	15	350	mid	3	0.995	1.02	1	1	30.0	32.9	9.99	7.13	0.71	HST based only on first report of stress.
	Inferred base, 300kg	15	300	mid	3	0.995	1	1	1	30.5	33.2	9.49	6.78	0.71	
	Inferred, 350kg,summer	18	350	summer	3	0.934	1.05	0.93	1	31.3	33.8	8.72	6.23	0.71	
2	Murdoch Angus animals	15	370	mid	3	0.995	1.07	1	1	28.0	33.0	12.0	7.0	0.58	Murdoch 'experiment 1'
	Inferred base, 300kg	15	300	mid	3	0.995	1	1	1	28.8	33.5	11.2	6.53	0.58	ML is 1.0 deg above point where
	Inferred, 300kg,summer	15	300	summer	3	0.995	1	0.93	1	29.6	33.9	10.4	6.07	0.58	mortality seemed likely soon
3	Murdoch Murray Grey X	13	340	mid	3	1.036	1.04	1	1	29.0	33.0	11.0	7.0	0.64	Murdoch 'experiment 2'
	inferred base, 300kg	15	300	mid	3	0.995	1	1	1	29.9	33.5	10.1	6.45	0.64	ML is 0.5 deg above point where
	inferred, 300kg,summer	15	300	summer	3	0.995	1	0.93	1	30.6	34.0	9.43	6.0	0.64	mortality seemed likely soon
7	Friesan	12	200	mid	3	1.057	0.87	1	1	29.0	33.4	11.0		0.6	SBMR.002, voyage 5, D4,P35.
	inferred base, 300kg	15	300	mid	3	0.995	1	1	1	28.2	32.9	11.8		0.6	
8	Euro cross bull calves	12	200	mid	3	1.057	0.87	1	1	31.0	34.6	9.0		0.6	SBMR.002, voyage 5, D5,P5,P19,P29&P37.
	inferred base, 300kg	15	300	mid	3	0.995	1	1	1	30.3	34.2	9.69		0.6	
9	Southern bulls	12	385	mid	3	1.057	1.09	1	1	29.5	33.7	10.5		0.6	SBMR.002, voyage 5, D3,P7&P47.
	inferred base, 300kg	15	300	mid	3	0.995	1	1	1	30.9	34.5	9.11		0.6	
	***BOS INDICUS* TABLE**														
6	Acclimatised, Darwin, 420kg	23	420	n/a	3	0.831	1.12	1	1	32.5	36.0	7.5	4	0.53	guess from SBMR.002, voyage 4.
	inferred base 420kg	15	420	n/a	3	0.995	1.12	1	1	31.0	35.2	8.98	4.79	0.53	ML taken above all wb noted (no mort.)
	inferred base 300kg	15	300	n/a	3	0.995	1	1	1	32.0	35.7	8.04	4.29	0.53	
5	Unacclimatised, TSV, 420kg	12	420	n/a	3	1.057	1.12	1	1	30.5	35.5	9.5	4.5	0.47	SBMR.002, voyage 3, guess
	inferred base 420kg	15	420	n/a	3	0.995	1.12	1	1	31.1	35.5	8.95		0.5	
	inferred base 300kg	15	300	n/a	3	0.995	1	1	1	32.0	36.0	8.01		0.5	
4	Murdoch *Bos indicus*	12	350	n/a	3	1.057	1.05	1	1	32.5	36.0	7.5	4	0.53	Murdoch Experiment 3
	inferred base 350kg	15	350	n/a	3	0.995	1.05	1	1	32.9	36.2	7.06		0.53	
	inferred base 300kg	15	300	n/a	3	0.995	1	1	1	33.3	36.4	6.71		0.53	

Table 3.2 Original and Inferred Sheep Parameters

DATA SET		ACCLIMATISATION WB TEMP	WEIGHT (KG)	COAT	FAT SCORE	Facc	Fweight	Fcoat	Fcond	HST	ML	HST diff	ML diff	MLdiff / HSTdiff	REFERENCE
MERINO TABLE															
10	Voyage 1 adults	12	52	shorn	3	1.057	1.01	1	1	29.5	35.0	10.5	5	0.48	Live.212 v1, lower mort.~32
	inferred base, 40kg	15	40	shorn	3	0.995	0.96	1	1	30.6	35.53	9.38	4.47	0.48	
11	Voyage 1 woolly ewes	12	54	woolly	3	1.057	1.02	1.12	1	28	34.29	12		0.48	Live.212 v1 D8, P30
	inferred base, 40kg	15	40	shorn	3	0.995	0.96	1	1	30.5	35.47	9.5		0.48	
12	Voyage 1 lambs	12	38	shorn	3	1.057	0.95	1	1	26	35.0	14	5	0.36	Live.212 v1, D5, P1&2
	inferred base, 40kg	15	40	shorn	3	0.995	0.96	1	1	26.7	35.24	13.3	4.76	0.36	
13	Voyage 2 adults	11	60	shorn	3	1.077	1.04	1	1	29.5	35.0	10.5		0.48	Live.212 v2, lower mort.~32.5
	inferred base, 40kg	15	40	shorn	3	0.995	0.96	1	1	31.1	35.74	8.94		0.48	
AWASSI TABLE															
14	Voyage 1 lambs	12	38	hairy	3	1.057	0.95	1	1	28	35.71	12		0.36	Live.212 v1, D9, P20
	inferred base, 40kg	15	40	hairy	3	0.995	0.96	1	1	28.6	35.92	11.4		0.36	

Table 3.3 Scaling Factors

Factor		***Bos taurus***	***Bos indicus***	**Sheep**
Base Weight (kg)		300	300	50
Weight Index n		0.33	0.33	0.2
Core Temperature (^{o}C)		40	40	40
F Condition	Fat Score 0	9	9	9
	Fat Score 1	0.9	0.9	0.9
	Fat Score 2	0.95	0.95	0.95
	Fat Score 3	1	1	1
	Fat Score 4	1.1	1.07	1.07
	Fat Score 5	1.2	1.2	1.2
F Coat	Mid	1	-	-
	Summer (shiny)	0.93	-	-
	Winter (hairy)	1.1	-	-
	Normal	-	1	-
	Hairy (Awassi only)	-	-	1
	Mid (10 to 25mm)	-	-	1.08
	Shorn (under 10mm)	-	-	1
	Woolly (over 25mm)	-	-	1.12
F Acclimatisation	Fully Acclimatised	0.79	0.79	0.79
	Fully Unacclimatised	1.26	1.26	1.26
	Slope	-0.0235 (per degree)	-0.0235 (per degree)	-0.0235 (per degree)
Twb Break	Fully Acclimatised	25	25	25
	Fully Unacclimatised	5	5	5

Table 3.4 Base Heat Stress Threshold and Mortality Limit Values for the 'Standard' Animals

Base Parameter	*Bos taurus*		*Bos indicus*			Merino		Awassi	
	beef	dairy	beef	25% indicus	50% indicus	adult	lamb	adult	lamb
Weight (kg)	300	300	300	300	300	40	40	40	40
Core Temperature (degrees C)	40	40	40	40	40	40	40	40	40
Condition (Fat Score)	3	3	3	3	3	3	3	3	3
Coat	mid	mid	N/A	N/A	N/A	shorn	shorn	hairy	hairy
Acclimatisation WB Temp	15	15	15	15	16	15	15	15	15
Base HST (degrees C)	30	28.2	32.5	31.25	31.875	30.6	26.7	31.9	28.6
Base ML (degrees C)	33.2	32.9	36.0	34.60	35.30	35.5	35.20	36.1	35.90
Beta distribution lower limit (degrees C)	30.31	29.88	34.30	32.30	32.30	33.58	33.17	34.52	34.15
Beta distribution upper limit (degrees C)	34.74	34.51	36.90	35.82	35.82	36.52	36.29	37.03	36.83

It is particularly difficult to get good data on mortality limits. It is not possible to kill large numbers of animals in the lab and, when significant mortality occurs at sea, the crew are understandably more concerned with managing the situation than making careful records of the weather and pen environments. For *Bos taurus*, voyage 1 of the Becrux gave some data and we have also used the opinion of the Murdoch University team that their *Bos taurus* animals were close to the limit when conditions were finally relieved. For *Bos indicus*, no data are available. Taking a mortality limit above the highest temperature at which animals were monitored does not give an accurate figure. Nevertheless, an estimate has been made. It can be revised at any time in the future as new data are examined.

We don't expect that we will ever see data which show mortality as a function of wet bulb temperature for a large group of one type of animal. Accordingly, we have had to synthesise the probability distributions of HST and ML. Appropriate to the nature of the problem, we chose a skewed beta distribution. This has the property that a small number of animals respond at lower temperatures but the distribution is more compressed above the 50 percentile. That is; no animals survive at wet bulb temperatures just a little above the temperatures that will kill half their number, whereas there are animals which are significantly 'softer' than most. In selecting the beta distributions, greater attention has been paid to the low temperature end. The top end of the distribution is really only of academic interest as a 50% mortality rate is already a major problem and so arguments over prediction of 60% versus 75% mortality are not useful.

The beta function probability distributions of mortality limit for key classes of animal are shown in Figure 3.1, Figure 3.2, Figure 3.3, Figure 3.4, Figure 3.5, Figure 3.6, Figure 3.7, Figure 3.8 and Figure 3.9.

Figure 3.1 Beta Function Probability Distribution – *Bos taurus* - beef

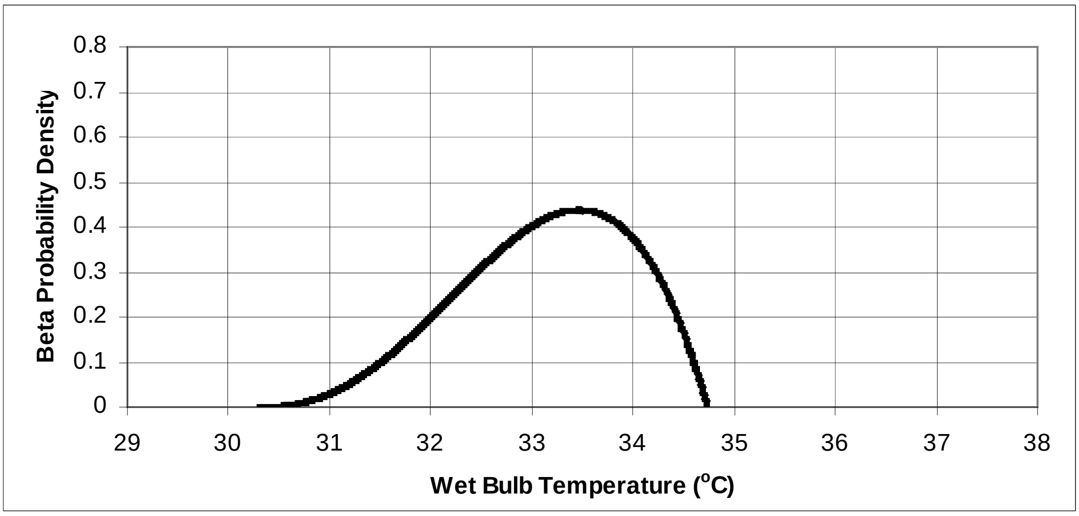


Figure 3.2 Beta Function Probability Distribution – *Bos taurus* - dairy

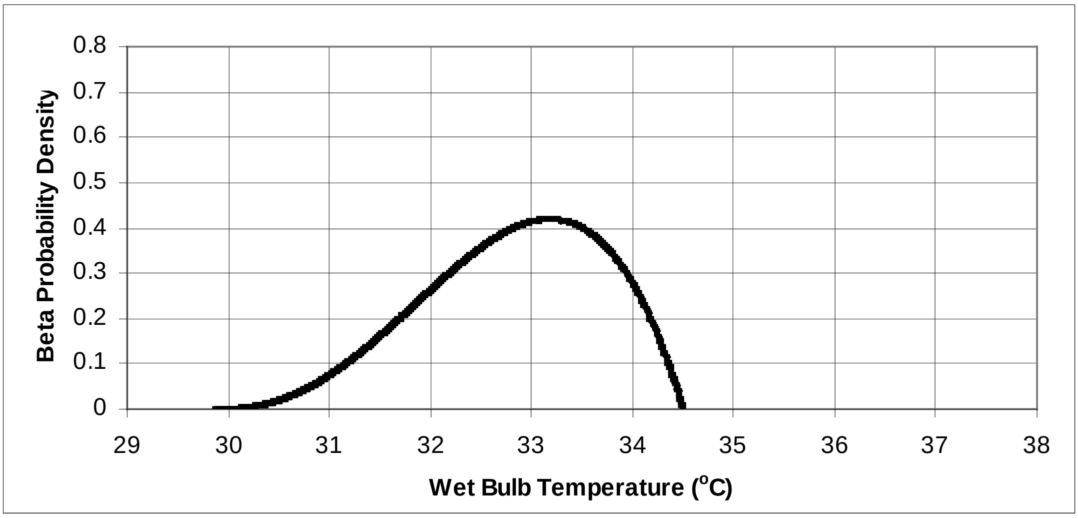


Figure 3.3 Beta Function Probability Distribution – *Bos indicus*

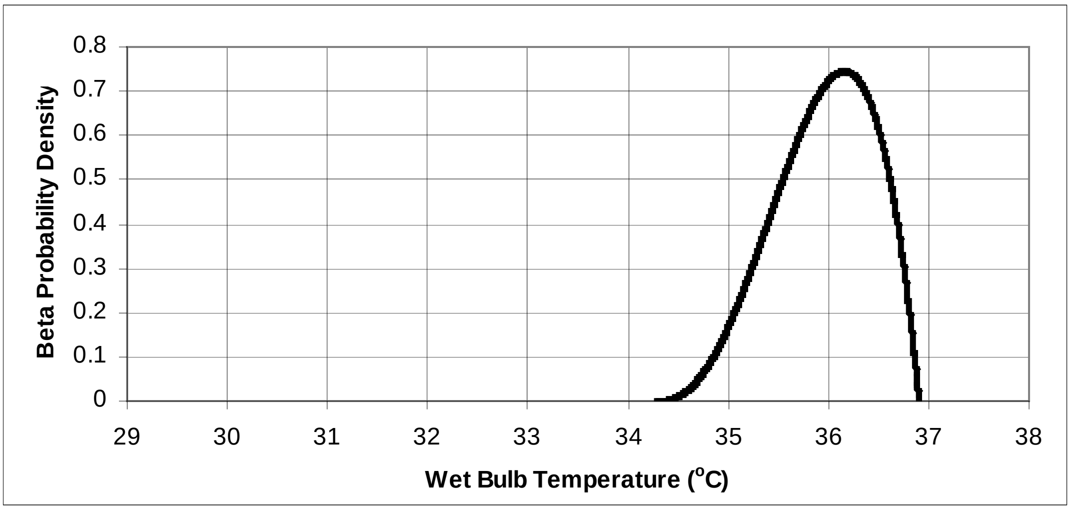


Figure 3.4 Beta Function Probability Distribution – 25% *Bos indicus*

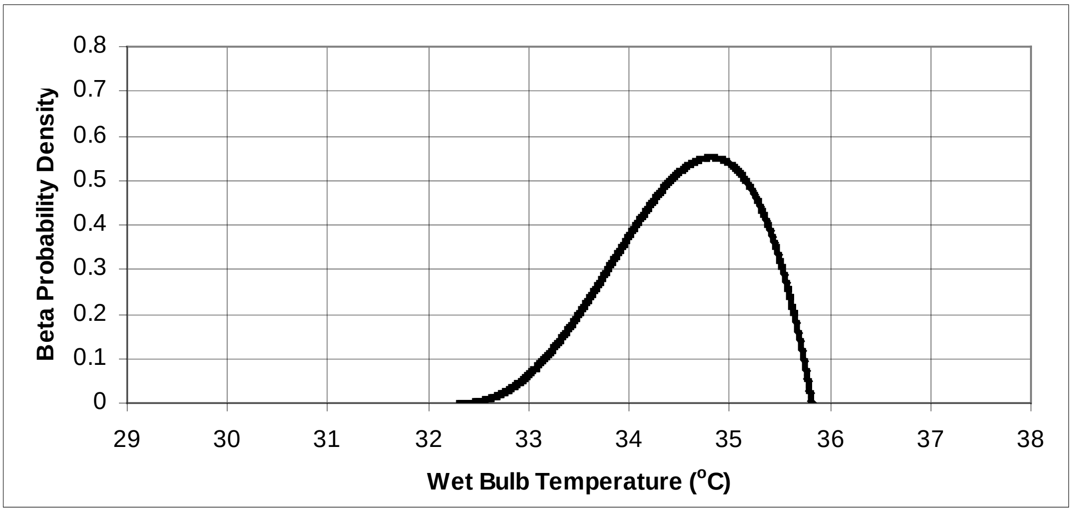


Figure 3.5 Beta Function Probability Distribution – 50% *Bos indicus*

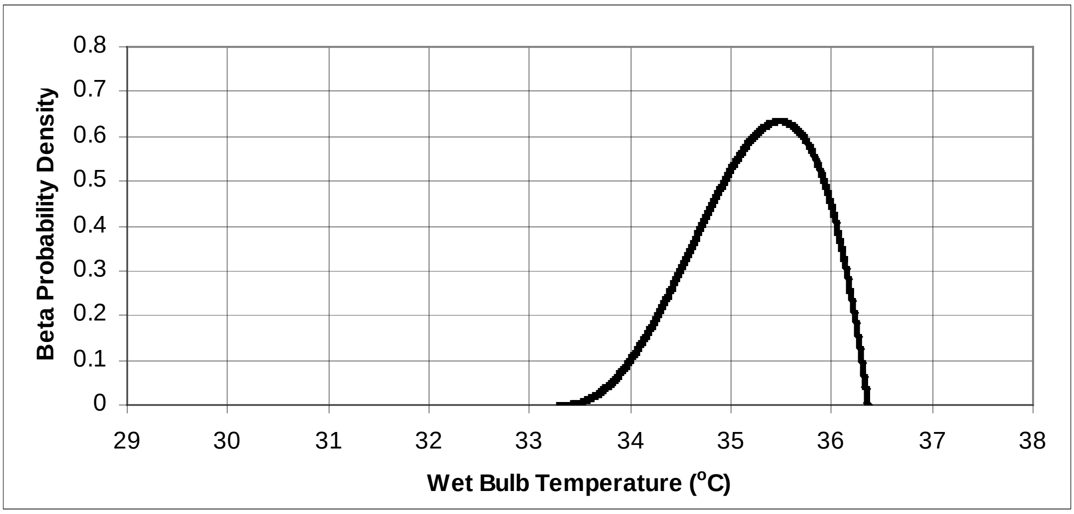


Figure 3.6 Beta Function Probability Distribution – Merino - Adult

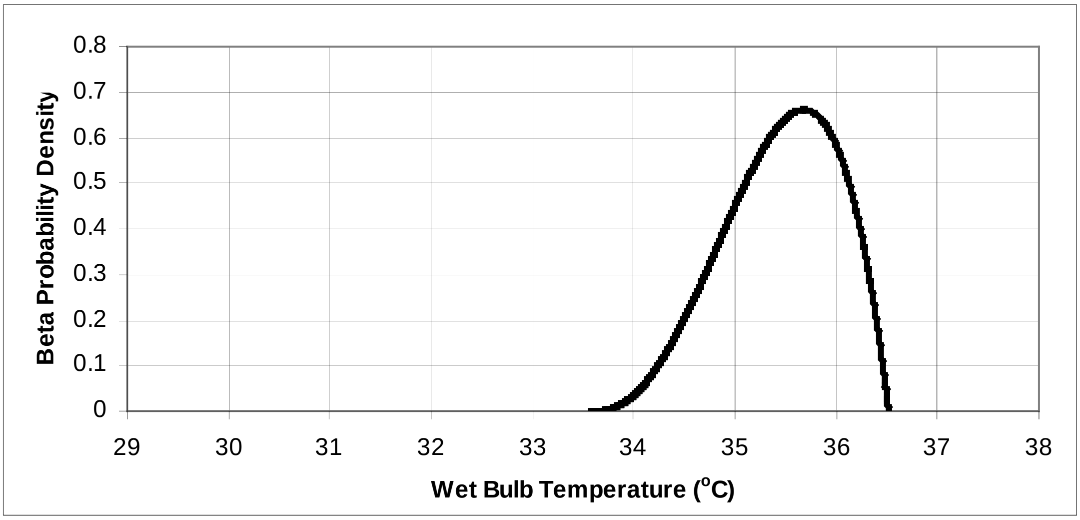


Figure 3.7 Beta Function Probability Distribution – Merino - Lamb

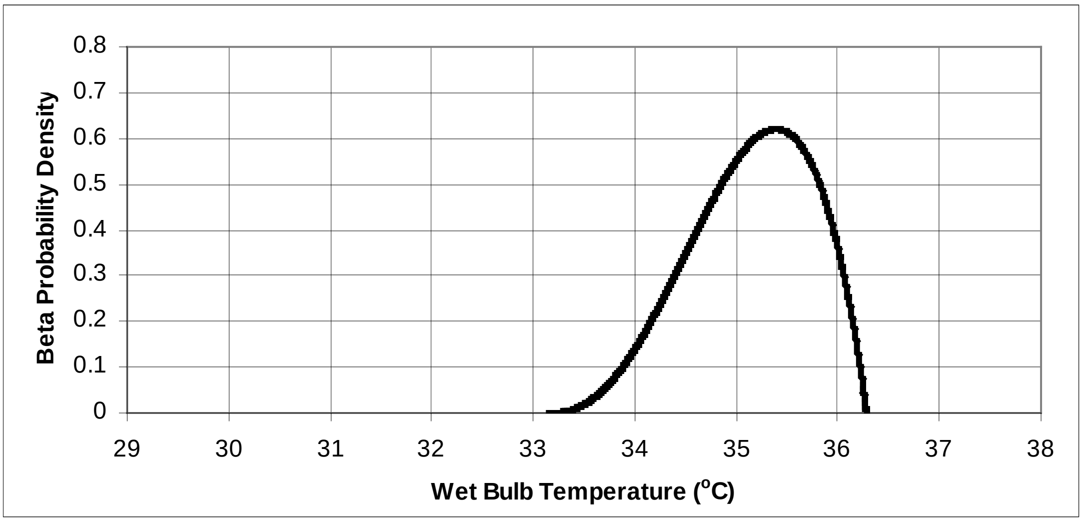


Figure 3.8 Beta Function Probability Distribution – Awassi - Adult

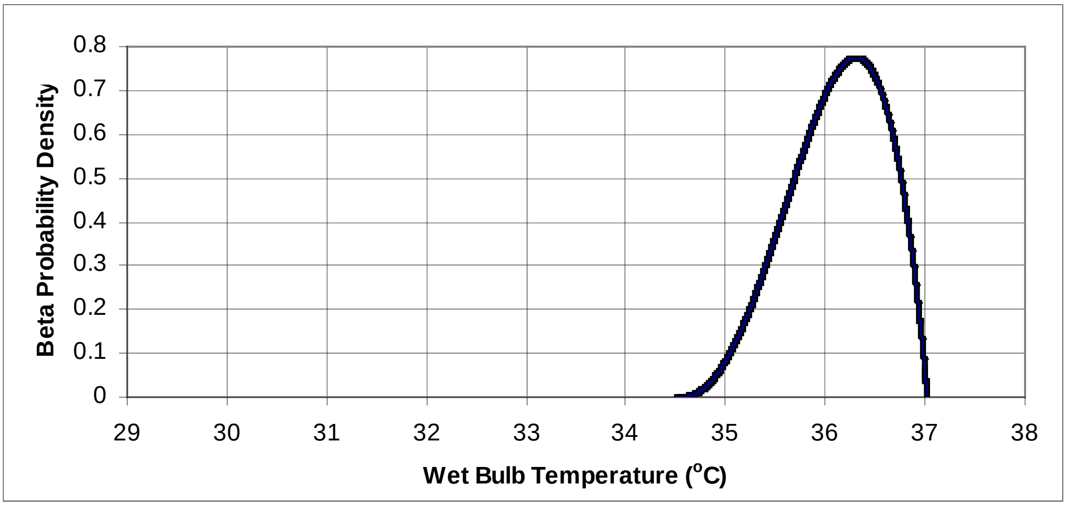
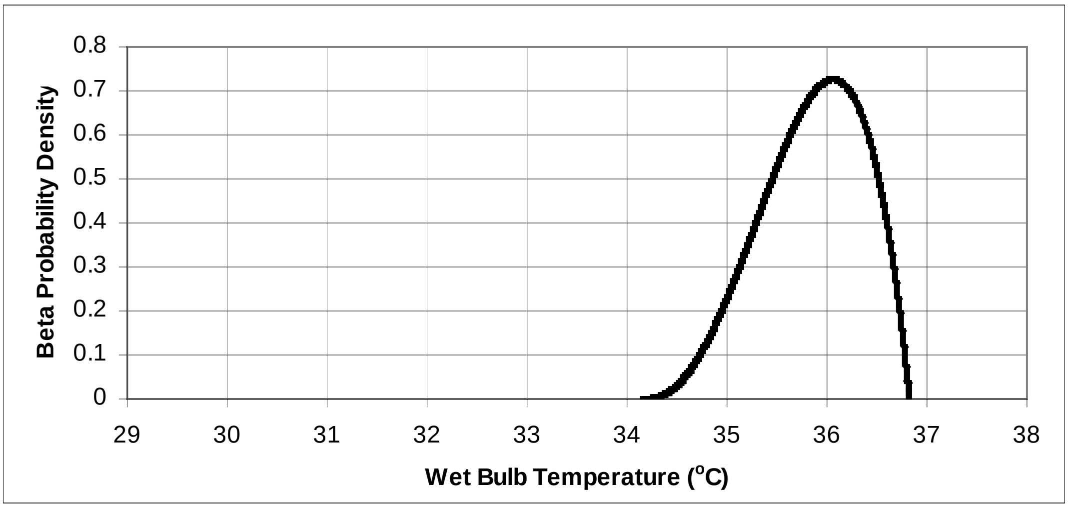


Figure 3.9 Beta Function Probability Distribution – Awassi - Lamb



3.3 Scaling HST and ML

As mentioned in the above section, heat stress threshold and mortality limit for any given line of animal are estimated by scaling the values from those of a standard animals of the same type. The various physical characteristics (weight, acclimatisation, coat and condition) will affect the temperature difference required between the animal and its environment for rejection of metabolic heat. The factors assigned to each feature act in the model to modify this temperature difference. That is; using T_{CORE} as the animal's core temperature and adjustment factors F for each characteristic:

$$(T_{CORE} – HST) = F_{ACC} \times F_{WEIGHT} \times F_{COAT} \times F_{CONDITION} \times (T_{CORE} – \text{base HST})$$

and similarly for mortality limit:

$$(T_{CORE} – ML) = F_{ACC} \times F_{WEIGHT} \times F_{COAT} \times F_{CONDITION} \times (T_{CORE} – \text{base ML})$$

As the probability beta distribution of HST and ML for any one animal type is uncertain, the scaling of the beta distribution limits with animal characteristics cannot be any more certain. Following again the principle that the difference between core and ambient wet bulb temperatures gives the controlling temperature scale, the spread of the beta distribution is adjusted in proportion to that difference. That is; 'softer' lines of animals, with a lower HST, will also have a wider spread of HST within the line. The shape parameters (P and Q) which determine the skewness of the beta distribution were set by judgement and have been kept constant across all animals. For the record, we have used P = 3.50 and Q = 2.00. For a 50 percentile of 35.09°C, the minimum and maximum of the beta distribution are 33°C and 36.2°C respectively. Other distributions, including those in Figure 3.1, Figure 3.2, Figure 3.3, Figure 3.6, Figure 3.7, Figure 3.8, Figure 3.7, Figure 3.8 and Figure 3.9, are scaled from this as described above.

The following sections describe the development of each adjustment factor.

3.3.1 Weight Scaling

The initial estimate of the weight factor is based on geometry. We make the simplifying assumption that animals of one breed are geometrically similar. This gives a surface area proportional to the two-thirds power of body mass. If the rate of production of metabolic heat per unit mass is constant (a fair approximation) then obviously the heat generated is proportional to mass. Assuming further, that the coefficients of heat transfer are independent of body mass, the required minimum temperature difference between core and wet bulb temperatures goes as the one-third power of mass. That is;

$\Delta T_{CRIT} \ \alpha \ m^{1/3}$ (*m* is animal mass)

This gives the first estimate of the weight factor as

$$F_{WEIGHT} = \left(\frac{m}{m_{STANDARD}} \right)^{\frac{1}{3}}$$

or, if we believe that the one-third power may not be quite right;

$$F_{WEIGHT} = \left(\frac{m}{m_{STANDARD}} \right)^{n}$$

When an animal of a given frame puts on weight, it does not follow the geometric rules above, with surface area growing more slowly with mass than described. This has the effect of increasing the exponent *n*, above, beyond 0.33. Animals with lots of weight for their frame may also attract a high condition factor and so we must be careful not to 'double count' the weight influence in both weight factor and condition factor.

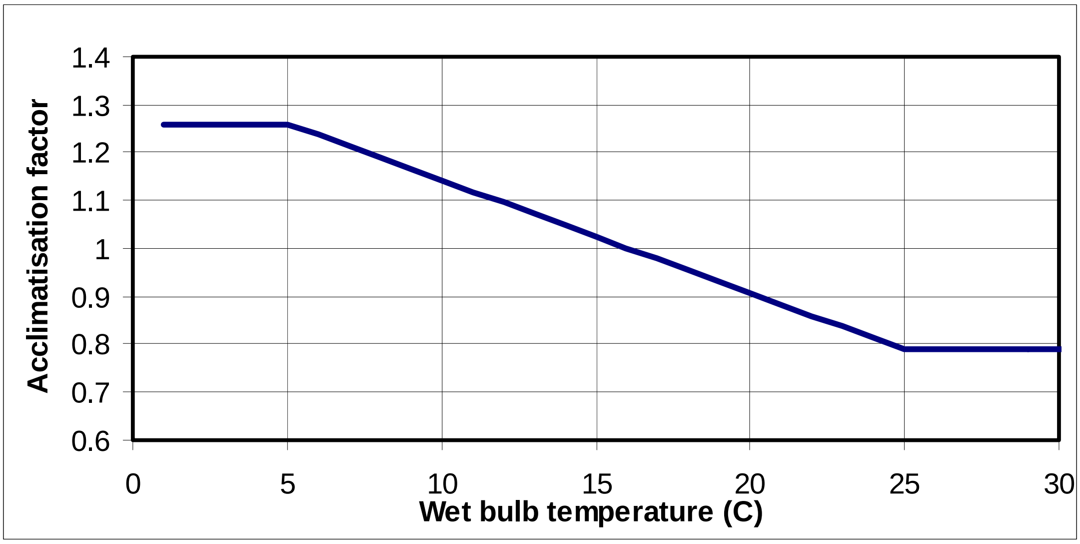
We have also not seen a strong weight influence in moderately sized (up to 60kg) sheep. For now we have settled on *n* = 0.33 for cattle and somewhat arbitrarily decreased this to *n* = 0.2 for sheep. This is discussed further in Section 3.5.2.

3.3.2 Acclimatisation

The form of the acclimatisation factor is shown in Figure 3.10. Wet bulb limits of 5°C and 25°C are taken as causing animals to be fully unacclimatised or fully acclimatised respectively. There is no physiological basis for this, however the rarity of wet bulb temperatures outside that range prevents it being a problem anyway. The calibration of acclimatisation within the range between 5°C and 25°C wet bulb is based on Voyages 3 and

4 of the SBMR.002 cattle ship ventilation project. Voyage 3 left from Townsville with *Bos indicus* weighing around 420kg and acclimatised to around 12^{o}C wet bulb. Voyage 4 left from Darwin with apparently similar animals also weighing around 420kg but acclimatised to 23^{0}C wet bulb. The difference in response between these two groups is the basis for the acclimatisation factor as plotted in Figure 3.10. The break points of the plot are also in Table 3.3.

Figure 3.10 Variation of Acclimatisation Factor with Acclimatising Wet Bulb Temperature



It may well be that *Bos taurus* acclimatise differently, however, in the absence of solid data on this, we take the factor to be the same as for *Bos indicus*. It should be noted that animals with no *Bos indicus* infusion are hardly seen in the warmer parts of Australia and so any error in the *Bos taurus* acclimatisation factor is less commercially significant.

Similarly, sheep are only exported in large numbers from the southern ports and so come from a limited range of climates. An acclimatisation effect will be difficult to establish experimentally from voyages. Also because of this, errors in the factor will have a smaller impact on risk estimates. For now we have adopted the *Bos indicus* curve as also applying to sheep.

3.3.3 Coat

The weighting to be given to coat in the risk assessment is difficult to decide because thick coats are commonly found on cold acclimatised animals with reasonable fat scores. That is; it is difficult to separate the various effects from analysis of the available data. Of course, provided that the risk answers make sense, it is not strictly necessary to decide how much emphasis to put on coat as against condition etc. Table 3.3 shows the outcome as assessed. The ‘standard’ *Bos taurus* animal is assumed to have a mid season coat. No coat variation is included for *Bos indicus*. The standard sheep is taken as shorn, with a 12% ‘de-rating’ of woolly sheep. Awassis are assumed to come in only one variety (hairy).

3.3.4 Condition

Many of the comments on the coat factor apply also to the condition factor. The descriptors for condition are fat score 1 to 5, following the well defined industry standard. Following industry opinion, and with no experimental verification, we have taken a fat score 5 as significantly de-rating the ability of all animals to cope with heat. Animals with a high fat score will also be accustomed to high fodder intakes and are likely to have a higher rate of metabolic heat generation, compounding their 'softness' under heat stress. Variation of response with fat score is one area where controlled environment room research is needed.

3.4 Thermal Modelling

3.4.1 Overview

A relation between the air speed and the critical core wet bulb difference has been developed to eventually be applied to different classes of animal. The earlier heat transfer analysis has been adapted with parameters reconfigured to allow determination of the critical core wet bulb difference. The thermal model incorporates radiation, convection (forced and natural), evaporation where applicable (forced and natural) and respiratory heat rejection. These are balanced against animal metabolic rate. Heat transfer relations for a number of conditions were calculated to assess sensitivities. These sensitivities indicated where further development of the model is required.

3.4.2 Details

For a series of wet bulb temperatures, thermal equations were set up to determine the relevant heat transfer component as described below.

- Radiation – this is a function of skin temperature and ambient conditions. It is assumed that the ambient dry bulb is the mean radiant temperature of the surroundings. The average skin temperature is used as the radiating temperature.
- Convection – two components of convection are assessed, forced and natural. For low air velocity through the pen, natural convection will dominate. Convective heat transfer is driven by the difference between the skin temperature and ambient air temperature. It was assumed that forced convection would be relevant to a proportion of animal surface (i.e. across the animals back), while natural convection would dominate on the remainder. This seems a fair assumption as air velocities underneath and on sides of animals would be low. The bulk air movement would mostly be in the space above the animals.
- Evaporation – two components of evaporation are assessed, forced and natural. As for convective heat transfer, the forced component would only act on a proportion of the animal surface.
- Respiration – this is a function of breathing rate, breath air condition and ambient air condition.

Other factors such as heat storage and direct conduction to surfaces were not assessed. Heat storage effects are not significant if conditions change slowly. Conductive heat transfer would be small compared to the other heat transfer components. The above components were summed and equated to the metabolic heat generation rate. For a series of wet bulb temperatures at a given relative humidity, the equations were balanced by firstly changing the animal skin temperature and then changing the air speed across the animal. The skin temperature was allowed to rise to an upper limit of 1^{o}C below core temperature. The air speed was then increased (if necessary) until thermal balance was achieved.

Hence, for a range of ambient wet bulb temperatures (and hence critical core wet bulb difference) the air velocity required to achieve thermal balance can be estimated. Given a known limiting critical core wet bulb difference, the required velocity to maintain appropriate heat transfer can be estimated.

A number of sensitivities are being assessed including the effect of changing humidity ratio, metabolic rate and the split between forced and convective cooling.

3.5 Validation from a Voyage

As shown in Table 3.2, sheep mortality limit data for this project were estimated from the LIVE.212 project voyages. Since then, data from Voyage 20 of the Al Shuwaikh have become available, compiled in considerable detail. We acknowledge the active assistance of Rural Export & Trading (WA) Pty Ltd (RETWA) in compiling this information. While the data themselves are commercial in confidence, the analysis method and the pertinent conclusions are described below.

The Al Shuwaikh has both open and closed decks. Data from open decks are very difficult to analyse as even short periods of low crosswind can dramatically affect outcomes, and also the stocking data do not record which side of the deck the particular line is penned in. Mortalities on the open deck were also relatively low, making statistical treatment less reliable. For these reasons, we analysed only the closed deck data.

In assessing heat stress related mortality, the influence of other causes had to be eliminated as far as possible. An assessment was made, based on the wet bulb temperature readings, as to the stage in the voyage where heat stress was a realistic possibility. RETWA then supplied mortality data by stocking line and sailing phase, so that mortalities in the initial cooler part of the voyage could be removed from the statistics for heat stress. A heat stress mortality rate for each line was then based on the number of animals in each line which reached the hot voyage phase.

The closed deck mortality data were reduced in two ways. First, the peak recorded deck wet bulb temperatures were used to make a 'prediction' of the mortality for each line, for comparison with the recorded mortality. Second, a relative mortality was calculated to see whether the trend of mortality limit with weight was correctly modelled.

3.5.1 Comparison of Actual and 'Predicted' Mortality

The deck wet bulb temperatures were recorded to the nearest degree centigrade, presumably with an observation tolerance of $\pm$ 0.5^{o}C. Using the methods of Section 6.1, the recorded deck wet bulb temperatures were also used to infer the ambient wet bulb temperature.

A number of lines had significantly higher or lower mortality rates than expected. Explanations for all except one under-prediction could be found in the data. This last under-prediction was for a line of 70kg rams from Fremantle. While the under-prediction is relatively minor, it suggested that the heavy rams may be less heat tolerant than the adopted heat stress model suggests.

The conclusion is that, with the uncertainties in temperature recorded, there is no inconsistency between voyage data and the 'HS' method given in this report, except perhaps a pointer to re-examine the mortality limits for heavy rams.

3.5.2 Relative Mortality

The recorded mortality rate for each line was divided by the 'expected mortality' figure from HS to give a 'relative mortality'. It should be remembered that the HS expected mortality figure is a statistical measure, acknowledging the weather probabilities, and does not necessarily describe an outcome for the actual voyage weather. For the present purpose, it served as a baseline from which the mortality rates of different lines were assessed relative to each other.

A few light lines appear to have been less susceptible than assumed by the model, while the heaviest lines are apparently more susceptible to heat than modelled (relative mortality of around 3). This implies that the weight factor applied in the heat stress calculation should be a stronger function of animal weight. As noted in Section 3.3.1, the exponent in the power law relating weight to weight factor for sheep was set at 0.2 on thin evidence, when geometric arguments suggested that is should be 0.33. It is recommended that this value be reviewed (and probably set closer to 0.33) at the next review of HS.

It is also noteworthy that all three of the heaviest lines on the voyage were rams. Thus, the data may include effects from both weight and testosterone. It may be that the result is due primarily to a higher metabolic rate in rams. With the present market offering almost no heavy wethers, and HS limiting the risk of future voyages, this question is unlikely to be answered by voyage results but could be addressed by controlled environment experiments on land.

4 Ship Parameters

The data necessary for estimation of Pen Air Turnover (PAT) have been received from the owners for all of the ships on the Middle East trade.

The data have been returned to the ship owners in the form of both Excel spreadsheets and database files formatted for input into HS. The ship PAT data are variable in quality. In some instances, the data are based on ‘nameplate’ or nominal design figures, while in other cases, they are sourced from as-built measurements of the flow supplied to each deck. Nominal design figures are often lower than the actual figures as ship builders and fan suppliers allow a margin to ensure that the outcome does not fall below the specification. Because of this, a detailed survey would be likely in most cases to increase the assessed livestock loading for a given risk level.

A detailed survey would also identify any maldistribution of air between decks and avoid the associated unevenness in risk.

Since PAT is such an important parameter in assessing heat stress risk, we recommend that all ships for which HS is to be applied undergo a survey as to the flowrate and distribution of supply air.

5 Open Deck Conditions

A methodology has been developed for the Computational Fluid Dynamics (CFD) modelling of generic loaded ship decks. Three modular cases have been numerically constructed to enable simulation of single tier cattle, single tier sheep and double tier sheep decks to practically any width. Widths of 24m and 36m were nominally chosen for the study. Each single case model required over 30 hours of computation time.

These deck modules have formed the foundation for all runs performed to date which include natural convection (no ventilation from cross wind or mechanical means), mechanically ventilated, and cross wind ventilated scenarios.

The specialist software package used for the current study was Fluent from Fluent Inc., Lebanon NH, USA. This package maintains approximately 60% of the global CFD software market.

Using a post-processor for data manipulation and analysis, the steady-state CFD results obtained enable a full 3D graphical representation of air temperature and humidity throughout the decks being modelled. Details are provided in Appendix C.

5.1 Animal Representation

The representation of animals within the computer models incorporates the following physical effects:

- Fluid blockage (blockage to the deck air flows by the animal's presence)
- Energy source from skin
- Energy source from breath
- Moisture mass source from skin
- Moisture mass source from breath
- Momentum source from breath action at the mouth

Geometrically, each animal is represented as a prismatic object located some distance above the deck floor. Key dimensions were chosen to be representative of typical real animals (ie. height, length, overall surface area). Using such simplified prismatic bodies enables a more efficient meshing (discretisation) of the computational domain. One major issue for consideration was the space and proximity of adjacent animals. In most instances meshing would have proved much more difficult, if not impossible, if more curvilinear or 'organic' animal geometries had been implemented.

Numerous such geometric animal models are positioned on each modular deck tier. Packing orientation and density for the initial runs has been chosen to be representative of typical conditions.

Animal breath is simulated by drawing in ambient air at the side of the head, heating it, adding moisture, and then emitting it as a steady continuous air jet from the mouth.

Typical thermodynamic data to be used in the modelling of the animals has been collected from numerous sources and rationalised to be self consistent.

5.2 Deck Representation

Each deck tier itself is modelled as a floor and roof only (no side rails) but includes provision for horizontal supply jets at each end. Roof beams are modelled as 2D blockages projecting down from the ceiling. A half-aisle has also been included to enable repetition of the same deck module across the width of the ship.

Periodic boundary conditions used on each deck module will enable taller and wider model assemblies to be readily meshed and run.

A variety of detailed ship drawings have been reviewed to determine the generic deck geometry used.

5.3 Summary of CFD Results

Complete details of all CFD results are provided in Appendix C

Figure 5.1 below summarises data from all cattle deck CFD runs performed and displays the variation of Effective PAT (defined in detail in Appendix C) with Mechanical PAT. Curves are drawn for various crosswind strengths. Results from this study have been used to develop the open deck operation guidelines in Section 7.3 of this report and the estimation of minimum required crosswind in the HS software.

Figure 5.2 below demonstrates the relationship between Effective PAT and crosswind for the cattle cases modelled (where cross wind was included).

Two 24m closed deck cases were also run; one with a Mechanical PAT of 40m/hr and another with a Mechanical PAT of 90m/hr to determine the relativity between closed and open deck mechanical PAT.

Figure 5.3 and Figure 5.4 similarly summarise the CFD simulations for sheep decks, Figure 5.2 and Figure 5.4 show the correlations adopted for Effective PAT as a function of crosswind for cattle and sheep respectively.

Figure 5.1 Summary of CFD Data for Cattle Decks. Variation of Effective PAT with Mechanical PAT

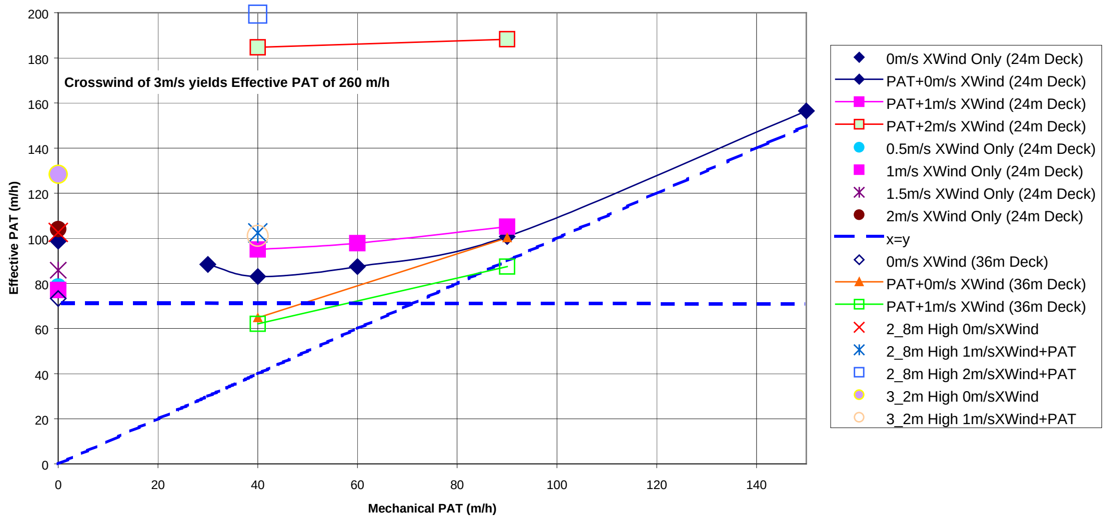


Figure 5.2 Variation of Effective PAT with Crosswind for Cattle Decks

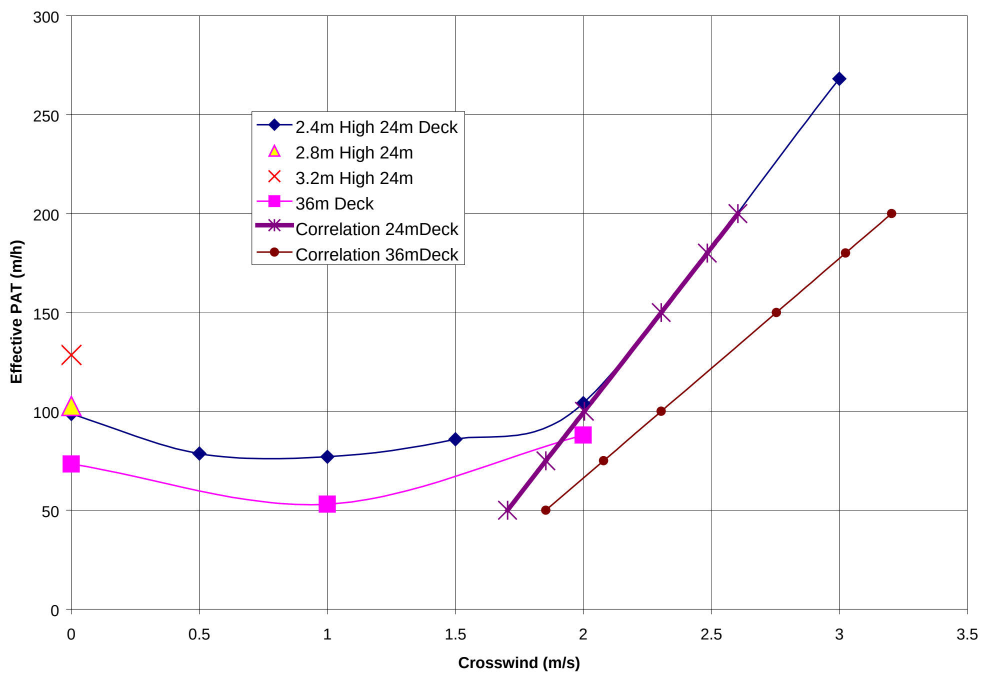


Figure 5.3 Summary of CFD Data for Sheep Decks. Variation of Effective PAT with Mechanical PAT

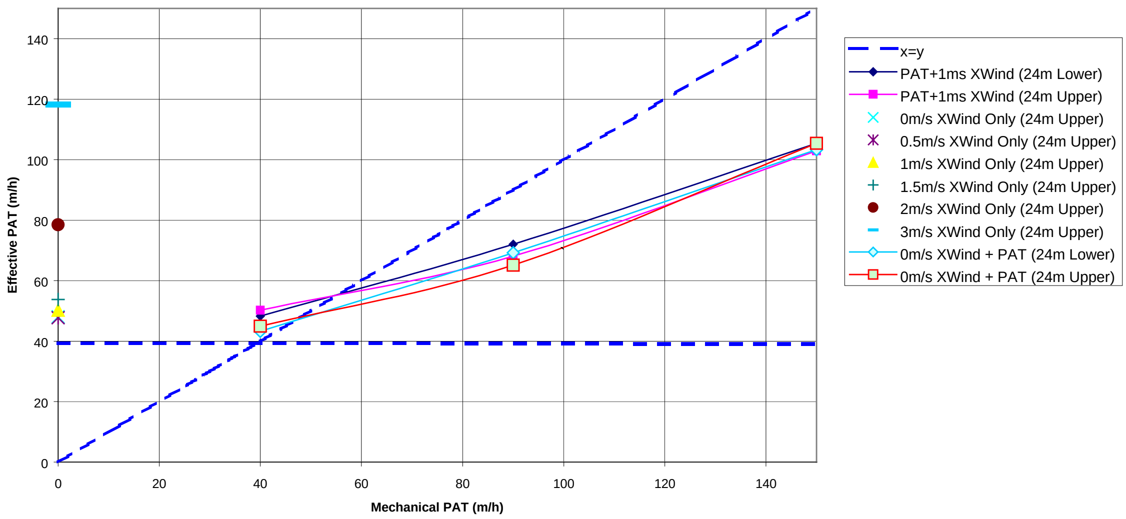


Figure 5.4 Variation of Effective PAT with Crosswind for Sheep Decks

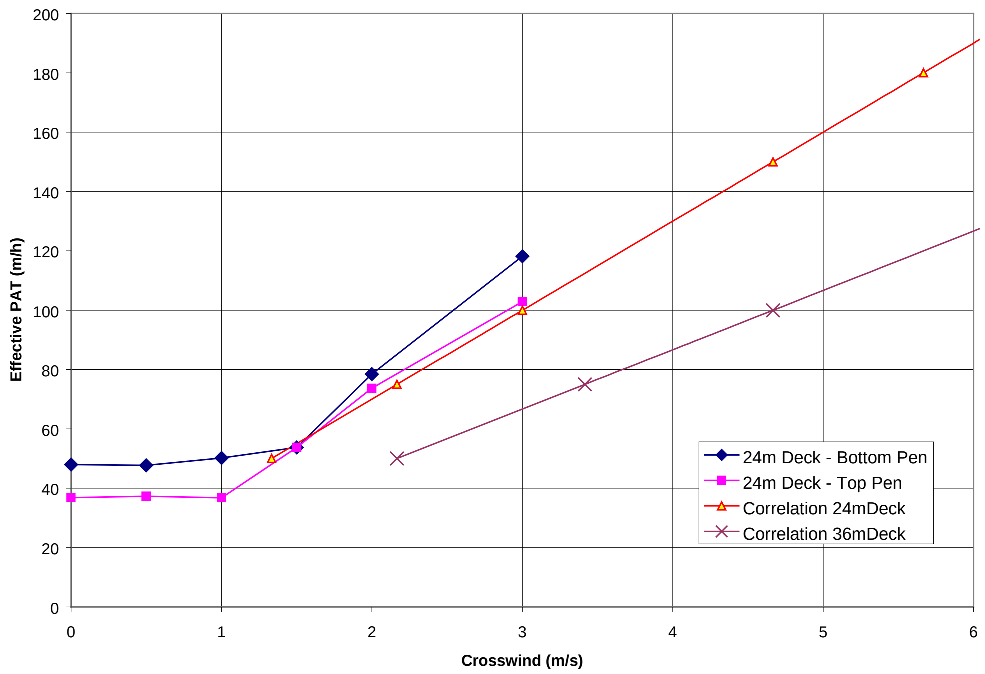
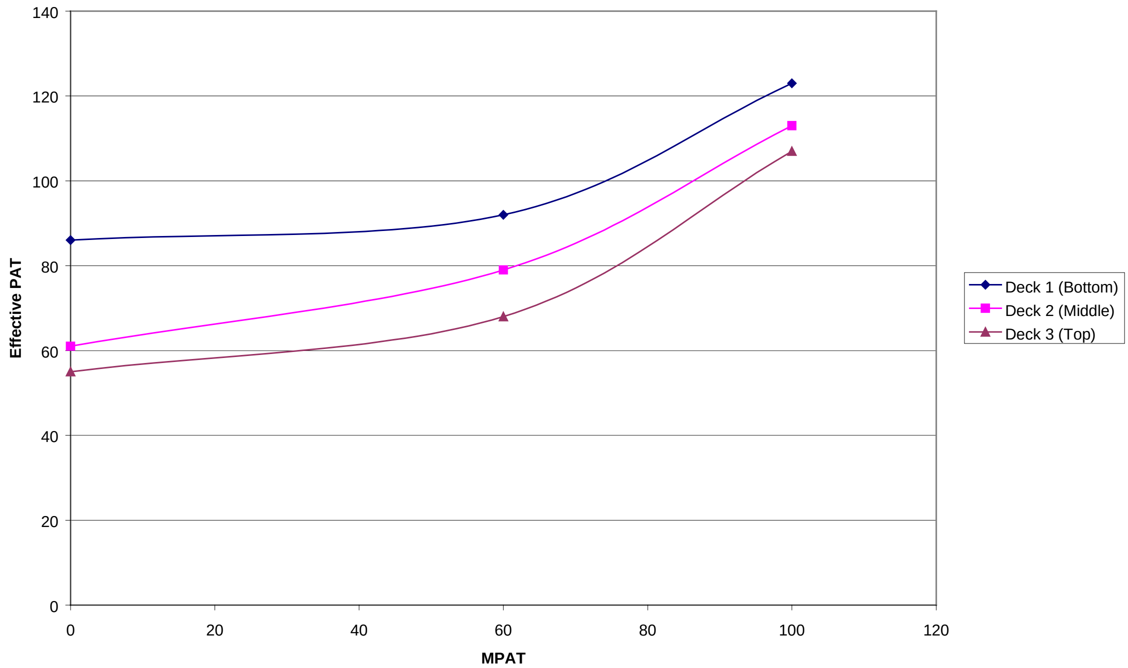


Figure 5.5 shows the effect of reingestion on three decks of cattle. Effective PAT is shown as a fraction of mechanical PAT for three successive decks.

Figure 5.5 Effective PAT Reduction by Reingestion



5.4 Deck and Crosswind Scaling

This section describes the mathematical modelling and similarity rules used to extrapolate CFD results to other geometries.

5.4.1 A Model of Reingestion

In very still conditions, heated air leaving one open deck at the sides will be partially reingested at the sides of the deck above. This obviously reduces the effective PAT on the higher deck. The amount of this reingestion depends on the mechanically supplied airflow and the deck width and height. The severity of the effect also increases with successive decks higher up the ship. The mathematics of the model are documented in Appendix D.

The result is a description for the PAT on deck 'N' based on the PAT for the lowest open deck (deck '1') and a 'reingestion fraction';

$$\mathrm{PAT\,N} = \mathrm{PAT\,1}\left(\frac{1-\mathrm{R}}{1-\mathrm{R}^{(\mathrm{N-1})}}\right)$$

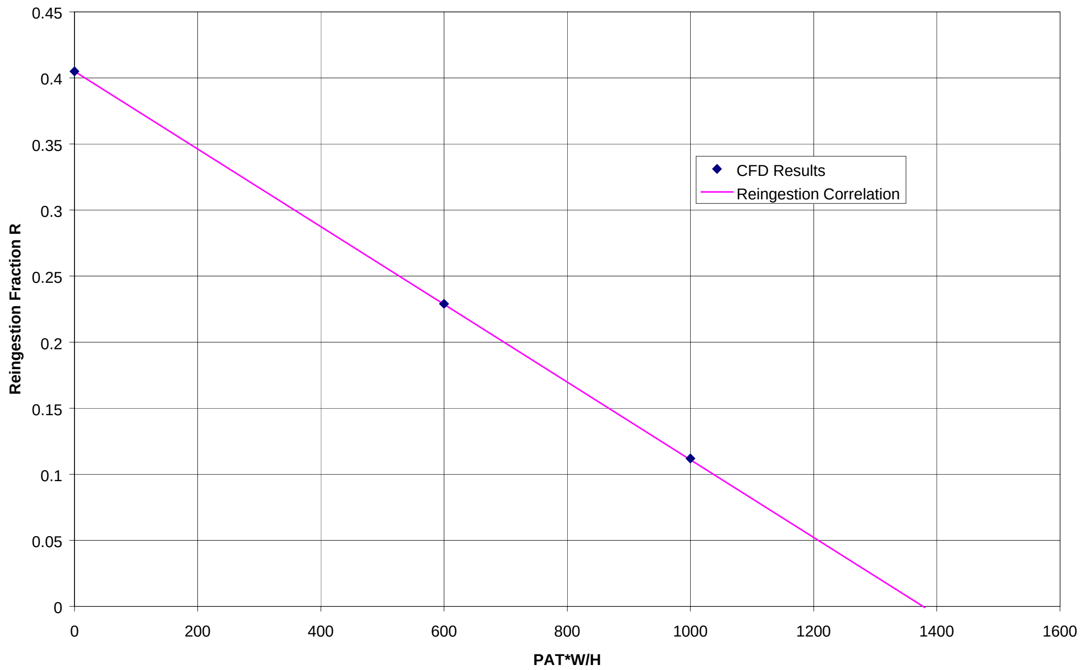
where the reingestion fraction is given by;

$$\mathrm{R} = 0.405 - 0.000294\left(\frac{\mathrm{MPAT}\times\mathrm{W}}{\mathrm{H}}\right)$$

Where: MPAT is the deck mechanical pen air turnover (m/hr)
W is the deck width (m)
H is the deck height (m)

Figure 5.6 shows the reingestion fraction interpreted from CFD runs on cattle decks and the correlation applied (equation above) to consolidate the information to allow calculation of conditions. Figure C.37 and Figure C.38 indicate that crosswinds of 1m/s are sufficient to prevent reingestion.

Figure 5.6 Reingestion Fraction Interpreted from CFD and Correlated to PAT, Deck Width and Deck Height



5.4.2 Natural Convection

As implicitly stated in the reingestion scaling above, the thermal buoyancy of air heated by the animals drives some air turnover even without any crosswind or supply air. The strength of this effect obviously depends on the deck height and width. Appendix D goes through the scaling arguments to conclude that PAT driven by natural convection (ignoring reingestion) is proportional to deck height and inversely proportional to the two-thirds power of deck width. Based on the CFD results, the natural convection PAT for a 24m wide, 2.4m high cattle deck was taken as 72m/hr with the figures for other decks scaled from that. For the 'standard' 24m wide sheep deck with 1.3m high double tiers, the natural convection PAT was taken as 42m/hr, with other decks scaled from that. The effect of the scaling can be seen in the equations in the flowsheets, Figure 5.7 and Figure 5.8.

Figure 5.7 Crosswind Assessment Flowsheet for Cattle Decks

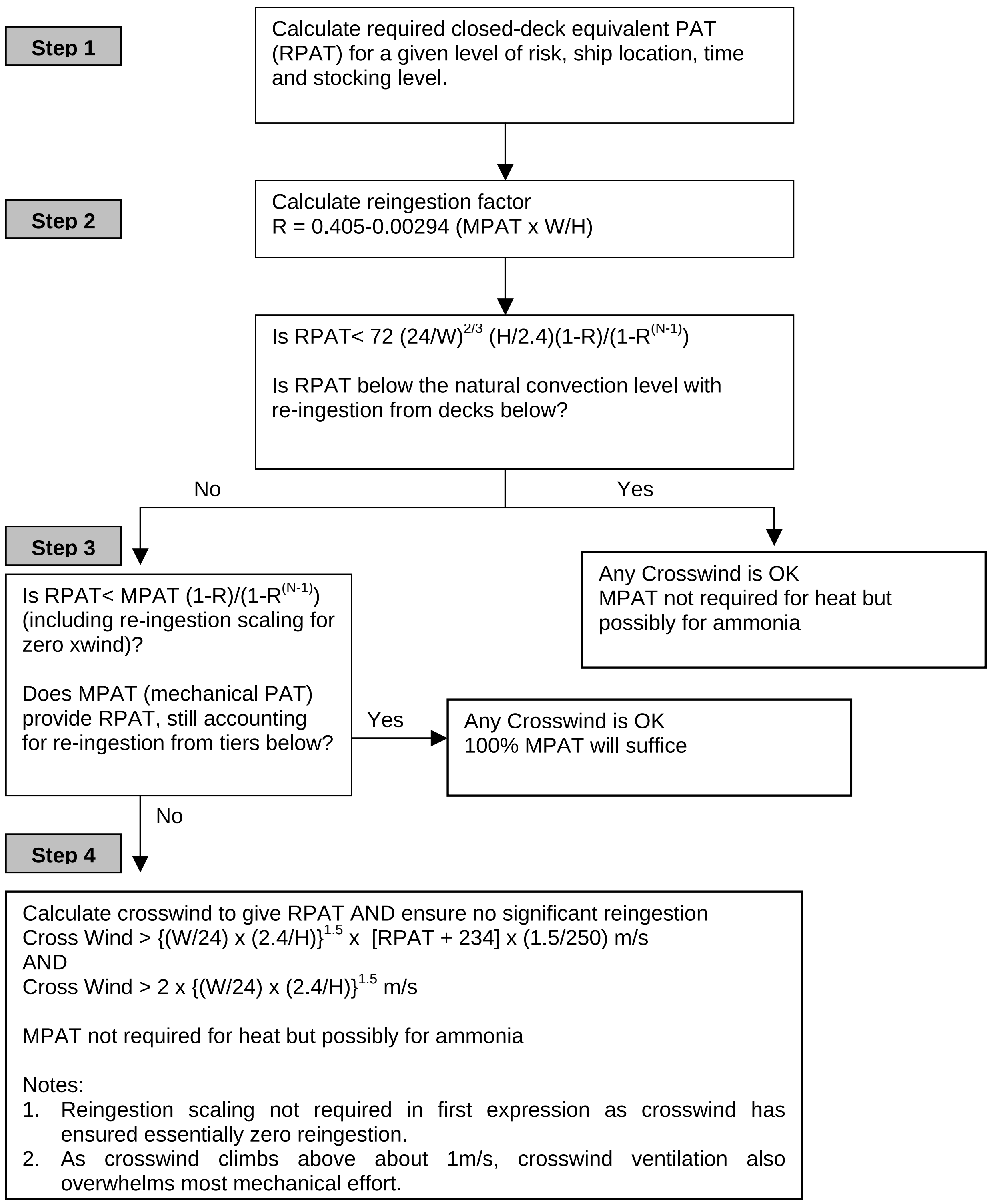
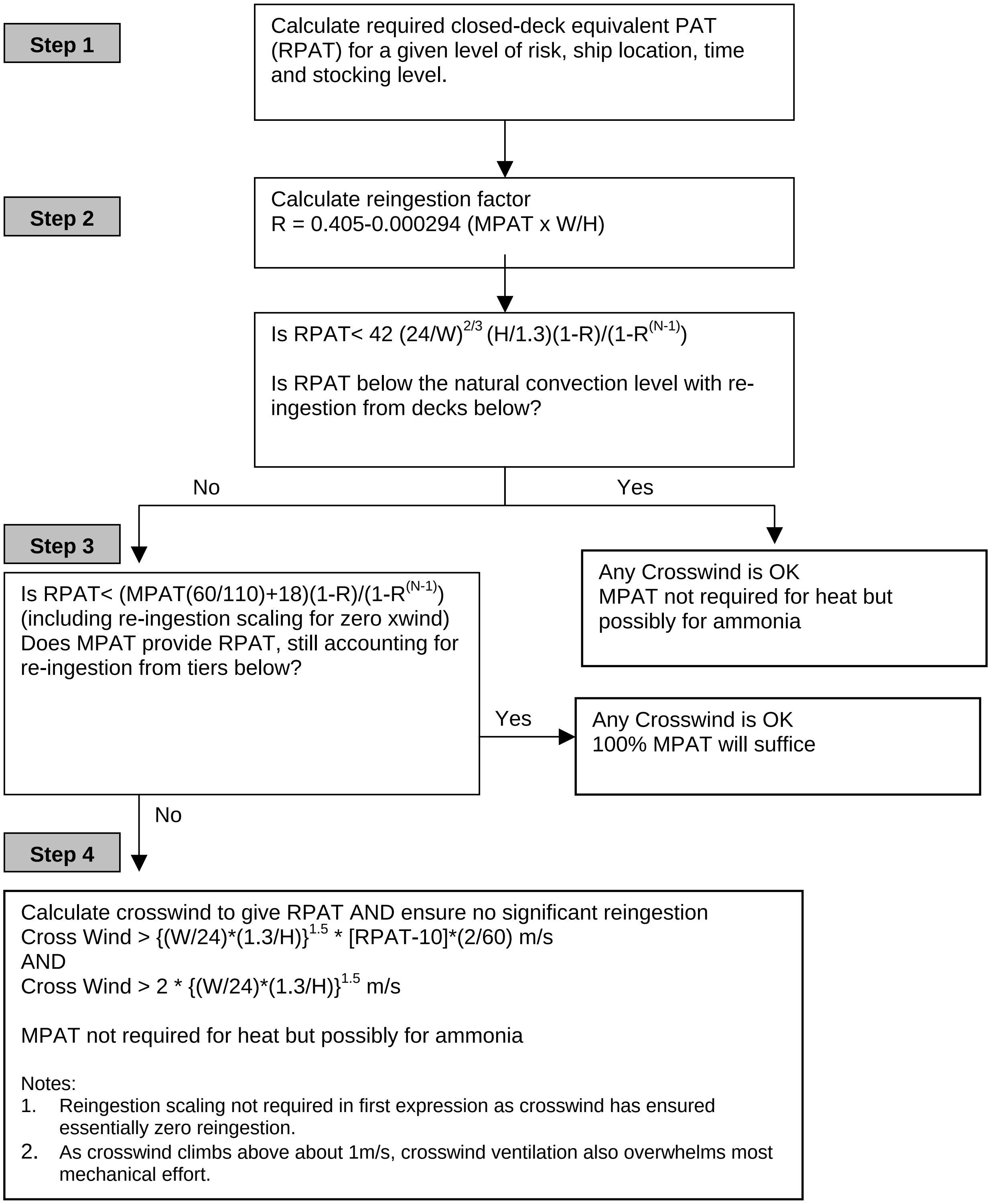


Figure 5.8 Crosswind Assessment Flowsheet for Double-tiered Sheep Decks



5.4.3 Crosswind Scaling

The resistance to crossflow is obviously greater for wide decks and less for tall decks. The scaling arguments in Appendix D conclude that the pen air turnover induced solely by crosswind is proportional to $(H/W)^{1.5}$ where H is deck height and W is deck width. At very low crosswinds, the effect of crosswind on PAT cannot be seen, as the flow is dominated by the natural convection forces. At more significant crosswinds, Figure 5.2 and Figure 5.4 gave rise to the following correlations for the 'standard' 24m wide sheep and cattle decks.

Cattle Decks: Crosswind PAT = 250 x V/1.5 – 234

Sheep Decks: Crosswind PAT = 60 x V/2.0 + 10

Where V is the crosswind velocity in (m/s) and the units of PAT are (m/hr).

These correlation equations are simply the equations describing the straight line tangents to the 24m deck data in Figure 5.2 (cattle) and Figure 5.4 (sheep). The correlations take effect in the last step of the flowcharts in Figure 5.7 and Figure 5.8.

5.4.4 Minimum Required Crosswind

The flowsheets in Figure 5.7 and Figure 5.8 show the process by which the minimum crosswind required for open decks is estimated. The steps in the process are explained as follows:

Step 1 – Required Pen Air Turnover
As mentioned earlier, the lack of useful wind statistics has led to the risk management for open decks being very different to that for closed decks. Rather than assessing risk for given PAT, the method for open decks first adopts a risk figure, and then looks for the crosswind to give the necessary PAT.

Step 1 in HS adopts the current risk guideline limit (2% chance of 5% or greater mortality) and calculates the required PAT for the livestock loading, seasonal weather variation and sailing route (Gulf or Red Sea). The weather statistics and animal factors are as described earlier. No account is yet made of the actual weather during sailing.

Step 2 – Is Natural Convection Enough?
In this step, the required PAT is compared to that which would be generated by natural convection, even taking account of the reingestion. If natural effects are sufficient, not only is there no crosswind requirement, there is also no requirement for mechanical air supply.

Step 3 – Is the Mechanical PAT Sufficient?
Still accounting for reingestion, the mechanical PAT may be sufficient to meet the required PAT. This is likely to be the case for very well ventilated ships, or more widely at cooler times of the year. In this case, no crosswind is necessary.

Step 4 – How Much Crosswind is Required?
By reaching Step 4 in the decision flowchart, we know that some crosswind is required. There are two calculations here. The first calculates the required crosswind using the correlations and scaling developed as above. It may be that the answer is very low and insufficient to eliminate reingestion. Any significant reingestion reduces PAT locally in some areas to the zero-crosswind levels and so we apply a second calculation to ensure that the crosswind is sufficient to prevent reingestion.

The flowsheets of Figure 5.7 and Figure 5.8 are embodied in Version 2.0 and later of the HS software.

6 Closed Deck Risk Estimate Calculation

The probability of heat stress or mortality for particular lines of stock being transported on a particular ship depends on:

- The type, breed, coat, condition, acclimatization and weight of livestock
- The particular ventilation rate (PAT) deck of the ship they are being transported on
- The time of year of the voyage
- The voyage route, destination port and duration of transit or stay in critical zones.

The statistical treatment of the above data has been as follows:

- The wet bulb temperature data are fitted to a Normal distribution (Section 2.3).
- The survival rate of livestock will be assumed to conform to a beta distribution (Sections 3.2 and 3.3).

The calculation procedure by which the above information is used to estimate risk is detailed in Section 6.2.

6.1 Deck Wet Bulb Temperature Rise

The environmental parameters relevant to the animals are not the ambient conditions but those in the pens. Following previous work (SBMR.002), the average rise in wet bulb temperature between ambient and exhaust flows is given by:

$\triangle Twb = 3.6 \times C \times M \times h / (\rho \times PAT)$

where: $\triangle$Twb is the wet bulb temperature increase (^{0}C)

C is the ‘constant’ of proportionality relating $\triangle$Twb to the internal energy rise. We have taken this as 0.23^{0}C/(kJ/kg)

M is the liveweight in the particular ventilation zone (kg/m^2) (M = beast weight ÷ area per head) (275kg/m^2 for cattle, 180kg/m^2 for large sheep, etc.)

h is the ‘per mass’ rate of metabolic heat. This is variable however here we will take 2W/kg for *Bos indicus* cattle, 2.4W/kg for *Bos taurus* cattle and 3.2W/kg for sheep.

ρ is the density of air (1.2kg/m^3)

PAT, the pen air turnover in m/hr, is the ratio of the fresh air flowrate (Q) in m^3/hr to the pen area (A) in m^2

The factor 3.6 at the front corrects units from W to kW and hours to seconds.

For deck areas with very low ventilation rates, there may be little jetting and slow mixing around the deck. In such cases, there may be differences in wet bulb temperature around the deck. Where air supply is strong, the assumption that the deck air is evenly mixed is a reasonable one, with air inlet jetting causing fairly rapid swirl and mixing around the deck.

To the extent that there are small differences in wet bulb temperature between apparently identical pens on one deck, the resulting spread in primal response will be indistinguishable experimentally from the physiological variability of the animals. That is; the variability in below-deck conditions will effectively widen the limits of the beta distribution assumed for the animals. Since those distributions are, to some degree, uncertain, a correction to them may be even less certain. More importantly, the beta distributions have been based on estimated 50 percentile data and estimates of wet bulb temperature causing 0.5 to 2 percent mortality rates on real ships. Because the data are sourced from the ships, they inherently include the effects of the deck non-uniformity on those ships. The difficult task of deck non-uniformity correction is thus avoided for the risk assessment.

Because the deck wet bulb temperature rise is a function of both PAT and the stocking rate, the effective deck wet bulb probability is calculated for each stocking entry in the software. A stocking entry is one line of animal on a particular deck.

6.2 Statistical Combination of Weather and Animal Parameters

With the wet bulb temperature probability distribution calculated as above for each line of animal on each deck, the mortality statistics are estimated and presented in two ways: i) expected mortality rate, and ii) probability of reaching a given mortality level.

6.2.1 Expected Mortality Rate

This is the standard way in which statistical conclusions are expressed. If a random experiment (the weather is 'random') were repeated exactly, many times over, the average outcome of all repetitions is termed the 'expected' outcome. Along with the clear mathematical meaning is a clear mathematical evaluation. Any narrow band of wet bulb temperatures has a certain probability of occurrence. The mortality for that event is the cumulative mortality up to the wet bulb temperature in question. By multiplying the probability of the wet bulb falling in that narrow range by the mortality for that wet bulb, we get a contribution to the estimate of expected mortality for that small fraction of possible weather. By repeating the calculation for successive small ranges of wet bulb temperature to cover all possible wet bulbs, and adding all the results, the total is the expected mortality for that stocking entry.

When the wet bulb bands considered become vanishingly small, the summation to get expected mortality becomes an integral. The mathematics is then as follows.

The cumulative mortality probability at a given wet bulb temperature M(Twb), is the integral of the mortality probability density function, m(Twb), up to that wet bulb:

$$M(Twb) = \int_{-\infty}^{\mathrm{Twb}} m(t)dt$$

The expected mortality rate is the integral over all wet bulbs of the product of the wet bulb probability density function, p(Twb), and the cumulative mortality probability M(Twb):

Expected Mortality = $\int_{-\infty}^{\infty} p(t)M(t)dt$

The above calculation is implemented in the risk estimation software for the weather, p(Twb) being Normally distributed and the animal response function, m(Twb), being a beta distribution as described earlier.

6.2.2 Probability of 5% Mortality

The 'expected mortality', while statistically valid, is not necessarily the preferred measure for those seeking to judge acceptability of risk. The emphasis is normally on the likelihood of mortality exceeding a limiting level. The current reporting limits are 1% mortality for cattle and 2% for sheep. At these levels, it is difficult to verify from voyage reports, the importance of heat stress relative to other causes. It is preferable for assessing past events and future outcomes, to look at a higher mortality level with an appropriately lower likelihood (reduced probability). We have chosen 5% mortality. At this level and above, if heat stress is not a major cause, the alternative explanation will be obvious (fire, sinking, etc.). We also note that adopting a probability measure at a higher mortality level does not imply acceptance of greater risk. A single voyage will have different probability of 1% and 5% mortalities, but both will be a snapshot of the same risk profile. We note that the adoption of risk standards is not the role of this report, neither do we comment on the variation of risk standard with mortality level.

The calculation of probability for a given mortality level in one stocking entry is more straightforward than that for expected mortality. The drawback is that combined results, to give a voyage average across different lines, are not necessarily meaningful. Consequently, these figures are given only for each closed deck stocking entry and not for the voyage as a whole.

To find the probability of exceeding 5% mortality, the cumulative distribution of animal response is first used to find the wet bulb temperature corresponding to 5% mortality. This wet bulb temperature is then compared to the cumulative probability curve for wet bulb temperature on the particular deck to find the probability of wet bulb temperature exceeding the 5% mortality value. As before, the wet bulb probability on the deck is taken as the ambient wet bulb probability shifted along the wet bulb scale by the deck wet bulb temperature rise.

6.2.3 Duration of Exposure

An early ambition for the statistical assessment was to allow, in the estimation of risk, for duration of exposure in a particular zone. This would have worked by adjusting the beta distributions of animals such that they become more susceptible to heat following some exposure, and to carry a progressive risk calculation along the voyage route. Several problems emerged with this approach. The largest problem is that, statistically, the weather in adjacent zones is strongly correlated and the weather, particularly wet bulb temperature is very strongly auto-correlated over time. This means that the probabilities of wet bulb temperature on successive days are not independent of each other. A far more sophisticated model of the weather involving comparison of weather time scales and ocean zone transition time scales would be required. The statistics then would most probably require a Monte-Carlo type simulation for each stocking entry as it was completed, requiring significant computing. In addition to the difficulty of implementation, there are very real limits on the benefits which may accrue from this approach. In particular, with heat at extreme levels, risk increases with duration, while heat at lower levels may generate some level of acclimatisation and protect against a subsequent, more severe, episode. That is; it is by no means clear how the animal parameters should be adjusted with duration. Other problems include:

- Uncertainty about final route, with multiple ports of discharge changing during the voyage.
- Relaxation of stocking density after the first discharge port changes deck parameters.

In the northern summer, it is apparent that the greatest risk occurs in the southern areas of the Gulf and the Red Sea. Transiting through those zones creates a risk. Transiting slowly creates higher risk, but only marginally so due to the strong auto-correlation of wet bulb temperatures, and the small increase in duration in those zones.

If an appropriate mathematical allowance can be defined, the first duration related risk increase to be allowed for would be where the first port of discharge is in the hottest zones. The additional duration of exposure due to tying up is probably the most significant duration effect.

7 Open Deck Risk Management

7.1 Overall Approach

Section 5 indicates the degree to which cross wind controls conditions in open decks. An assessment of risk on open decks also requires a knowledge of the wind behaviour in ports of discharge. There are two approaches to this. The first is to assess the fraction of time for which the wind is below some critical level. This approach however, ignores the ability of the ship's master to avoid the obvious still conditions. The real statistic of interest is the probability that the cross wind drops below the 'critical' level while the vessel is in port, catching the master by surprise. Unfortunately, while we have identified the statistic of interest, the available data are patchy and give no such temporal information. There are insufficient data to realistically identify true diurnal trends. The countries contacted for more detailed port wind data were not able to provide it. The ship wind data available are largely recorded by humans and exhibit known biases. There is a tendency for wind speeds to be recorded in multiples of 5 knots. Some numbers (e.g. 11) are not favoured by humans. There is also a slight bias against odd numbers (except 5). In higher wind speeds, there is a tendency to bias the observation towards the higher wind gusts rather than the true mean wind speed. This characteristic becomes less evident in wind speeds below 15 knots.

A targeted monitoring programme in the discharge ports would help to fill the information void, however initial data would only be applicable one year after commencement, with statistics becoming more solid over several years.

As the wind data limitations preclude a numerical risk estimation for open decks as done for the closed decks, we cannot foresee an 'acceptable risk' benchmark for open decks. Across many industries, the approach in such instances of ill-defined probability is to take measures to make the risk 'as low as reasonably practical'. This approach, often labelled with the acronym 'ALARP', obviously has less statistically predictable outcomes and the benchmark is set not by a risk level but by consideration of what risk reduction measures are 'reasonably practical' and whether those measures have been taken (in this respect, the open deck risk approach becomes more like that applied to the risk of salmonellosis).

It is our view that, for ships built after the date of Revision D of this report, it is reasonably practical to mechanically ventilate open decks to give effective pen air turnovers in still air that would meet risk requirements if assessed as a closed deck. That is; we recommend that risk for open decks on newly built vessels be assessed as for closed decks. While this may add capital cost (it is not certain), it will reduce the risk of heat stress and, at the same time, free the vessel from operational restrictions on docking when 'still' air is likely.

The avoidance of risk and achievement of greater operational flexibility are in themselves good business reasons for 'full' ventilation of open decks and may, on a cost benefit analysis, justify any extra capital and operating costs involved.

For open decks on existing vessels, which cannot already meet closed deck risk criteria, the 'reasonably practical' benchmark will obviously be different. We consider that it is reasonably practical for most of the existing fleet to 're-furbish' existing ventilation systems to increase flowrate. We understand that there are many ships which have still not taken such simple measures as replacing tight 'mushroom cap' inlets with either bell mouth inlets or low-loss covered inlets.

Other opportunities to economically improve open deck air supply on a ship by ship basis should be identified by a professional engineering review of each ship involving both measurement and calculation. In order to avoid a conflict of interest in making such a firm recommendation in this report, Maunsell will, on request, nominate others who are capable of undertaking the work.

Once all reasonably practical measures have been taken with the ship's equipment to give generous supply air flows, if the open deck risk is still not acceptable by closed deck assessments, the 'reasonably practical' benchmark is different again.

Having exhausted equipment options, we look to the reasonably practical operating measures. There are opportunities for operating ships to avoid still air and to use crosswind beneficially. The practical avoidance of still air requires knowledge of the port weather patterns. We give below general descriptions of the discharge port wind patterns, followed by 'reasonably practical' guidelines for when not to dock. The generality of the information on which these criteria are based and their simplistic nature mean that they are likely to be inaccurate in some circumstances. The criteria are intended to be separable from this report, to be updated and maintained by the industry as further data come to hand.

In summary, we propose that the risk management of open decks be addressed in three ways:

(i) Build new ships with 'full' ventilation of open decks and assess risk on those vessels as for closed decks. Over many years, with fleet renewal, this will make other approaches redundant.
(ii) Improve the ventilation of existing open decks as far as is reasonably practical.
(iii) Require that open decks not meeting closed deck criteria be operated to a set of guidelines which minimise the risk due to low crosswind.

7.2 Discharge Port Wind Behaviour

7.2.1 General comments

In port, there is a higher likelihood of persistently calm conditions a few hours after dark through until mid morning, due to the formation of nocturnal temperature patterns. Also, if it is calm offshore, there is a very good chance that nearby ports will also have light winds. At the very low wind speeds we are looking at here, there may be a significant variation in the number of calms experienced from one part of the port to another (assuming there are large warehouses, piles of shipping containers, etc near by). The orientation of the ship relative to the prevailing wind direction is also important, as wind along the ship generates no effective crosswind. Also, the superstructure of the bridge can act as a wind break for the decks on its lee side.

There are a number of "rules of thumb" that can be applied as follows:

- In general, if it is nearly calm over the open waters outside the port, conditions inside the port are likely to be worse.

- If winds are light, in the mid afternoon in particular, expect a very calm night unless a significant weather system is approaching.

- If there is a uniform deck of cloud overhead, prolonged calm weather is more likely, particularly if winds are light as the cloud deck approaches. This rule has fewer exceptions in the summer months.

- With approaching cumuliform cloud, especially cumulonimbus (thunderstorm clouds), there is a good chance the light wind period is about to end.

- Outside of the coldest months of the year (November to March), in sunny conditions all Middle East ports can be expected to have a sea breeze in before noon.

- If there is a breeze from the north at sunrise (except at Kuwait and Aqaba), expect an early fresh sea breeze.

- If there is a breeze from the south at sunrise (apart from Aqaba, Kuwait, Fujairah and Muscat) there could either be an approaching dust storm or several hours of calm conditions are possible. Wait until the sea breeze arrives before entering port. For Fujairah and Muscat, a moderate southerly or south easterly often means the winds will not drop to calm quickly.

7.2.2 Red Sea Ports

Abadiya

Data are too sparse for a good distribution. There is a definite wind minimum in March (2 knots or less around 18% or the time) that extends into April. Also a slight minimum from October to November. The March into April period of time is when the sea breeze effects are reduced and the winter weather patterns that produce windy conditions are in decline. The October to November period is prior to the winter weather systems developing but at a time when the sea breezes are in decline.

Aqaba

Data are too sparse to draw any conclusions. It is to be expected that the comments for Abadiya apply here in terms of seasonality of calms.

Jeddah

A reasonably representative set of wind observations are available from the ship data. The greatest number of calms tend to occur in the seasonal transition periods of April – May and also October-November. They will almost always be in the early hours of the morning to mid morning. It is rare for the winds to be calm in Jeddah after mid morning. It is very well exposed to the prevailing NNW winds that blow down the Red Sea. Also periods of calm weather tend to be short lived in this part of the Red Sea (12 hours duration or less). They are likely to occur at times of elevated wet bulb temperature in the summer months.

7.2.3 Gulf Ports

Kuwait

A very patchy data set with some months too poorly represented to make any comment. The most prolonged calm periods are during the late summer period from August to September. At this time of the year the Gulf is very warm to hot and sea breezes can become less reliable and more prone to dying out quickly at sunset. Light winds can last several days at a time. There are shorter calm periods during the colder winter months in between the passage of the northern winter weather systems. The duration of these varies with the weather pattern.

Dhahran/Bahrain

The dataset is quite variable from one month to the next with some months having insufficient data for firm conclusions to be drawn. There are two periods of the year prone to calm weather. The first is in March - April during the transition period from winter to summer when the winter weather patterns have eased and the sea breezes are yet to become reliable. The second is from August to September. At this time of the year the Gulf is hot and the broad scale weather patterns tend to be weak. This situation is exacerbated by the Gulf of Salwa to the south that becomes even hotter than the broader Gulf during the summer months. These conditions mean light winds over open waters and weak sea breezes along the coast. These conditions can last several days.

Dubai

A reasonable dataset is available for the Dubai region. Dubai is relatively well exposed to the northerly winds that tend to blow down the Gulf for much of the year. The calmest conditions tend to occur in winter (December to February) when the weather systems force a weak ridge over the central and southern Gulf. Also during the passage of the ITCZ across the region (separating the northerlies from the south easterlies that tend to blow up the Gulf of Oman during the height of the SW Monsoon through the Arabian Sea). This occurs twice - once in July as it moves northwards and again in September as it returns to the south, with a slight decrease in the number of calms in August compared to the months either side. These calms are likely to be persistent and coincide with high wet bulb episodes.

Fujairah

This dataset looks suspicious in the fact that there is a very large variation in the number of observations from one month to the next. It is apparent that there is a relatively high incidence of light wind episodes in the Fujairah region. During the winter months this region tends to sit under a weak ridge. During summer, the ITCZ passes over the region twice. It tends to be sheltered from the prevailing northerly winds that blow down the Gulf proper and is far enough up the Gulf to be out of the core of the prevailing SE winds during the height of the SW Monsoon.

Muscat

The region off Muscat has one of the best sets of wind data available. However, the port itself tends to be a little more sheltered than these data would tend to indicate as it sits in the lee of a point to the south east that shelters it from the prevailing south easterlies during the SW Monsoon. Muscat is subject to calm conditions year round as there tends to be poor assistance to the sea breeze from the prevailing weather patterns. The windiest months are July and August when the SW Monsoon is at its peak - assisting the SE airflow up the Gulf of Oman. This dies away quickly with October and November being the calmest time of the year with calm conditions close to 20% of the time. During other times of the year there is likely to be a weak pressure gradient over the region. However, on most occasions a sea breeze can be expected during the afternoon, dying out quickly at sunset.

7.3 Open Deck Operation Guidelines

While the guidelines follow the same method for all open decks, limits are different for different deck widths and different animals. The descriptive material below is covered more precisely in Section 5.4, however the tables and descriptions can assist in understanding the issues.

7.3.1 Effective Crosswind

As mentioned earlier, the orientation of the dock relative to the breeze is very important in determining the crosswind. The effective crosswind to be used in this assessment is simply the windspeed multiplied by the sine of the angle between the wind direction and the ship's keel line:

$$V_{effective} = V\sin\text{(wind angle)}$$

That is; a wind directly along the vessel generates no crosswind, while one from the beam (wind angle = 90^o) is 100% crosswind (sin(wind angle) = 1). While this can be evaluated readily on a calculator, the factor (sin(wind angle)) to go from wind speed to effective crosswind is also tabulated below for wind angles in steps of 10^o.

Table 7.1 Crosswind factor (sin(wind angle))

Wind Angle from Keel Line	Crosswind Factor
0	0
10	0.17
20	0.34
30	0.50
40	0.64
50	0.77
60	0.87
70	0.94
80	0.98
90	1.0

For example; a 10 knot breeze from 20^o (port or starboard) of the (bow or stern) gives an effective crosswind of 10 x 0.34 = 3.4 knots (1.7m/s).

7.3.2 Effective PAT in Still Air

As shown by the CFD, the animal heat generates buoyancy driven flows which cause some air exchange. With zero wind, the hot plume leaves the deck ceiling on both sides (for example; Figure C.35) and would be reingested into the deck above. In this way, successively higher decks would get hotter and hotter (the effective PAT approaches zero). With more than one open deck (one tier cattle or one, or more than one, two tier sheep deck), risk levels may become unacceptable if crosswinds are so low that the plume leaves both sides of the deck. Table 7.2 gives the minimum crosswind required to ensure through ventilation, with no exhaust on the upwind side (for example; Figure C.39).

Table 7.2 Minimum Crosswind for Through Ventilation

Deck Width (m)	Minimum Crosswind	
	(m/s)	(knots)
18	1.0	2.0
24	1.2	2.4
30	1.4	2.8
36	1.6	3.2

The consequences for higher decks at crosswinds below this are given in Section 5.4.1.

7.3.3 Effective PAT in Light Crosswinds

The CFD work in Section 5 demonstrated that buoyancy driven ventilation in open decks did generate some effective PAT. Where the crosswind is higher than in Table 7.2, but still not strong enough to control conditions, the combination of light breeze and buoyancy ensures a certain effective PAT on the decks. At some times of the year, this may be sufficient to keep risk low. Table 7.3 gives the effective 'natural' PAT in light cross breezes.

Table 7.3 Effective Natural PAT for Crosswinds Greater than in Table 7.2 (no re-ingestion from decks below)

Deck Width (m)	Effective PAT (m/hr)	
	Single Tier [(1)]	Two Tier [(2)]
18	94	47
24	80	40
30	72	36
36	64	32

[(1)] 18m and 30m decks extrapolated from 24m and 36m deck models
[(2)] Estimates based on pen area increase only. No results for the two tier case.

7.3.4 PAT with Strong Crosswinds

Strong crosswinds obviously generate effective ventilation of open decks. Table 7.4 gives estimates of the effective PAT for stronger crosswinds.

Table 7.4 Effective PAT (m/hr) with Crosswind

Deck Width and Tiers	Crosswind (m/s)				
	1.0	**1.5**	**2.0**	**3.0**	**4.0**
18m Single Tier	88	94	117	300	400
18m Two Tier [(2)]	44	47	59	150	200
24m Single Tier	N/A	80	100	260	350
24m Two Tier [(2)]	N/A	40	50	130	175
30m Single Tier	N/A	72	88	230	300
30m Two Tier [(2)]	N/A	36	44	165	150
36m Single Tier	N/A	N/A	80	210	280
36m Two Tier [(2)]	N/A	N/A	40	105	140

[(2)] Two tier data have been simplistically estimated as half the single tier values. This is optimistic as, not only is the pen space roughly doubled, the cross flow resistance is higher, decreasing air flow.

As can be seen from Table 7.4, even a moderate crosswind (4m/s or 8 knots) ensures high PAT figures.

This conversion from m/s to knots is: 1m/s = 1.944 knots.

7.3.5 Operating Guidelines

These guidelines are recommended for open decks which have not met risk criteria when evaluated as closed decks.

Constraints

1. Do not proceed into port (at any ambient temperature) if it seems plausible that the crosswind will fall below the values given in Table 7.2.
2. Estimate (by using HS software or manually using the information in this report) the PAT and hence the crosswind required for a particular vessel loading and destination port.
3. Establish the preliminary wind direction and the deck orientation in the port, calculate the crosswind factor (Table 7.1) and the true wind speed required from the prevailing direction.
4. After reading the port wind notes in Section 7.2, plan to stay at sea if there is a small chance that crosswind at the dock will fall below required values.
5. Carry sufficient feed and water to cover for likely docking delay or to reach an alternative (windier) port.

8 Software

The software is further detailed in the HS User's Manual and the program help file.

8.1 Function

The purpose of the 'HS' risk estimate software is to enable both exporters and shipping company personnel to be able to estimate a mortality risk for livestock, given voyage, vessel and livestock details. Within the software package, weather and livestock survival data are used, with input given by the user, to calculate an estimated risk for a particular set of circumstances.

8.2 Platform

The software is developed using Visual Basic for the front end of the package, including the graphical user interface and risk estimate calculations. Microsoft Access is used to develop the database used to store the information required to perform the necessary calculations.

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Appendix A Weather Details

A.1 Discharge Port Climatology

The following section looks specifically at the periods from May through to October and November to April on a port by port basis, with the full year's wet bulb data included in Appendix A.

Muscat

Data from Seeb International Airport was used as a proxy for Muscat port.

Muscat is the southern-most port considered in this report. Situated on the western shores of the Gulf of Oman, it is sheltered from the influences of winter low and frontal systems that affect ports further to the north. The Gulf of Oman is relatively deep off Muscat, as it is off Fujairah, and hence its temperature is less variable than for ports further to the north. The mean daily dry bulb and wet bulb temperatures closely match those of Fujairah, although they are very slightly lower. Temperatures (both wet and dry) climb significantly during April with the movement of the sun north of the equator. It is subject to occasional relatively short lived bursts of heat, although its more southern location makes these bursts slightly less frequent and not as strong as at Fujairah as they tend to be associated with the passage of developing heat troughs linked to northern frontal systems. The wet bulb temperatures also begin to rise during March and April, although not to a level that would be likely to cause heat stress in livestock with any significant frequency.

Being the southern most port, the sun is higher in the sky than at other ports by the start of May. Wet bulb temperatures above 26^{o}C are common from May onwards. Most days from June to September experience humidities with the wet bulb temperature above 26^{o}C. Temperature and humidity start to drop rapidly during October, although there are still short-lived high humidity events. The most consistently humid month is July, although the decline in humidity in August is minimal. The month of September sees the greatest range of wet bulb temperatures, with a small number of extreme events where the wet bulb temperature exceeds 30^{o}C.

Fujairah

One of the southern-most ports located just south of the Straits of Hormuz, Fujairah does not experience the same degree of cool to cold conditions as the ports further to the north. The deeper waters of the Gulf of Oman also do not cool to the same extent as the shallower waters of the Persian Gulf further to the north. None-the-less, the conditions at Fujairah do moderate significantly from those experienced between May and October. There tends to be a slight increase in the breezes through the Straits of Hormuz that helps to moderate the climate a little in Fujairah during these months. Temperature and humidities reach a minimum value in mid January through to early February when they start to climb again. Although Fujairah does start to experience consistently higher temperatures in April, the wet bulb temperatures do not reach the same levels as they do in the months that follow.

The hot and humid season in Fujairah sets in by early May. This is the earliest of all the ports included in this report. The humidity rapidly climbs during May and remains high from June through until the end of September. There is little difference in the humidity levels between July and August, which are the most humid months of the year. Some cooler and drier spells start to be experienced in October, but it is still possible that animals may experience heat stress caused by high heat and humidity.

Dubai (applicable also to nearby Emirates ports)

Dubai, located in the southwest of the Persian Gulf, is consistently warmer than the ports to its north. Although not directly affected by the mid-latitude frontal systems further north, it benefits from the cooling of the Persian Gulf and the cool winter-time conditions over the inland desert areas. January is the month with lowest wet and dry bulb temperatures, although the rise in February is only marginal. Temperatures start to rise in March and particularly April as the inland deserts begin to warm with the increased length of the days. However, the hot spells still tend to be short and transient with the wet bulb temperatures not responding quickly.

Dubai is inside the Persian Gulf and hence is affected by a mixture of the southern extremities of the northern weather systems and the heating and cooling of the Gulf itself. Its weather regime is somewhat different to that of Fujairah and Muscat. The hot and humid season commences in late May and is well established by mid June. July is the most humid month with August only fractionally lower. The high humidity levels do not really drop away until the first week of October when the transition is quite rapid. By the end of October high humidity events become less common.

Doha

Being relatively open to the Persian Gulf waters without the continental effects of the Arabian Peninsula experienced by most of the other ports, Doha's humidity profile tends to mirror the response of the sea temperatures of the open waters of the Persian Gulf. Initially relatively mild and dry in May, the humidity levels climb slower than for the ports further south during June and even into the first week of July. August tends to be a very humid month with few lower humidity spells. The humidity levels drop slowly during September and more rapidly in October, although there are still a few high humidity episodes even in mid October.

Bahrain

Although very close in both latitude and proximity to Dhahran, its location on an island at the top of the Gulf of Salwa provides Bahrain with arguably one of the mildest of climates of the eight ports considered here during winter. Its wet bulb temperatures are consistently higher than both Dhahran and Kuwait, linked directly to the fact it is surrounded by the Persian Gulf. It could well be that these wet bulb values more closely reflect the values that ships plying the Persian Gulf will be experiencing during winter. As is the case for Kuwait and Dhahran, the wet bulb temperatures reach a minimum value in late January and February when they slowly start to climb again. Dry bulb temperatures also start to climb in March and April, but not to the same extent as at the mainland ports.

Bahrain's position on an island surrounded by the Persian Gulf makes its humidity profile similar to that of the Persian Gulf itself. The similarities with Doha are self evident with fewer low humidity episodes when dry desert air moves over the city. It is prone to periods of persistent high humidity, however, in terms of pure temperature, it does not get as hot as either Doha or Dhahran.

Dhahran (Ad Dammam)

Dhahran's humidity profiles should provide a close approximation to those of the nearby port of Ad Dammam.

Situated a few hundred kilometres south of Kuwait, Dhahran displays many of the same climatic features as Kuwait, only not quite to the same extent. The shallow Persian Gulf off Dhahran cools during the winter months but not as much as it does further north. Therefore wet bulb temperatures do not fall quite as much as they do further north, although they do moderate considerably from their summer values. They reach a minimum in late January to early February. Dry bulb temperatures, which remain relatively low from November through until the end of February, start to rise in March with a bigger jump in April. As in Kuwait, the wet bulb temperatures take longer to respond to rising air temperatures due to the moderating influence of the Persian Gulf.

Sea breezes are an almost daily occurrence, with strong wind events usually limited to one or two days at a time, however when they do occur, humidity can drop markedly. Dhahran tends to experience a mix of continental air and Persian Gulf air weather patterns, giving it a relatively wide range of humidities, even in the peak months of summer. However, the shallow waters of the Gulf of Salwa to the south east provide a reservoir of very high humidity air – arguably the most humid open ocean waters in the world – and so Dhahran / Dammam can experience very humid conditions.

Kuwait

Kuwait is the most continental of all the ports included in this report, having large land masses relatively close by in all directions except the south east quadrant.

Kuwait is the northern-most port in the Persian Gulf. The shallow nature of the Persian Gulf in this region allows it to cool significantly from its high summer values, reducing the average humidity significantly during winter. This is also assisted at the end of winter by the relatively cool waters that flow into the northern end of the Gulf from the Tigris and Euphrates Rivers. In many respects the climate of Kuwait behaves more like a true inland desert city than a coastal city as the maritime influences are smaller than at the other ports considered here. This leads to a marked cold season during the December to February period. Like Aqaba, Kuwait is influenced by the mid-latitude winter low and frontal systems. However, they tend to have lost most of their rainfall by the time they reach Kuwait, serving only to keep temperatures down.

Temperatures start to rise in March with a much larger rise in April. However, as the Persian Gulf sea temperature tends to lag behind the air temperature, the wet bulb temperature does not climb as rapidly as does the dry bulb temperature. By April there can be one or two day hot spells, although the humidities during these events tends to remain only moderate.

Its northern location makes it relatively mild for the greater part of May and the end of October. There are some hot spells, but overall they are short lived. The wet bulb temperatures are yet to reach significant levels in May. Both temperature and humidity rise during the month of June. From July through to September temperatures are consistently high and wet bulb temperatures exceed 26^{o}C on a regular basis. Temperature and humidity levels decline fairly rapidly during September and are generally relatively low in comparison to other ports in the Persian Gulf in October.

Jeddah

Jeddah, midway down the eastern side of the Red Sea, is not directly influenced by the winter lows and frontal systems that pass over Aqaba and sometimes Adabiya. The temperature of this part of the Red Sea, being deeper than the Persian Gulf, does not change as much between summer and winter as both the Persian Gulf and northern tip of the Gulf of Aqaba. This results in Jeddah having one of the consistently warmer winter climates of the ports included in this report. Both wet and dry bulb temperatures start to climb during March and particularly April, when one or two short lived hot spells may occur. However they are transient in nature, not lasting long enough for the wet bulb temperatures to fully respond to the heat. On approximately 2% of days in April the wet bulb temperature exceeds 25^{o}C.

Jeddah has a more consistent climate than some other ports being right on the edge of the Red Sea on a straight and relatively featureless coastline, experiencing fewer real extremes in comparison to its eastern counterparts. The temperature and humidity builds during May, but it is really from late June through to September that the temperature is consistently high and wet bulb temperatures reach 26^{o}C. August and September are consistently humid with humidity level peaking due to the slower response of the deep Red Sea to increased heating. Mid to late October marks a rapid return to milder conditions.

Aqaba

Aqaba, at the northern tip of the Gulf of Aqaba in the Red Sea, is the northern most of the ports included in this analysis. It is subject to the southern-most extremities of winter frontal systems that move rapidly eastwards through the Mediterranean Sea, sometimes producing snow on the inland plateaus of Iraq and Saudi Arabia. Temperatures, both dry and wet bulb, are quite moderate throughout this period. This is particularly so for the period November to February when virtually no hot days occur. Temperatures (wet and dry bulb) do start to rise in March and particularly April but not to levels high enough to cause concern.

Being the northern most Red Sea port, Aqaba has the shortest period of hot and humid weather of the eight ports included in this report. Periods of high temperature and humidity are relatively uncommon in May and June but start to appear in July. Periods of high temperature, with wet bulb temperatures occasionally reaching 26^{o}C, are experienced from late July to mid September. By October the temperatures are rapidly falling with a slower but significant decline in humidity.

Adabiya

The analysis for the Egyptian port of Adabiya, on the western side of the Red Sea, relatively close to Suez, used a limited dataset from the relatively close developing resort town of Ras Sedr. The port exhibits strong continental characteristics in its humidity regime due to the constricted nature of the Gulf of Suez. Periods of high temperature are common from June to September. However, the wet bulb temperatures rarely reach 24^{o}C and in the three and a half years of record available, the wet bulb temperature has never averaged 26^{o}C for a full 24 hour period. By October the temperatures are rapidly falling with a corresponding decline in humidity.

A.2 Departure Port Wet Bulb Climatology

Most Australian ports of departure have significantly lower wet bulb temperatures than the ports of arrival in the Middle East. Southern ports such as Esperance, Ceduna, Port Lincoln, Adelaide, Portland and Melbourne rarely reach wet bulb values of 20^{o}C, averaging only 16 or 17^{o}C even at the height of summer. Highest wet bulb values are normally experienced at the height of summer – particularly during January and February. Conversely the lowest wet bulb temperatures – often around 9 or 10^{o}C – are experienced in July. This is almost exactly opposite to the wet bulb climatology of the Middle East ports of arrival.

Although wet bulb temperatures rise for the west coast ports of Fremantle and Geraldton, they still only reach a January mean value of around 20^{o}C. The wet bulb value may reach 26^{o}C on occasions but these tend to be confined to isolated days, after which the wet bulb rapidly drops again.

The rise in mean wet bulb temperature is dramatic once north of 21^{o}S on the west coast (or once north of North West Cape). In this region the warm waters of the Timor and Arafura Seas lead to a sudden increase in port wet bulb temperatures. Onslow, Karratha and Port Hedland all have wet bulb temperatures averaging near 25^{o}C in January and February. Wet bulb temperatures reach or exceed a mean value of 26^{o}C from Broome around to Nhulunbuy. Wyndham, with a January mean wet bulb of 27^{o}C, has the highest humidity of any Australian ports included in this study, followed closely by Nhulunbuy. The wet bulb temperatures remain high through the Gulf of Carpentaria region, generally remaining in the 25 to 26^{o}C region.

The eastern seaboard has a relatively predictable wet bulb climate grading from high values of around 25^{o}C in January at Cairns through 24^{o}C at Mackay and Rockhampton down to 22^{o}C at Brisbane. This corresponds to the gradual cooling of the Coral Sea and the associated East Australian Current (EAC). The EAC maintains higher wet bulb temperatures down the NSW coastline than would normally be expected. Newcastle has a January wet bulb of 21°C, Wollongong 20°C and Bateman's Bay 19°C.

Wet bulb values across Australia fall significantly as winter approaches. At the height of winter in July, the highest wet bulb temperatures in Australia are found in the Gulf of Carpentaria ports of Nhulunbuy, Karumba and Weipa. In these regions the wet bulb temperatures average 21°C. All other ports experience much lower wet bulbs. Even Darwin (19°C) and Wyndham (18°C) have relatively mild wet bulb conditions during the cooler half of the year.

Table A.1 Wet Bulb Distribution for Seeb (Muscat) (^oC) for January through December

Seeb	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	10.0	11.6	15.6	15.8	17.6	20.8	21.0	21.6	14.5	17.5	15.9	13.7
1st percentile	11.0	11.8	15.9	15.8	18.1	21.1	22.1	23.3	16.9	18.0	16.1	14.0
2nd percentile	11.7	12.1	16.2	15.9	18.9	21.2	22.3	23.5	18.6	18.4	16.3	14.5
5th percentile	12.3	13.2	16.3	16.6	19.4	21.7	23.3	24.4	19.8	18.9	17.2	15.5
10th percentile	13.0	14.0	16.5	17.9	20.0	22.9	24.3	25.0	21.5	19.6	18.1	16.1
20th percentile	14.5	14.9	17.4	18.6	20.9	24.0	25.9	25.6	23.6	20.4	19.0	17.1
30th percentile	15.3	15.4	17.9	18.9	21.3	25.6	26.6	26.1	24.9	21.3	19.3	17.8
40th percentile	16.0	16.1	18.6	19.3	21.8	26.1	27.0	26.5	25.6	22.2	19.6	18.6
50th percentile	16.3	16.7	19.1	20.1	22.4	26.9	27.4	27.0	26.2	22.9	20.0	19.1
60th percentile	16.5	17.5	19.7	21.0	23.1	27.3	27.7	27.3	26.7	23.5	20.6	19.9
70th percentile	17.0	18.1	20.3	21.6	24.5	27.8	28.0	27.6	27.5	24.0	21.0	20.2
80th percentile	17.5	18.9	21.1	22.3	25.6	28.2	28.3	27.9	28.2	24.9	21.6	20.7
90th percentile	17.9	21.0	21.9	22.8	26.8	28.7	28.8	28.5	29.2	25.7	22.2	21.2
95th percentile	18.6	21.3	22.7	23.2	28.2	29.1	29.0	28.8	30.4	26.2	22.6	21.8
98th percentile	20.2	21.6	23.1	23.6	28.5	29.2	29.3	29.3	31.6	26.9	22.6	22.2
99th percentile	20.3	21.6	23.5	23.7	28.9	29.7	29.3	29.4	32.3	27.2	22.7	22.2
maximum	20.4	21.6	24.0	23.7	29.5	29.9	29.6	30.1	33.6	27.7	22.7	22.3

Table A.2 Wet Bulb Distribution for Fujairah (^oC) for January through December

Fujairah	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	9.8	12.0	14.5	16.6	23.2	19.9	21.2	22.3	21.3	19.2	16.4	13.7
1st percentile	10.6	12.5	14.7	16.7	24.0	21.8	21.9	23.5	22.4	19.7	16.9	14.1
2nd percentile	11.4	12.9	14.8	16.7	24.2	22.2	22.5	24.9	22.7	20.2	17.4	14.4
5th percentile	12.7	13.4	15.0	17.2	24.7	23.0	24.5	25.6	24.3	20.7	18.0	14.6
10th percentile	14.7	14.0	15.3	17.6	25.1	24.3	26.3	26.7	25.7	21.2	18.4	14.9
20th percentile	15.2	14.3	16.1	19.1	25.7	25.2	27.6	27.4	26.4	22.0	18.8	17.6
30th percentile	15.4	14.6	16.9	19.5	26.1	26.2	28.4	27.8	26.8	22.8	19.2	18.2
40th percentile	15.8	15.5	17.5	20.5	26.5	27.0	28.7	28.5	27.1	23.2	19.8	18.5
50th percentile	16.2	16.0	18.4	20.8	26.9	27.6	29.1	28.8	27.4	24.2	20.3	19.3
60th percentile	16.7	16.9	19.2	21.4	27.3	28.4	29.4	29.1	27.7	24.5	20.8	19.7
70th percentile	17.3	17.9	19.7	22.2	27.6	28.7	29.7	29.4	27.9	25.2	21.2	20.7
80th percentile	18.0	18.5	20.7	22.6	28.2	29.2	30.0	29.9	28.4	25.6	21.8	21.3
90th percentile	18.7	19.8	21.8	23.2	29.1	29.7	30.4	30.2	28.9	26.9	22.7	21.7
95th percentile	19.2	20.3	22.5	23.7	29.8	30.0	30.8	30.5	29.2	27.6	23.2	22.1
98th percentile	19.9	20.4	22.8	24.3	30.5	30.4	30.9	30.8	29.4	28.2	23.7	22.2
99th percentile	20.1	20.7	22.8	24.5	30.6	30.6	31.0	31.1	29.7	28.5	23.9	22.3
maximum	20.2	21.0	22.9	24.6	31.0	31.1	31.3	31.3	30.0	28.9	24.0	22.4

Table A.3 Wet Bulb Distribution for Dubai (^oC) for January through December

Dubai	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	9.2	12.0	15.6	16.0	18.3	20.4	21.7	22.7	22.5	18.1	16.2	13.5
1st percentile	9.5	12.2	15.7	16.5	18.5	21.1	22.8	23.6	22.6	19.4	16.5	13.9
2nd percentile	10.1	12.4	15.8	16.9	19.0	21.4	22.9	24.0	22.6	20.0	16.8	14.3
5th percentile	11.9	13.3	16.1	17.4	19.9	22.1	23.5	24.5	23.0	20.4	17.6	14.8
10th percentile	12.2	13.8	16.6	17.7	20.4	23.3	24.7	24.9	23.9	21.4	18.1	15.4
20th percentile	13.6	14.1	17.5	18.5	21.1	24.1	25.7	25.5	25.0	22.3	18.6	16.7
30th percentile	14.1	14.6	17.7	19.1	22.0	24.8	26.3	26.0	25.4	22.8	19.0	17.7
40th percentile	14.7	15.4	18.1	19.8	22.4	25.3	26.9	26.4	26.0	23.2	19.4	18.2
50th percentile	15.0	15.9	18.3	20.1	23.0	25.8	27.2	26.8	26.3	23.8	19.9	18.8
60th percentile	15.2	16.3	18.6	20.3	23.3	26.3	27.6	27.3	26.7	24.2	20.1	19.2
70th percentile	15.4	16.8	18.9	20.8	23.7	26.7	28.2	27.8	27.3	24.6	20.6	19.5
80th percentile	16.5	17.2	19.3	21.2	24.2	27.4	28.4	28.2	27.6	25.4	21.2	20.0
90th percentile	18.0	17.7	20.2	21.9	25.0	27.8	29.0	29.0	28.2	26.6	22.2	20.5
95th percentile	18.6	18.1	21.0	22.8	25.7	28.3	29.2	29.3	28.5	27.3	23.3	20.7
98th percentile	19.3	18.2	21.3	23.5	26.7	29.0	29.5	30.1	28.9	27.8	24.0	21.0
99th percentile	19.5	18.2	21.4	23.6	26.9	29.1	29.8	30.4	29.1	28.1	24.1	21.3
maximum	19.9	18.3	21.4	23.7	27.7	29.3	30.1	30.5	29.5	28.7	24.1	21.7

Table A.4 Wet Bulb Distribution for Doha (^oC) for May through October

Doha	May	Jun	Jul	Aug	Sep	Oct
Minimum	17.0	19.2	20.6	21.5	21.4	19.4
1st percentile	17.3	19.3	20.9	22.1	22.3	20.4
2nd percentile	17.6	19.6	21.1	22.5	22.7	20.8
5th percentile	18.3	20.8	21.5	23.3	23.2	21.7
10th percentile	18.8	21.1	22.1	24.7	24.2	22.5
20th percentile	19.6	21.6	22.8	25.9	24.9	23.1
30th percentile	20.4	22.5	23.8	26.9	25.5	23.4
40th percentile	20.9	23.3	25.1	28.1	26.0	23.7
50th percentile	21.5	23.8	26.1	28.8	26.8	24.3
60th percentile	22.0	24.4	26.9	29.2	27.1	24.7
70th percentile	22.7	24.9	28.0	29.6	27.5	25.5
80th percentile	23.4	25.8	28.8	29.9	28.1	26.0
90th percentile	24.4	27.1	29.6	30.4	29.1	26.6
95th percentile	25.0	27.6	30.4	30.7	29.6	27.4
98th percentile	25.8	28.0	31.0	30.9	30.1	27.9
99th percentile	26.8	28.6	31.5	31.3	30.2	28.5
maximum	31.6	28.9	31.6	31.3	30.2	28.6

Table A.5 Wet Bulb Distribution for Bahrain (°C) for January through December

Bahrain	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	10.3	10.5	14.2	15.5	17.9	20.0	22.5	24.4	23.2	20.5	14.1	13.4
1st percentile	10.5	11.0	14.3	16.5	18.5	22.0	23.5	24.9	24.0	21.2	14.3	13.6
2nd percentile	10.6	11.4	14.3	16.7	19.0	22.2	23.9	25.0	24.2	21.3	14.7	13.8
5th percentile	11.1	12.1	14.6	17.4	19.9	22.9	24.3	25.6	24.7	22.1	16.0	14.1
10th percentile	11.1	12.8	15.0	17.9	21.1	23.6	24.8	26.1	25.1	22.7	16.5	14.2
20th percentile	12.4	13.6	16.4	18.6	21.7	24.3	25.5	26.9	25.7	23.4	17.4	15.3
30th percentile	13.0	13.7	16.6	19.0	22.4	24.7	26.1	27.5	26.1	24.1	18.3	16.6
40th percentile	13.3	14.3	17.1	19.5	23.1	25.2	26.6	28.5	26.5	24.6	18.7	17.4
50th percentile	14.2	14.7	17.5	20.0	23.5	25.5	27.1	29.3	26.9	25.0	19.6	18.1
60th percentile	14.5	15.2	17.9	20.4	24.0	25.9	27.6	29.7	27.3	25.5	20.1	19.0
70th percentile	15.3	15.7	18.6	20.9	24.4	26.3	28.1	30.0	27.6	25.9	20.7	20.8
80th percentile	16.2	16.7	19.0	21.6	25.0	26.7	28.9	30.3	28.2	26.2	21.9	21.2
90th percentile	18.4	17.2	19.7	22.7	25.6	27.4	30.0	30.8	29.1	26.6	22.9	21.7
95th percentile	18.8	17.7	21.0	24.9	26.1	28.0	30.7	31.5	29.8	27.2	23.5	22.2
98th percentile	19.2	18.3	21.5	27.2	26.9	28.5	31.0	31.7	30.5	27.7	23.8	22.9
99th percentile	19.6	18.6	21.7	28.2	27.2	28.8	31.2	31.8	30.6	27.8	24.0	23.1
maximum	20.2	18.9	22.0	28.6	27.3	30.0	31.7	32.0	31.0	28.3	24.3	23.1

Table A.6 Wet Bulb Distribution for Dhahran (^oC) for January through December

Dhahran	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	8.0	5.9	10.2	14.1	17.0	19.1	20.1	20.7	20.3	16.9	8.6	9.5
1st percentile	8.5	6.4	10.5	14.4	17.1	19.3	20.3	21.4	20.3	18.3	8.9	10.4
2nd percentile	8.9	7.0	10.7	14.6	17.5	19.6	20.5	21.6	20.4	19.1	9.8	10.9
5th percentile	9.5	9.1	11.1	14.9	17.8	20.2	21.0	21.8	21.0	19.4	13.0	11.1
10th percentile	9.9	9.6	11.8	15.8	18.1	20.7	21.5	22.6	21.4	20.0	14.6	11.9
20th percentile	10.8	11.2	12.7	17.0	19.3	21.3	22.1	23.3	22.3	20.8	15.3	12.8
30th percentile	11.6	11.7	13.3	17.8	20.0	21.7	22.9	24.3	22.9	21.4	16.0	14.7
40th percentile	12.0	12.0	14.8	18.2	20.6	22.0	23.3	25.5	23.6	21.9	16.5	15.9
50th percentile	12.6	12.4	15.2	18.8	21.1	22.5	23.7	26.3	24.3	22.3	17.7	16.6
60th percentile	12.9	13.1	15.7	19.3	21.8	22.9	24.4	27.6	24.8	22.9	18.2	17.6
70th percentile	13.3	13.6	16.3	19.8	22.3	23.5	25.4	28.6	25.4	23.5	18.7	19.4
80th percentile	13.8	14.2	17.3	20.1	23.1	24.3	26.9	29.2	26.1	24.1	19.9	19.8
90th percentile	14.8	15.2	18.0	20.8	24.3	25.5	28.6	29.8	26.9	25.0	20.9	20.7
95th percentile	15.4	15.8	18.3	21.3	25.4	25.9	29.7	30.3	28.0	25.7	21.4	20.9
98th percentile	16.4	16.9	18.6	21.5	26.3	27.2	30.0	30.6	29.1	26.1	22.1	21.2
99th percentile	16.6	17.1	18.8	21.6	27.1	28.1	30.3	30.8	29.3	27.3	22.6	21.4
maximum	16.8	17.3	19.1	21.7	28.0	28.8	30.4	31.1	32.7	29.8	23.1	21.7

Table A.7 Wet Bulb Distribution for Kuwait (^{o}C) for January through December

Kuwait	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	5.1	10.8	13.4	14.8	13.9	16.4	4.6	18.4	15.5	12.7	3.8	6.0
1st percentile	5.2	11.2	13.7	14.8	14.7	16.6	18.6	19.0	16.5	13.6	4.1	7.0
2nd percentile	5.5	11.5	14.0	14.9	14.8	16.7	18.6	19.2	16.7	14.3	4.5	7.7
5th percentile	6.2	12.4	14.4	15.8	15.4	17.7	18.8	19.6	17.4	15.1	7.1	8.2
10th percentile	6.7	12.8	15.0	15.9	16.2	18.0	19.2	19.8	17.9	15.5	10.5	9.3
20th percentile	7.0	13.0	15.5	16.7	17.3	18.9	19.7	20.4	18.6	16.3	11.5	10.0
30th percentile	8.2	13.8	16.1	17.5	17.9	19.2	19.9	20.8	19.0	17.0	12.4	11.9
40th percentile	9.3	14.7	16.4	18.2	18.3	19.4	20.3	21.0	19.4	17.7	13.4	13.1
50th percentile	10.0	15.1	16.7	18.5	18.6	19.7	20.6	21.3	20.0	18.5	13.6	13.8
60th percentile	10.6	15.8	17.3	18.9	19.0	19.9	21.0	21.8	20.4	19.0	13.9	15.4
70th percentile	11.1	16.4	17.9	19.6	19.5	20.3	21.5	22.3	20.9	20.1	14.6	16.3
80th percentile	11.8	16.9	18.3	20.6	19.9	20.7	22.0	23.4	21.6	20.9	15.5	17.1
90th percentile	12.7	17.9	19.2	21.7	20.5	22.0	23.9	26.1	22.7	22.7	16.7	18.7
95th percentile	15.5	18.8	20.2	22.8	21.0	22.7	24.7	28.4	24.9	23.8	17.3	19.1
98th percentile	16.7	19.7	20.4	22.9	22.2	24.1	25.7	29.7	27.1	25.1	18.6	19.6
99th percentile	16.9	20.0	20.6	23.1	23.5	24.5	26.5	29.9	28.2	26.2	18.7	19.8
maximum	17.2	20.3	20.9	23.4	23.9	25.1	29.1	30.4	28.6	26.7	18.7	19.9

Table A.8 Wet Bulb Distribution for Jeddah (°C) for January through December

Jeddah	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	12.2	14.6	16.5	16.9	18.1	20.4	20.0	23.4	22.8	19.6	17.1	15.0
1st percentile	12.3	14.9	16.6	17.4	19.0	20.6	20.7	23.5	24.3	20.6	17.5	15.1
2nd percentile	12.3	15.1	16.7	17.8	19.2	20.9	20.9	23.5	24.5	21.3	18.0	15.1
5th percentile	12.4	15.5	17.2	18.0	20.1	21.5	21.6	24.4	24.9	22.0	19.6	15.5
10th percentile	14.8	15.9	18.2	19.5	20.7	22.2	22.4	24.6	25.2	23.0	19.8	16.8
20th percentile	15.2	16.9	19.3	21.0	21.6	22.8	23.4	25.4	25.7	23.7	21.1	18.5
30th percentile	16.2	18.0	20.2	21.5	22.3	23.1	24.1	25.8	26.0	24.2	21.4	19.1
40th percentile	16.9	18.8	20.8	21.9	22.9	23.7	24.5	26.4	26.6	24.8	21.8	19.7
50th percentile	17.5	19.6	21.1	22.2	23.3	24.0	24.8	26.9	26.9	25.1	22.0	20.3
60th percentile	17.9	20.1	21.8	22.4	23.9	24.3	25.4	27.5	27.1	25.3	22.5	20.9
70th percentile	18.5	21.0	22.2	22.7	24.4	24.8	25.9	27.9	27.4	25.8	22.8	21.1
80th percentile	19.0	21.6	22.5	23.3	24.9	25.4	26.7	28.4	27.8	26.2	23.2	21.9
90th percentile	20.3	22.2	22.9	23.9	25.6	26.0	27.2	29.0	28.3	26.6	23.6	22.3
95th percentile	20.8	22.6	22.9	24.1	25.9	26.4	27.6	29.8	28.7	26.9	24.1	23.3
98th percentile	22.3	23.2	23.2	25.0	26.3	26.5	27.8	29.9	28.9	27.4	24.4	23.5
99th percentile	22.5	23.3	23.7	25.2	26.5	26.8	27.9	30.1	29.2	27.5	24.4	23.7
maximum	22.6	23.5	24.4	25.3	27.0	27.2	28.3	30.6	29.5	27.8	24.4	24.0

Table A.9 Wet Bulb Distribution for Aqaba (°C) for January through December

Aqaba	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	8.0	9.5	13.4	14.8	16.1	18.0	20.6	21.9	15.8	14.5	12.1	9.6
1st percentile	8.0	9.7	13.7	14.8	16.5	18.7	21.1	22.0	19.3	15.5	12.2	9.8
2nd percentile	8.1	9.9	14.0	14.9	16.9	19.5	21.2	22.2	20.3	16.4	12.6	10.1
5th percentile	9.0	10.0	14.4	15.8	17.4	20.2	21.7	22.7	20.6	17.6	14.1	10.6
10th percentile	10.0	10.6	15.0	15.9	18.2	20.7	22.2	23.0	21.5	18.3	14.4	11.8
20th percentile	10.5	11.0	15.5	16.7	19.0	21.3	22.6	23.5	22.1	19.3	14.8	12.2
30th percentile	11.0	11.5	16.1	17.5	19.5	21.9	23.0	24.1	22.7	20.0	15.7	12.8
40th percentile	11.4	11.9	16.4	18.2	19.8	22.3	23.5	24.6	23.2	20.5	16.2	13.4
50th percentile	11.9	12.2	16.7	18.5	20.1	22.7	23.9	25.1	23.7	21.0	16.3	13.7
60th percentile	12.3	13.1	17.3	18.9	20.8	23.0	24.3	25.6	24.1	21.4	16.7	14.3
70th percentile	12.7	13.7	17.9	19.6	21.3	23.3	24.7	25.9	24.5	22.0	17.5	14.7
80th percentile	12.9	14.0	18.3	20.6	21.9	23.5	25.5	26.3	25.2	22.7	18.1	15.5
90th percentile	13.2	14.9	19.2	21.7	22.8	24.1	26.1	27.4	25.9	23.9	18.5	16.1
95th percentile	13.3	15.3	20.2	22.8	23.5	24.6	26.7	27.8	26.2	24.3	18.9	16.3
98th percentile	14.0	15.4	20.4	22.9	24.5	25.2	27.9	28.6	27.2	25.7	19.4	16.6
99th percentile	14.3	15.6	20.6	23.1	24.7	25.5	28.0	33.8	27.4	25.9	19.5	18.4
maximum	14.6	15.8	20.9	23.4	25.3	26.6	28.2	33.8	28.5	26.1	19.5	21.0

Table A.10 Wet Bulb Distribution for Adabiya (^oC) for January through December

Adabiya	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	5.9	7.6	8.2	12.0	14.7	16.6	20.4	19.9	18.5	14.2	9.3	7.8
1st percentile	6.5	8.0	8.6	12.7	14.7	17.4	20.4	20.2	18.7	14.3	10.3	7.8
2nd percentile	7.1	8.6	9.0	13.0	14.8	17.9	20.8	20.5	18.7	14.5	11.0	8.0
5th percentile	8.0	9.0	10.0	13.3	15.2	18.2	21.1	21.1	19.5	15.4	11.7	8.3
10th percentile	8.6	9.4	10.7	13.7	15.8	18.6	21.2	21.8	20.2	16.4	12.6	9.7
20th percentile	9.5	9.8	11.6	14.2	16.4	19.5	21.6	22.2	20.7	17.9	13.6	10.8
30th percentile	9.9	10.1	12.1	14.5	17.0	19.8	21.9	22.4	21.0	18.6	14.1	11.4
40th percentile	10.3	10.4	12.7	14.9	17.4	20.1	22.1	22.5	21.2	19.0	14.7	12.1
50th percentile	10.8	10.9	13.1	15.3	17.7	20.4	22.4	22.7	21.4	19.2	15.2	12.4
60th percentile	11.2	11.2	13.7	15.5	18.2	20.7	22.6	23.0	21.7	19.8	15.6	12.8
70th percentile	11.8	11.6	14.5	16.2	18.6	20.8	22.8	23.2	22.0	20.1	16.0	13.2
80th percentile	12.4	12.1	15.0	16.7	18.8	21.1	23.3	23.6	22.3	20.6	16.6	13.4
90th percentile	12.7	13.1	15.8	17.4	19.6	21.6	23.8	23.8	22.6	21.3	17.0	13.9
95th percentile	13.5	13.5	16.2	17.9	19.8	22.1	24.0	24.2	23.1	21.7	17.4	14.5
98th percentile	14.7	13.8	17.0	19.1	20.0	22.5	24.1	24.5	23.8	22.9	18.2	14.9
99th percentile	15.5	14.4	17.3	19.3	20.4	22.6	24.3	24.7	23.8	23.2	18.5	15.0
maximum	16.1	14.6	19.7	20.3	21.1	23.2	24.7	24.8	24.2	24.1	19.9	15.5

Appendix B Animal Details

B.1 Key Terminology: A Brief Overview

The concepts of thermoneutral zone and upper critical temperature are central to an understanding of heat stress in cattle, sheep and goats. Unfortunately, however, there is considerable confusion in the literature about the exact meaning of these terms, as explained below.

The Thermoneutral Zone (TNZ)

The TNZ has been variously defined as the range of environmental temperatures:

- at which body temperature can be maintained in the normal range *primarily by vasomotor mechanisms* [that is, sensible heat transfer through convection and radiation] (Robinson, 2002);
- where heat loss is kept constant *by regulation of both sensible and evaporative* [that is, latent] *heat loss.* In this zone, factors other than climate (for example, feeding level, physical activity and stress) determine the heat production (Schrama et al., 1996); or
- within which metabolic rate is minimum, constant and independent of temperature (Mount, 1979)

According to Kadzere (2002), the TNZ range is affected by age, species, breed, feed intake, diet composition, previous state of temperature acclimatisation, production, specific housing and pen conditions, tissue insulation (fat, skin), external insulation (coat) and animal behaviour.

These definitions can be considered *in terms of process and outcome*. The first definition is based on a change in the process of heat transfer, whereas the second and third rely on a description of the outcome (that is, heat loss is constant or metabolic rate is minimal). Using the latter two definitions in concert, the deep body temperature should remain constant throughout the TNZ.

There are several reasons why the latter two definitions in combination may be of greater relevance to live export:

- firstly, the definition of process will be inherently difficult to measure. Sensible and evaporative methods of heat loss are used by cattle at all temperatures. The relative importance of each method is dependent on ambient conditions, with cattle losing about 10% of their body heat by evaporation at -10^{o}C and 80% by the same method when ambient conditions rise to 30^{o}C (Robinson, 2002). Therefore, there will be some uncertainty regarding the point at which vasomotor mechanisms cease to be the primary method of heat loss. In addition, Stacey (2000) cautions that the respiratory rate of cattle at a given ambient temperature is not fixed but will depend on many influences including body condition of an animal and time of day.

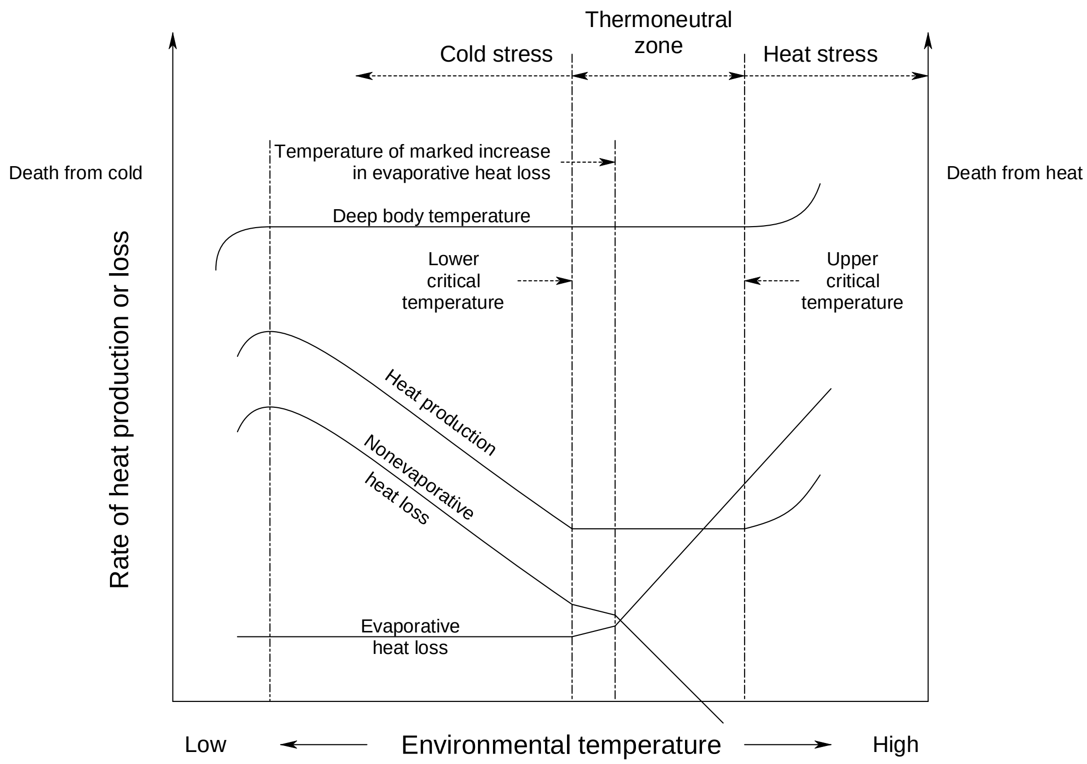
- secondly, heat production should remain relatively constant during live export because animals are confined and have a relatively constant intake of feed that seeks to meet (but generally not exceed) maintenance requirements. In these circumstances, the upper limit of the TNZ would coincide with the development of a net heat gain (as a result of an imbalance between heat production and heat loss).

The Upper Limit of the TNZ

The upper critical temperature (UCT) has generally been defined as the upper limit of the TNZ. Reflecting the varying definitions for TNZ, however, there remains disagreement regarding the definition of the UCT. It is variously defined as the ambient temperature when:

- the metabolic rate increases;
- evaporative heat loss increases; or
- tissue thermal insulation is minimal (Silanikove, 2000).

The following figure, modified from Mount (Mount, 1979), provides one useful illustration of the concepts of TNZ and UCT. According to this interpretation (and in agreement with the second TNZ interpretation), heat production, collective heat loss (through evaporative and sensible means) and deep body temperature each remain constant throughout the TNZ. Therefore, provided the deep body temperature is maintained, animals can experience a substantial increase in evaporative heat loss (and a corresponding decrease in non-evaporative heat loss) whilst still within this zone.



To avoid confusion surrounding the current terminology, and to ensure that the term is meaningful within industry, it is suggested that UCT be substituted with the term 'heat stress threshold' (HST) in the heat stress management model. This concept has been raised previously (Parkhurst et al., 2002). In the context of live animal export, the HST is defined as the ambient wet bulb temperature at which heat balance (and therefore the deep body temperature) can no longer be controlled using available mechanisms of heat loss. Similarly, the mortality limit (ML) would be defined as the ambient wet bulb temperature at which the uncontrollable rise in deep body temperature leads to death.

B.2 Heat tolerance in relevant species

B.2.1 Published Information

Detailed information has been published about heat tolerance in different animal species. Unfortunately, however, the environmental information that has been quoted in much of this work is incomplete. Consequently, it is generally not possible to extrapolate these findings in wet bulb temperatures. To illustrate, Mount (1979) states that *Bos taurus* and *B. indicus* animals do not modify their behaviour for temperature adaptation between 2 and 21°C and 10 and 27°C, respectively. However, no information about relative humidity is given, and equivalent wet bulb temperatures cannot be calculated.

B.2.2 Experimental Information

(Note that all quoted temperatures refer to wet bulb temperature, unless otherwise specified)

B.2.2.1 SBMR.002: Investigation of Ventilation Efficacy on Livestock Vessels

Detailed information about the SBMR.002 work is presented elsewhere (Stacey, 2001).

During SBMR.002, animal heat tolerance was assessed on the basis of changes to respiratory rate. Any direct comparison between this and other studies must be undertaken with care, given that rectal or core body temperature is – by definition – a more-direct measure of HST. Despite these concerns, the study results significantly contribute to our understanding of heat tolerance during live export as follows:

- *Between-study comparison* will be possible, after first understanding the relationship between body temperature and respiratory rate in response to heat. Data relevant to this relationship recently became available, based on the simultaneous observation during LIVE.209 of body temperature and respiratory rate in animals exposed to conditions of high temperature and humidity.
- The study provides valuable information about *the relative effect* on heat tolerance of a range of variables including breed, acclimatisation, weight and age

Cattle

The following details are relevant to each voyage:

- Voyage 1: Brahman/Brahman cross steers from Qld and NT, loaded in Darwin
- Voyage 2: Brahman/Brahman cross steers, loaded in Wyndham
- Voyage 3: Brahman/Brahman cross steers, loaded in Townsville
- Voyage 4: Brahman/Brahman cross steers loaded in Darwin, ex-pastoral shorthorns (mainly *Bos taurus*) loaded in Fremantle
- Voyage 5: a range of *Bos taurus* animals, including ex-pastoral shorthorns from WA and mainly bulls, loaded in Fremantle
- Voyage 6: mainly merino wethers (also merino lambs, Awassi ewes and goats), loaded in Fremantle (small numbers of cattle, breed not stated)

On each voyage a limited number of pens were monitored for environmental parameters and animal response. Those observations which gave good data for the present purpose are noted in Table 3.1 and Table 3.2.

As an illustration of the data from SBMR.002, Figure B.1 and Figure B.2 below are taken from the final report. They show the variability within one line of animals as well as the difference between breeds (Figure B.1) and the differences due to acclimatisation (voyages 3 and 4) (Figure B.2).

Figure B.1 SBMR.002 - All Voyages Respiration Rate against Wet Bulb Temperature

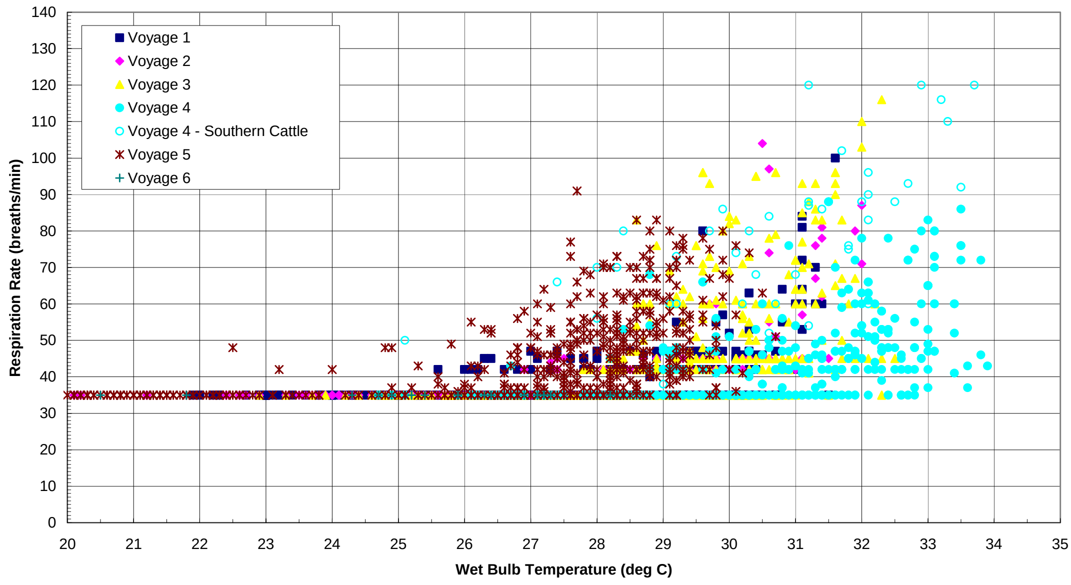
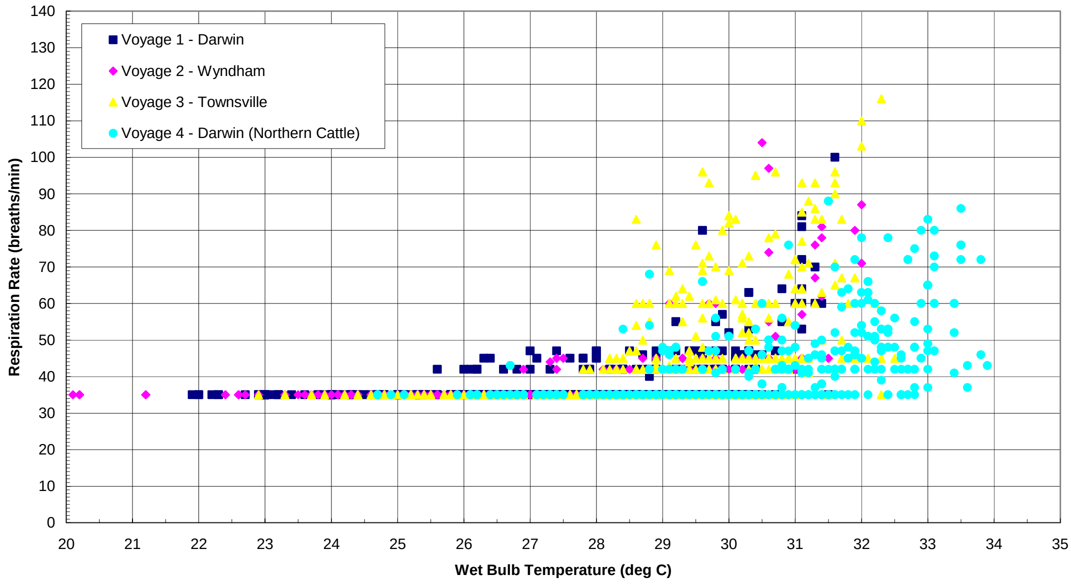


Figure B.2 SBMR.002 - Effect of Acclimatisation on Respiration Response



The numerical data are developed more fully in Table 3.1, however in general terms the key observations are:

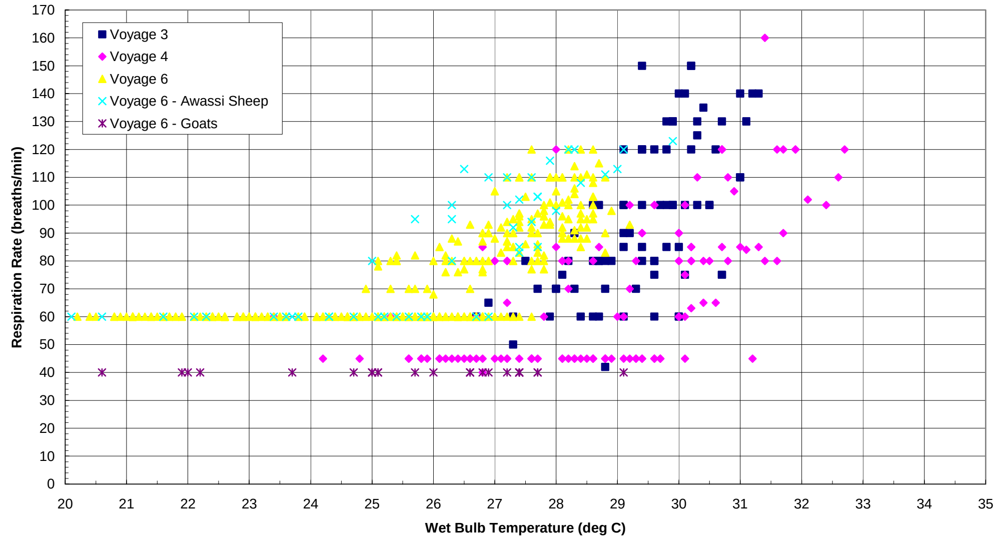
- *Bos taurus* animals (sailing on Voyages 4 and 5 only) are less heat tolerant than *Bos indicus* animals (Voyages 1-4). In *Bos taurus* animals, the respiratory rate increase are associated with environmental conditions of 25-26°C (wet bulb; in the least heat tolerant animals) to 29-30°C (all animals). In *Bos indicus* animals, an increase in respiratory rate is first noted once deck conditions reach 28-29°C, although some animals do not exhibit increased respiration until conditions reach 32-33°C. There is a 3-4°C difference between the breeds.

- Acclimatisation of *Bos indicus* (with differences of 11°C in ambient wet bulb temperature) resulted in 2-3°C difference in HST.

- Weight and age vary HST by 1-3°C

Sheep

Figure B.3 Respiratory Response of Sheep and Goats to Wet Bulb Temperature (from SBMR.002)



Again assuming a close correlation between core body temperature and respiratory rate, the HST of sheep varied between voyages. During Voyages 3 (July/August 2000; sheep loaded in Fremantle; closed decks) & 4 (September 2000; sheep loaded in Fremantle, sheep on open decks), there was a rise in respiratory rate associated with a deck wet bulb temperature of 27-30°C. During Voyage 6 (December 2000; sheep loaded in Fremantle; sheep on open and closed decks) the respiratory rate rise was associated with a wet bulb temperature of 25-28°C.

B.2.2.2 LIVE.209: Physiology of Heat Stress in Cattle and Sheep and the Efficacy of Electrolyte Replacement Therapy

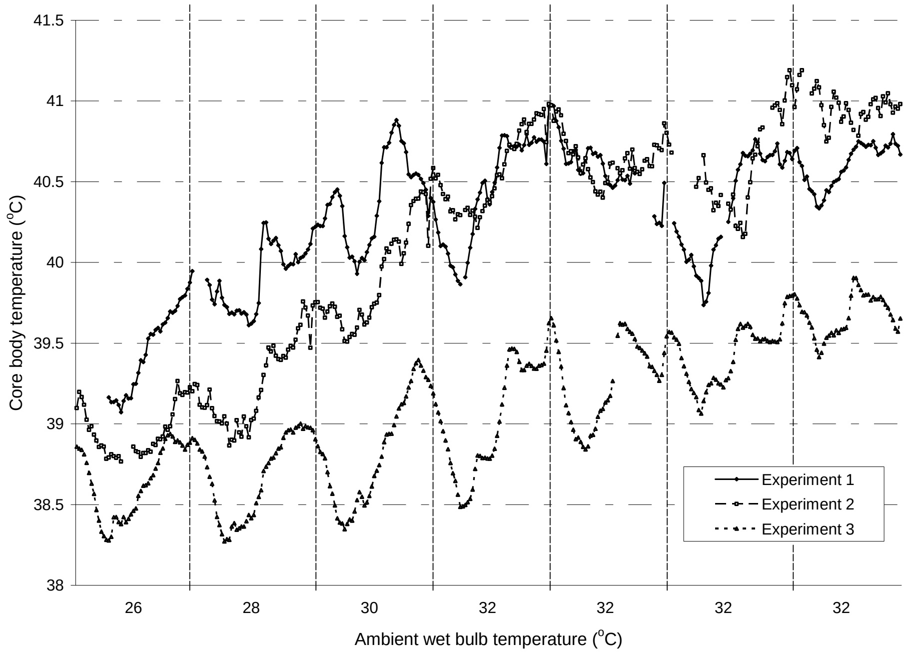
Detailed information about this work has been kindly provided by David Beatty and Anne Barnes, Murdoch University

- The first experiment was undertaken during late April/early May 2002 with six Angus and Angus-cross heifers (weight range 336 to 408 kg).
- The second experiment was undertaken during June 2002 with six Murray Grey-cross and Angus-cross heifers (weight range 312 to 368 kg)
- The third experiment was undertaken during August 2002 with six pure-bred Brahman heifers

Figure B.4 presents the mean core body temperature during days 3-9 of the experiments (with room wet bulb temperature increasing from 26 to 32°C)

Figure B.4 Core Temperature Response During LIVE.209 Experiments

(Wet Bulb Temperature is noted in place of day number on the axis)



Key observations include:

- There is clear evidence of diurnal variation in body temperature (see also Mount, 1979), with values generally being higher during the day and lower at night.

- It is generally accepted that 38.5°C represents the average body temperature of cattle, with animals being considered hyperthermic if the body temperature exceeds 39.5°C (Radostits et al., 2000). In these experiments, the *Bos taurus* animals consistently exceeded a mean body temperature of 39.5°C when ambient temperature reached 28°C (first experiment) and 30°C (second experiment). In experiment 3, the mean body temperature of the *Bos indicus* animals increased steadily, exceeding 39.5°C on the fourth day that ambient wet bulb conditions were 32°C.

- Duration of heat plays an important role in animal response to heat, with animals being more tolerant to short term, in comparison to long-term, periods of high wet bulb temperatures.

Respiratory Rate Changes

Figure B.5 and Figure B.6 present core body temperature and respiratory rate changes in 18 animals (6 in each of three separate experiments) during LIVE.209:

Figure B.5 Changes in Mean Respiratory Rate (from LIVE.209)

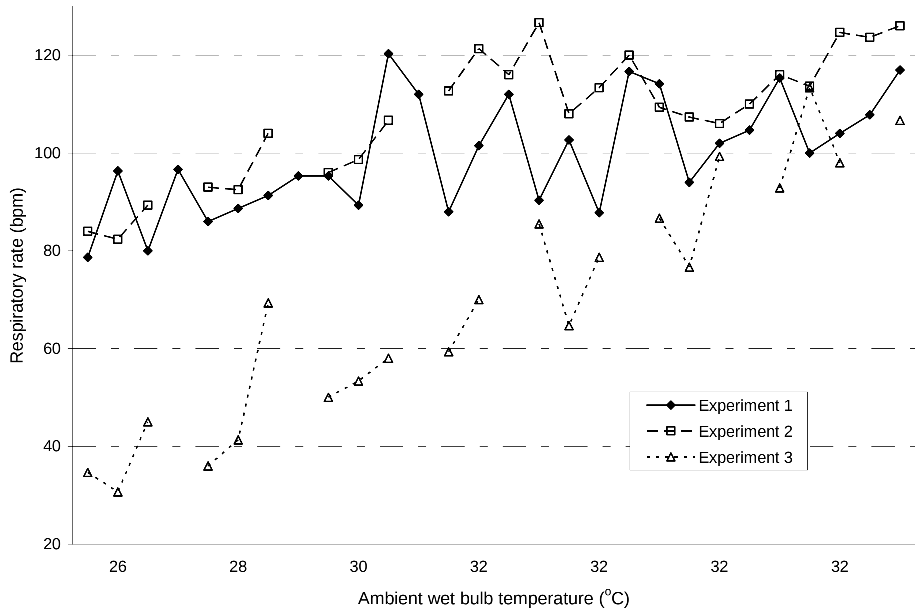
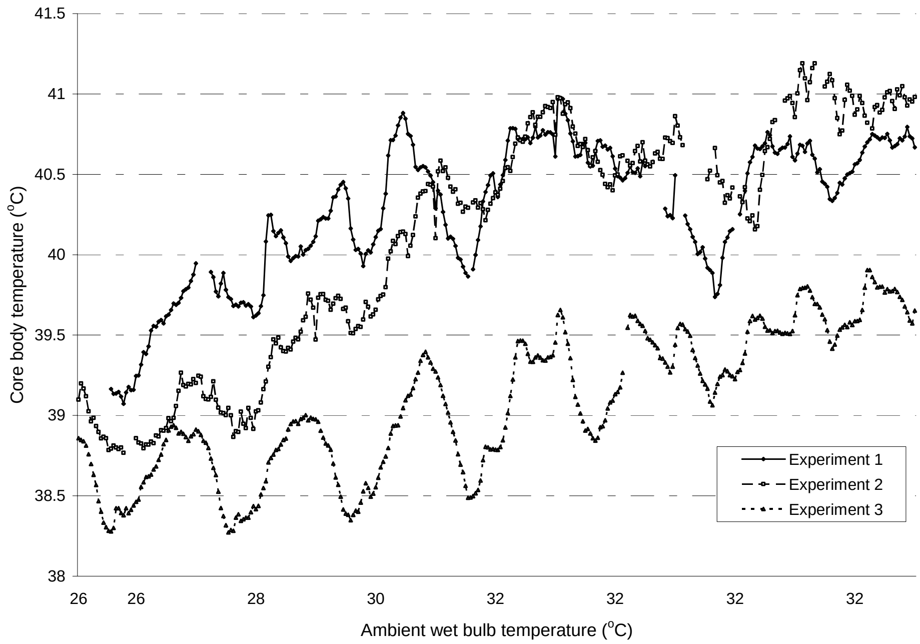


Figure B.6 Changes in Mean Core Body Temperature Changes (from LIVE.209)



These graphs suggest a close relationship between respiratory rate and core body temperature, with both following a similar increase throughout the period of observation. This finding is in general agreement with general observations that were made during this experiment, suggesting that elevated respiratory rates following immediately after an increase in core body temperatures[1]. During the LIVE.209 work, the *Bos indicus* animals

[1] Email from Anne Barnes (05FEB03)

(Experiment 3) were consistently more heat tolerant than *Bos taurus* animals (Experiments 1 and 2), as measured on the basis of both core body temperature and respiratory rate.

A rise in core body temperature of 0-5^{o}C is seen to correlate with respiration rates of around 90 breaths per minute for *Bos taurus* animals and around 75 breaths per minute for *Bos indicus* animals.

Key conclusions:

- Animals become less tolerant to heat with increasing duration in hot conditions
- The HST of *Bos taurus* animals lies between 28 and 30^{o}C. Other factors, including body weight, genetics and time of year, may have played a role in the between-experiment differences in the response of animals to heat.
- The HST of *Bos indicus* animals is probably greater than 32^{o}C wet bulb, but will reduce to this level if heat exposure is prolonged

B.2.2.3 LIVE.212: Investigation of Ventilation Efficacy on Live Sheep Vessels

This study investigated the effect of ventilation on heat stress in sheep during long-haul voyages to the Middle East. Voyage 1 was conducted during June/July 2002 and Voyage 2 during September 2002. Detailed information about these voyages is presented elsewhere (Stacey and More, 2002a; Stacey and More, 2002b).

Figure B.7 and Figure B.8 illustrate the correlation between deck wet bulb temperature and rectal temperature on Voyages 1 and 2:

Figure B.7 Voyage 1 (comparing B wethers [orange symbols], Muscat wethers [blue] and Merino wether lambs [green])

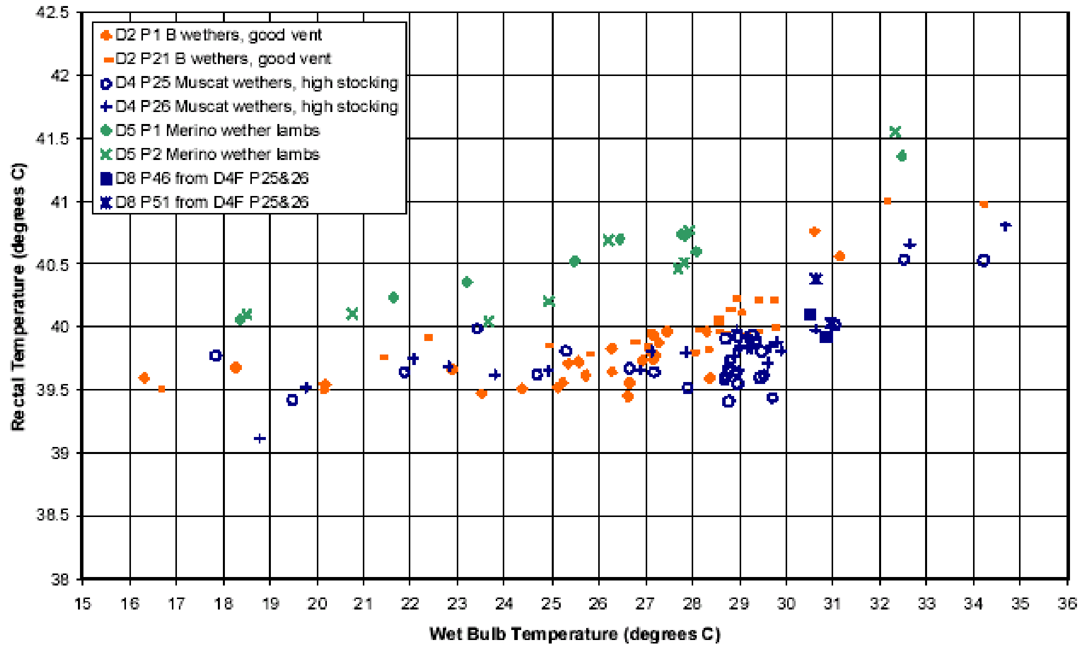
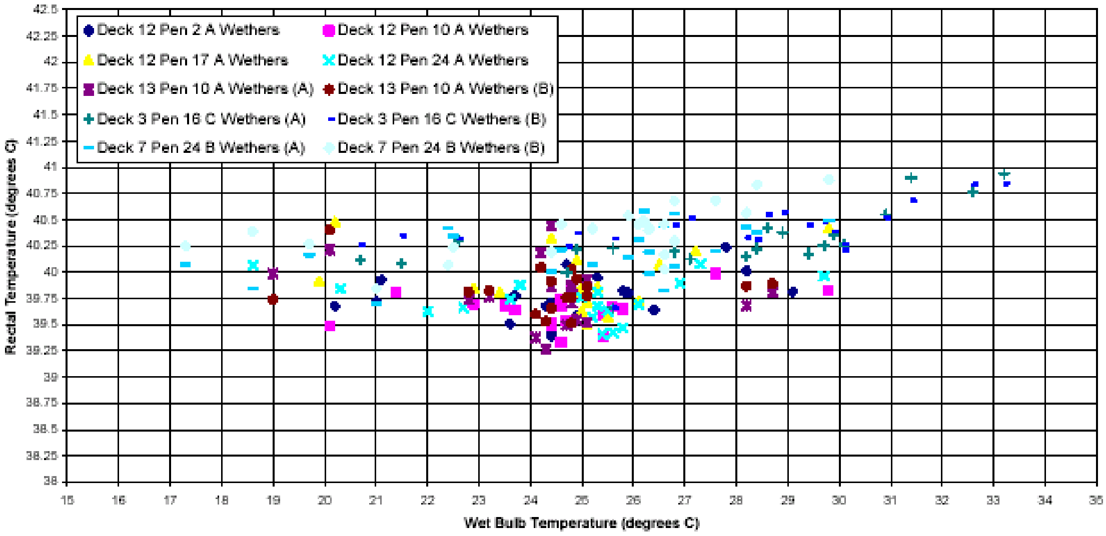
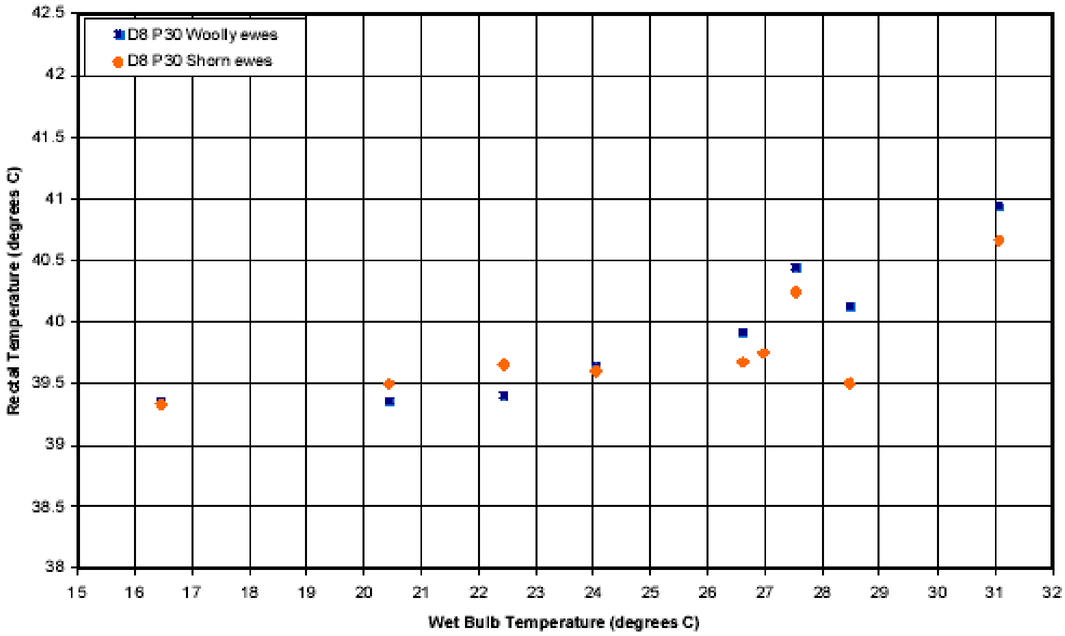


Figure B.8 Voyage 2 (a range of Merino wethers)



Both shorn (~10 mm of wool) and woolly (>25 mm) sheep were observed during Voyage 1. Figure B.9 presents the correlation between body temperature and wet bulb temperature:

Figure B.9 Correlation of Body Temperature and Wet Bulb Temperature



Key conclusions:

- It was impractical to measure exact respiratory rates in sheep during the voyage.
- During voyage 1, the UCwbT for *adult sheep* varied between 28 and 30°C. During voyage 2, this parameter was estimated to lie between 26 and 30°C, with the lower end of this range possibly being extended by animals that were compromised for other reasons (including disease). For *young sheep*, the UCwbT may be lower, however, this is less clear because given the gradual rise in rectal temperature as the wet bulb temperature rose above 22°C. During Voyage 1, the *Awassi lambs* were more resistant to heat than Merino lambs. Although data are scant, it appears that the UCwbT for Awassi lambs is greater than 29°C.

- Once the wet bulb temperature exceeded 26^{o}C, the woolly ewes were hotter than the shorn ewes by a factor of 0.2-0.4^{o}C. Because data is scarce when the ambient wet bulb temperature reached 29-30oC, it is difficult to determine the UCwbT for these two different lines of animals.
- During voyage 2, there was a spike in mortality rate as the deck wet bulb temperature reached 32^{o}C. This may represent the lower range of the death temperature in adult Merino sheep. Based on anecdotal information collected during the voyages, Awassi sheep were more heat tolerant than Merinos, even though they were woolly at loading. The mortality rate was much lower in Awassi as compared with Merino sheep during Voyage 2. Given the role of heat during this voyage, the death temperature is likely to be higher in Awassi as compared to Merinos.

B.2.3 Voyage Investigations

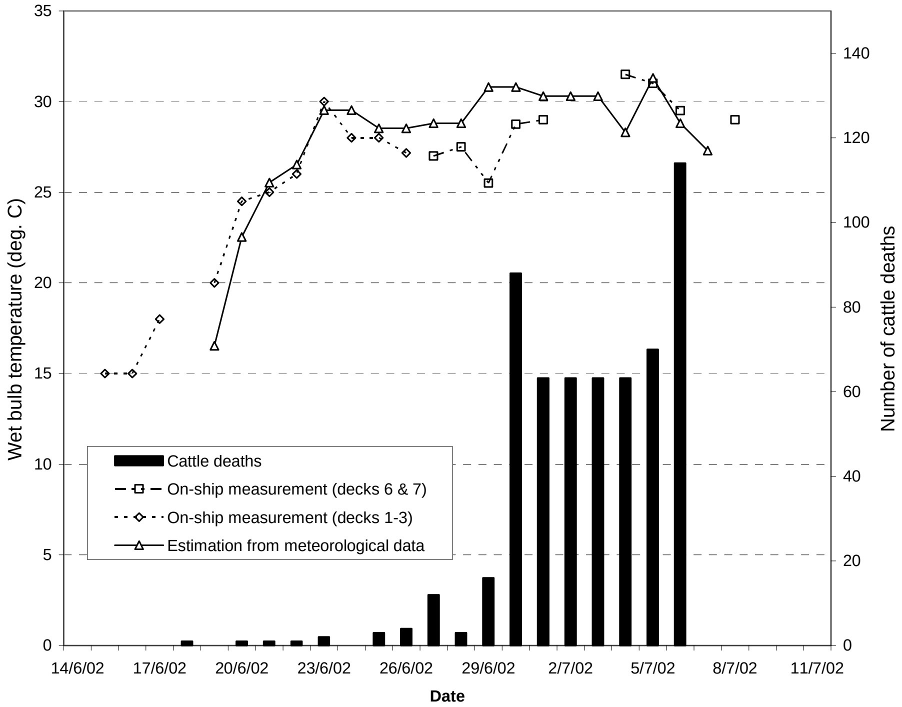
B.2.3.1 Investigation of Mortalities During Voyage 1 of the MV Becrux

Cattle Information

Detailed information about this investigation is presented elsewhere (More, 2002). The following figure presents the epidemic curve and wet bulb temperatures (measured on-ship and extrapolated from meteorological data) on the cattle decks. The measured data is believed to be reasonably accurate (More, 2002, pp. 35-37). A range of meteorological data[2] was used to estimate the daily ambient wet bulb temperature. Deck conditions were calculated by inflating these estimates by the wet bulb rise (1.53^{o}C to the 26 JUN 02 whilst the cattle were on the closed decks, then 1.80^{o}C subsequently).

[2] These data included ship observations from the Bureau of Meteorology (BoM) voluntary observing ships, drifting buoys, land stations and satellite imagery (Infra-red, Quikscat and SSMI). Wet bulb temperatures were back-calculated from dew points using BoM humidity tables, and scatterometer (satellite-derived sea surface winds) and other charts were also consulted.

Figure B.10 Wet Bulb Temperatures and Mortality on Voyage 1 of MV Becrux



Key observations include:

- The *Bos taurus* animals were not acclimatised, and most were well-conditioned with a long winter coat. The *Bos indicus* were mainly sourced from a property north of Adelaide, where wet bulb temperatures (in the weeks prior to loading) were 1-2^{o}C warmer than in western Victoria.
- Heat stress was limited to *Bos taurus* animals. None of the *Bos indicus* animals showed signs of heat stress
- Signs of heat stress in cattle were first noted (particularly in well-conditioned animals with a long winter coat) on 23JUN02. Deck conditions: 30^{o}C (measured)/29.5^{o}C (estimated). On all previous days in this voyage, deck conditions had not exceeded 26^{o}C (measured)/26.5^{o}C (estimated).
- Many animals were suffering from heat stress and there were a (relatively) small number of deaths during 24JUN02-28JUN02. *During this period, deck conditions were relatively constant averaging 27.5^{o}C (measured) /28.8^{o}C (estimated)*
- The sharp rise in deaths (coinciding with 'animals going down all over the deck') commenced on 29/30JUN02. Maximum deck wet bulb temperatures during this period were 28.8^{o}C (measured)/30.8^{o}C (estimated)
- The epidemic continued unabated during 01JUL02-06JUL02. During this period, deck conditions were relatively constant averaging 30.25^{o}C (measured) /29.9^{o}C (estimated). Deck conditions were likely to have been higher than this in the outer pens (where deaths were concentrated)
-

Key conclusions:

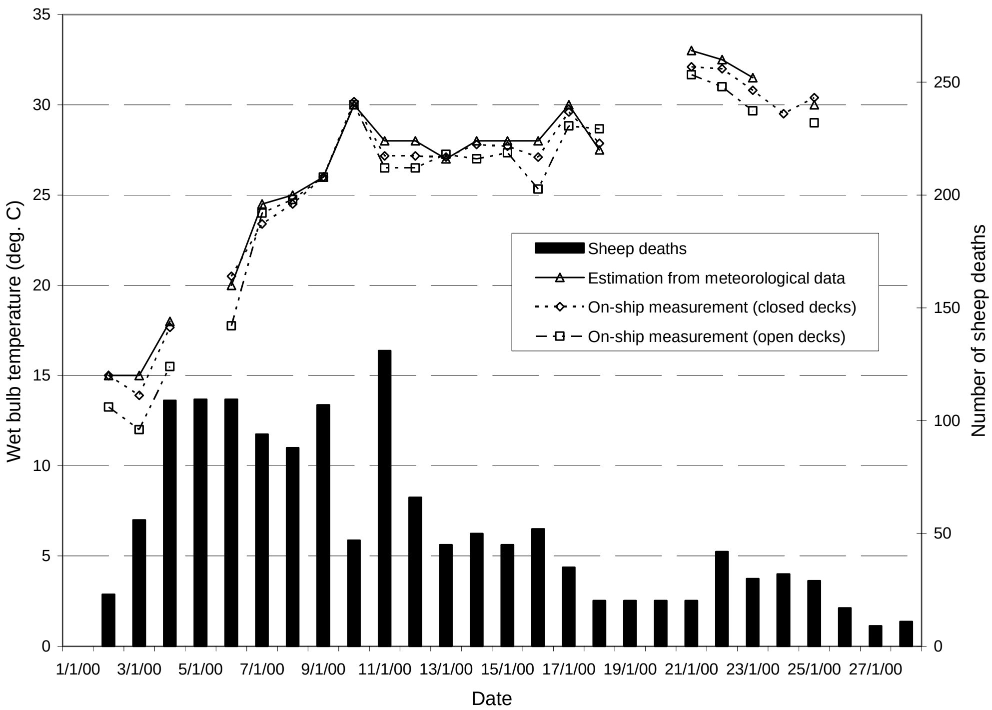
- Interpretation is somewhat obscured by the differences (albeit relatively small) between the measured and estimated values.
- The HST for all cattle was greater than 26.0^{o}C (measured)/26.5^{o}C (estimated)
- The HST for at least the most susceptible *Bos taurus* animals was equal to or less than 27.5^{o}C/28.8^{o}C. For the majority of the *Bos taurus* animals, the HST was certainly considerably less than 28.8^{o}C/30.8^{o}C.
- The HST for all of the *Bos indicus* animals was higher than 31.5^{o}C/31.3^{o}C (the highest measured wet bulb temperature on the cattle deck during the voyage)

- There were a substantial number of deaths among the *Bos taurus* animals once deck temperatures reached 28.8°C/30.8°C

Sheep Information

Detailed information about this investigation is presented elsewhere (More, 2002). The following figure presents the epidemic curve and wet bulb temperatures (measured on-ship and extrapolated from meteorological data) on the decks where sheep were held. As stated previously, the measured data are believed to be reasonably accurate. Further, we could also estimate the daily deck wet bulb temperature based on detailed meteorological data and information about the likely wet bulb rise.

Figure B.11 Wet Bulb Temperatures and Mortality Rate among Sheep on Voyage 1 of MV Becrux



Key observations include:

- It is very unlikely that heat stress was a significant cause of death in sheep during this voyage. Firstly, heat stress was never noted by the voyage veterinarian as a cause of morbidity or mortality. Secondly, there is good epidemiological evidence[3] to support feedlot-related salmonellosis and persistent inappetence-salmonellosis-inanition as the primary causes of death. The small rise in mortality late in the voyage when wet bulb temperatures reached 32°C may indicate heat effects being a contributing cause.

[3] This evidence includes the following:

- *The temporal pattern of losses* – there is a lack of temporal association between mortality and deck conditions;
- *The pattern of losses among animal groups* – the animals at greatest risk of dying were the Portland-loaded animals. These animals would be at greatest risk of dying from feedlot-related salmonellosis
- *Knowledge of weather conditions on-loading* - the weather at Portland was both cold and wet in the period prior to loading. These conditions, and associated problems leading to inconsistent feed intake, are key risk factors for feedlot-related salmonellosis

Key findings include:

- Because the clinical condition of these sheep (with respect to heat stress) is unknown, it is not possible to estimate the UCT of these sheep
- The death temperature in these sheep was higher than 32.0^{o}C/31.3^{o}C (the highest daily temperature recorded during this voyage)

B.3 Additional Questions Relevant to the Risk Management Model

B.3.1 Aspects of the Physiology of Sweating

In cattle, there are two kinds of sweating. Insensible sweating occurs continuously. In contrast, thermal sweating occurs as ambient temperatures rise. There has been some debate about relative differences in thermal sweating among *Bos indicus* and *B. taurus* animals. Although both species have the same type of sweat glands (one to each hair follicle), the number of sweat glands and the rate of sweating in *Bos indicus* cattle is higher due to a higher density of hair follicles (1698/cm^2 and 1064 cm^2 for *B. indicus* and *B. taurus,* respectively). In *B. taurus* animals, sweating increases rapidly as temperatures reach 15-20^{o}C, but then plateaus. In contrast, *B. indicus* animals have initially lower evaporation rates, but with an exponential rise when temperatures were 25 to 30^{o}C, and a potential for increasing rises up to 40^{o}C. Reported sweating rates include:

- Twofold increase to 77 g m^{-2} h^{-1} from the scrotum after exposure to a temperature of 40^{o}C
- Fivefold increase to 279 g m^{-2} h^{-1} following exposure to 36.2^{o}C (Kadzere et al., 2002)

In comparison, in man sweating can result in water loss varying between 28 and 438 gm^{-2} h^{-1} (Mount, 1979). It appears that sweat glands are located uniformly throughout the coat of cattle, although specific information to this effect has not been cited. There is no evidence that sweat glands in *B. indicus* are more concentrated on the dewlap (which are much for prominent in *B. indicus* as compared with *B. taurus* animals) than on other areas of the body (Mount, 1979).

B.3.2 Aspects of the Physiology of Respiratory Evaporation

B.3.2.1 Cattle

In cattle, the pattern of respiration is characterised by rapid respiration and small tidal volume (Riebold, 2003), noting that tidal volume is the amount of gas passing into and out of the lungs in each respiratory cycle (Blood and Studdert, 1988).

B.3.2.2 Sheep

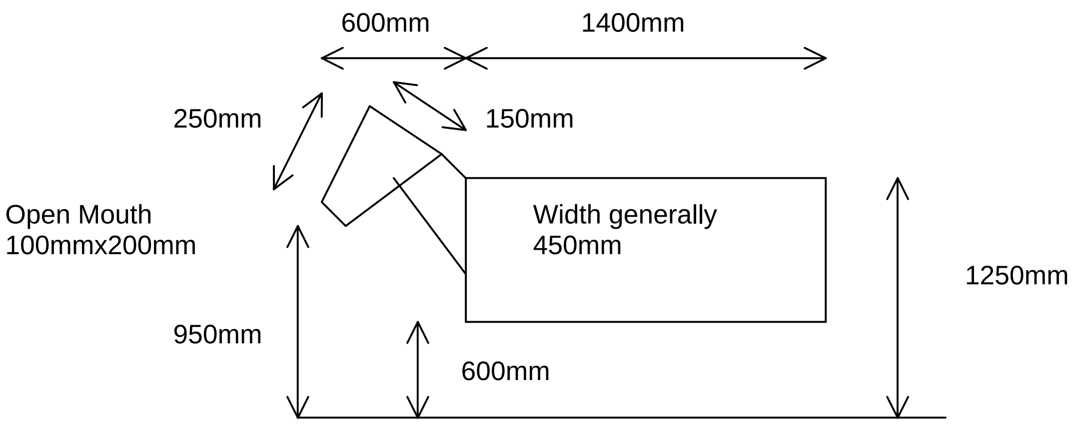
In previous modelling work with sheep, the tidal volume was assumed to average 0.25 l (Stafford Smith et al., 1985). In reality, the tidal volume will decline – at least initially – with an increasing respiration rate.

Appendix C Computational Fluid Dynamics (CFD)

C.1 Cattle Parameters

Cattle were modelled as a prismatic volume with a simple head and neck structure as shown in Figure C.1. The cattle legs were considered to have only minor influence on overall convective flow and as such were not explicitly modelled. The average animal dimensions used are shown below in Figure C.1. These were determined from averages taken from published sources and were confirmed with measurements at The University of Queensland Veterinary School Farm.

Figure C.1 Schematic of Cattle Representation



The typical cattle mass selected for the study was 350kg (typical mass across a range of different lines). A stocking density of 30 animals/pen was used for cattle (1.38m^2/animal).

Sources of heat and water vapour (from evaporation) were included at the body and head, and within the mouth of each animal. The distribution of these sources for each animal is shown below in Table C.1.1.

Table C.1.1 Distribution of Heat and Water Vapour Sources Within Cattle CFD Model

Total Metabolic Rate	840W	100%
Sensible Heat at Skin	126W	15% of Metabolic
Skin Water generation (sweat)	0.049g/s (126W latent)	15% of Metabolic
Respiratory Sensible Heat	88W	10.5% of Metabolic
Respiratory Water generation	0.195g/s (500W latent)	59.5% of Metabolic

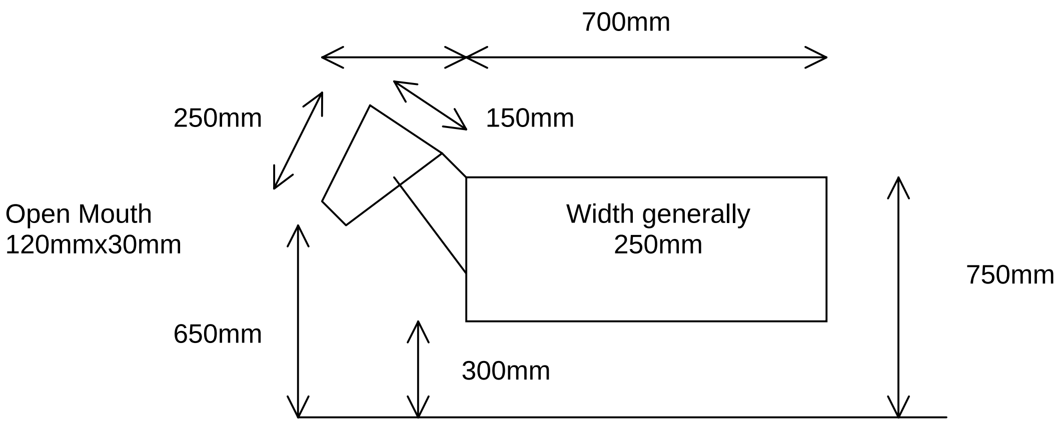
To simulate animal breath as steady-state flow, the “mouth” volume was modelled to draw in surrounding air at the sides and expel it through the mouth orifice.

A mouth exit velocity of approximately 1m/s was assumed. No detailed data could be located giving specific breath volumes and velocities for cattle. Knowing this detail could have enabled a more accurate distribution of heat within the modelled zone. The assumed value was checked by considering the heat rejected in the breath and assuming that the out-flowing breath would be nearly saturated (near 100% relative humidity). Assuming also that the breath out-flow was close to body core temperature, the enthalpy of the air-in and air-out could be determined. Balancing this energy against the heat rejected in the breath, gave the required volumetric flow rate. Given the typical mouth dimensions for each animal, the resulting breath velocities could be estimated.

C.2 Sheep Parameters

Sheep were modelled as a prismatic volume with a simple head and neck structure as shown in Figure C.2 below. The sheep legs were considered to have only minor influence on overall convective flow and as such were not explicitly modelled. The typical animal dimensions used are shown below in Figure C.2. These were determined from averages taken from published sources and were confirmed with measurements at The University of Queensland Veterinary School Farm.

Figure C.2 Schematic of Sheep Representation



The typical sheep mass selected for the study was 50kg (typical mass across a spectrum of different lines of sheep). A stocking density of 120 animals/pen was used (0.345m^2/animal) for the study.

Sources of heat were included at the body and head, and within the mouth of each animal with water vapour also emitting from the mouth. The distribution of these sources used for each sheep is shown below in Table D.2.

Table D.2 Distribution of Heat and Water Sources Within Sheep CFD Model

Total Metabolic Rate	160W	100%
Sensible Heat at Skin	32W	20% of Metabolic
Skin Water generation (sweat)	0g/s (no sweat)	0% of Metabolic
Respiratory Sensible Heat	19.2W	12% of Metabolic
Respiratory Water Generation	0.0425g/s (109W latent)	68% of Metabolic

To simulate animal breath as steady-state flow, the "mouth" volume was modelled to draw in surrounding air at the sides and expel it through the mouth 'orifice'.

A mouth exit velocity of approximately 1m/s was assumed. No detailed data could be located giving specific breath volumes and velocities for sheep. Knowing this detail could have enabled a more accurate distribution of heat within the modelled zone. The assumed value was checked by considering the heat rejected in the breath and assuming that the out-flowing breath would be nearly saturated (near 100% relative humidity). Assuming also that the breath outflow was close to body core temperature, the enthalpy of the air-in and air-out could be determined. Balancing this energy against the heat rejected in the breath, gave the required volumetric flow rate. Given the typical mouth dimensions for each animal, the resulting breath velocities could be estimated.

C.3 Deck Parameters

Each pen 'unit' was modelled as a 6m x 8m modular unit with a 0.6m 'half walkway' making the pen itself 5.4m x 8m. The unit can be repeated to form a deck assembly in multiples of 6m width. Symmetry conditions used were appropriate to minimize the overall number of computational volumes or cells required for solution.

The above parameters were selected as 'typical' based on a review of drawings of six existing livestock vessels:

- Corridale Express
- Al Shuwaikh
- Al Messilah
- Becrux
- Shorthorn Express
- Farid F

Ceiling support beams 200mm below the ceiling were included to simulate blockage effects on horizontal flow at the roof level. Pen rails were considered to not significantly influence the flow and therefore were not included in the modelled geometry.

Sheep Pen Height: 1300mm
Cattle Pen Height: 2400mm

Heat transfer was modelled as zero through the wall and roof surfaces.

Ventilation risers with the cross section dimensions 1200mmx1500mm were included at the end of each pen from floor to ceiling, resulting in an effective pen floor area of 41.4m^2.

C.4 Domain Parameters

Each computational domain, including a number of pens and aisles, was open to atmosphere on the seaward side of the model, with the other side of the model being at the ship centreline. Pressure boundary conditions were employed at these locations to enable free flow into and out of the computational domain. An incoming turbulence intensity of 5% was assumed.

For both cattle and sheep, heat input reduction due to the death of animals subjected to untenable conditions was not modelled. That is; all animals continued standing and emitting metabolic heat at all temperatures.

C.5 CFD Parameters

The CFD package Fluent was used for this study. A steady-state segregated implicit solution was implemented with 2nd order interpolation.

The mesh used was a hybrid mesh consisting of both 1st order hexahedral and tetrahedral elements. Over 2.4 million elements were used for each model. Run times typically were of the order of 30 to 40 hours.

A two-species ideal gas model was used for the air mixture modelled. Most fluid properties were determined using a mixture-dependent ideal-gas formulation.

The turbulence model implemented was the Realisable k-ε model with standard wall functions.

C.6 Analysis and Data Manipulation

Key risk assessment data for the CFD study were based on 24m and 36m wide single-tier cattle decks. With a heat generation rate of typically 595W/m^2, cattle were considered to present the worst ventilation scenario when compared to sheep which typically have a heat generation rate of approximately 508W/m^2. Trends developed from the results are expected to represent generally most typical livestock situations. Two cases for a 24m closed cattle deck were also run in order to establish the relativity in ventilation effectiveness between open and closed situations.

Data output from the CFD included dry bulb temperature and local water mass fraction. From this a user-defined function was programmed to calculate local wet bulb temperature assuming a constant specific heat for air and a constant enthalpy for the saturated vapour component. Wet bulb values provide a guide to tenability of the local conditions.

The following correlation developed from standard tabulated psychrometric data was implemented.

WBT (°C) = -1.266247e-9 * (h)^2 + 4.390482e-4*(h) –1.121885

where h = enthalpy (J/kg)

Using this relationship with the static temperature and water mass fraction from the solution data, contours of wet bulb temperature could be plotted directly in °C.

For the purposes of risk analysis an "Effective PAT" was defined as the equivalent closed deck pen air turnover (m/h) to achieve a nominated WBT at the height of animal mouths. assuming perfect mixing of air across the deck. The WBT used for the calculation was determined from the maximum value of a 2.4m long running average along two rake lines; one just above (1m height) and one just below (0.8m height) the animal mouths. The position of the two rake lines of 100 sampling points used is shown in Figure C.23. This technique removed the highly localised hot and cold areas from the analysis which nominally the animals could easily avoid. In reality this maximum WBT should be representative of the highest bulk wet bulb temperature that an animal would experience in the given situation.

A selection of colour contour plots is provided below.

Specifically a plot of wet bulb temperature for each cattle run is plotted in Figures D.24 to D.41. Each of these plots show wet bulb temperatures in °C in the vertical symmetry plane on the centreline of the decks. Wet bulb temperatures are uniformly ranged between 30°C – blue (ambient) to 37°C – red (the maximum recorded).

C.7 Accuracy

Computational Fluid Dynamics (CFD) is a numerical simulation or modelling technique and a tool for facilitating predictions and calculations. It is not expected to perfectly reflect reality. The accuracy of the presented results achieved is limited to the accuracy of the mathematical models implemented, simplifications made for animal and deck representations, and thermodynamic data used.

C.8 Model Summary

Cattle – One Tier

Geometry Modelled:	24m deck width with deck heights of 2.4, 2.8 &3.2m, 36m deck width with 2.4m height
Ambient Temperature:	32.25°C
Ambient Relative Humidity:	85% (mass fraction of water 0.02622)
Mechanical Ventilation:	none, 30 PAT, 40 PAT, 60 PAT, 90 PAT, 150 PAT
Cross Wind:	none, 0.5m/s, 1m/s, 1.5m/s, 2m/s, 3m/s
Deck Configuration:	Open and Closed

Sheep – One Tier

Geometry Modelled:	Deck 24m wide and 2.4m high
Ambient Temperature:	32.25°C
Ambient Relative Humidity:	85% (mass fraction of water 0.02622)
Mechanical Ventilation:	none
Cross Wind:	none (still ambient)
Deck Configuration:	Open

Sheep – Two Tier

Geometry Modelled:	Deck 24m wide, tiers 1.3m high
Ambient Temperature:	32.25°C
Ambient Relative Humidity:	85% (mass fraction of water 0.02622)
Mechanical Ventilation:	none
Cross Wind:	none (still ambient)
Deck Configuration:	Open

CFD modelling currently being undertaken includes simulations for two other deck widths, and cases with cross winds and forced (mechanical) ventilation.

Figure C.3 Representative Cow Geometry used for CFD Study

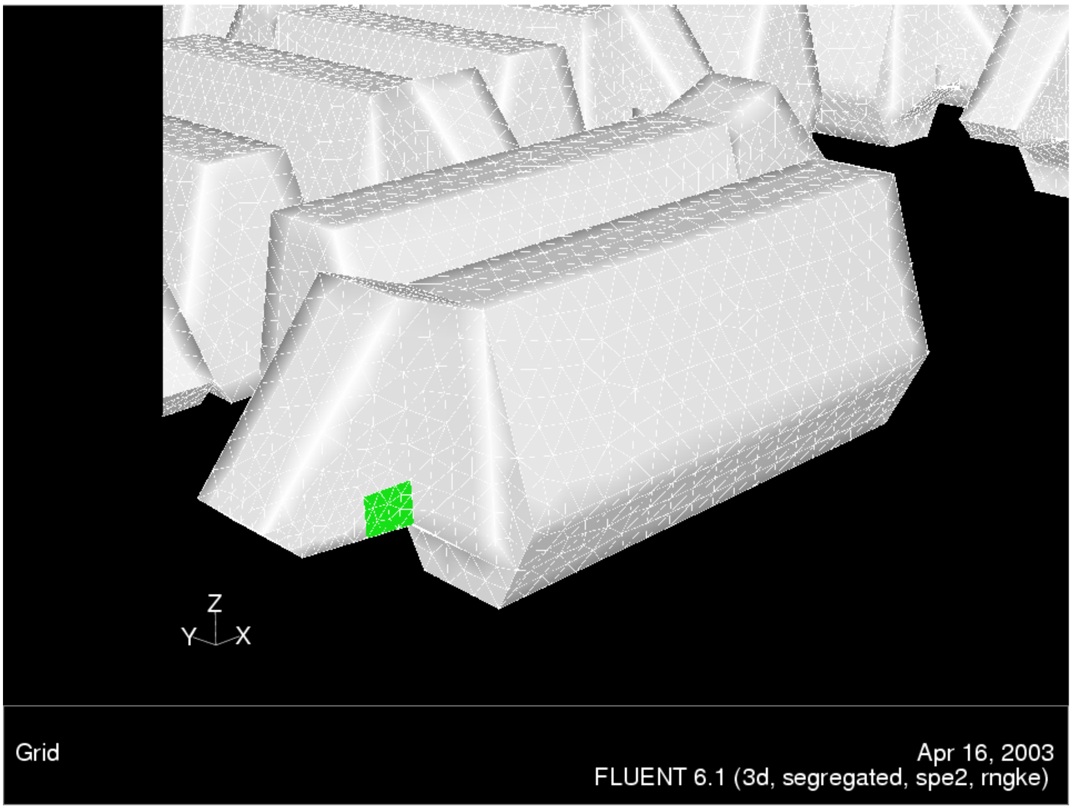


Figure C.4 Representative Sheep Geometry used for CFD Study

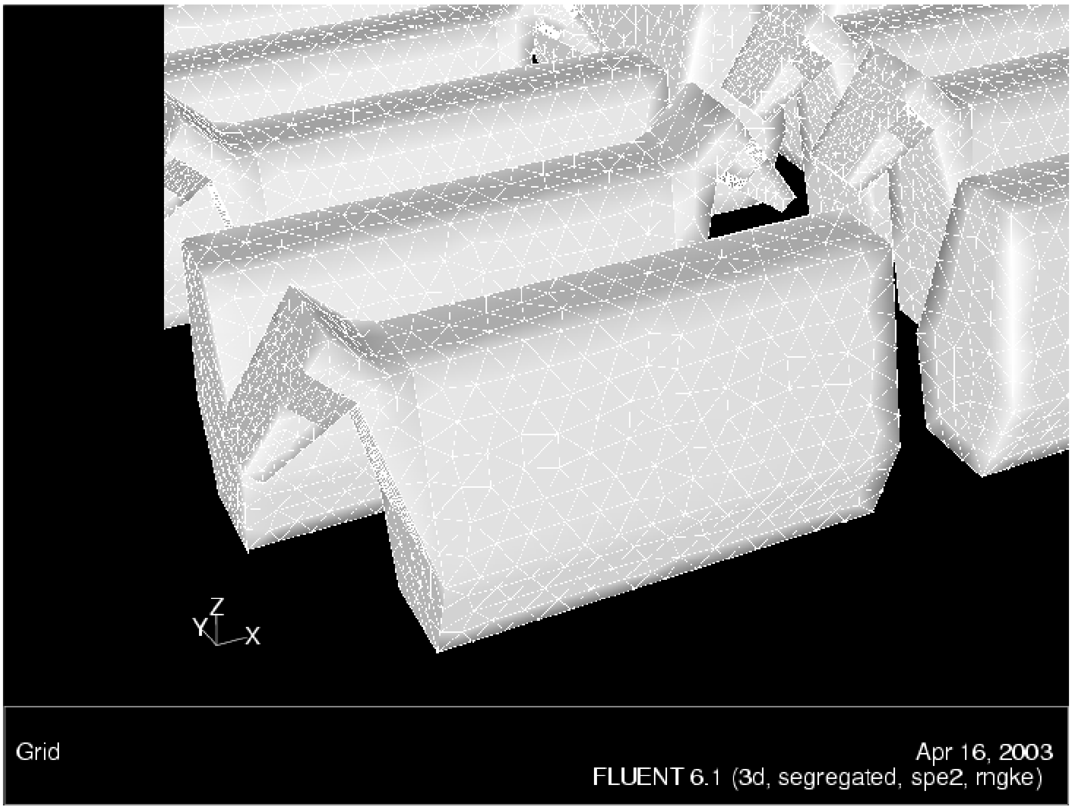
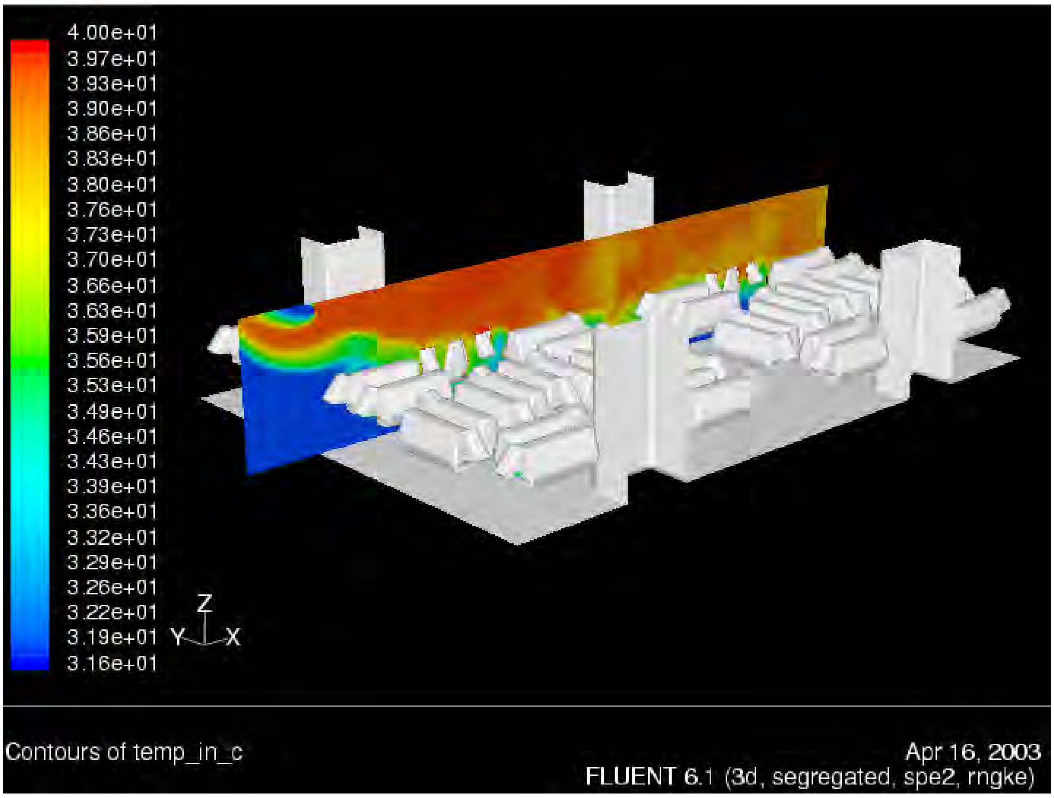


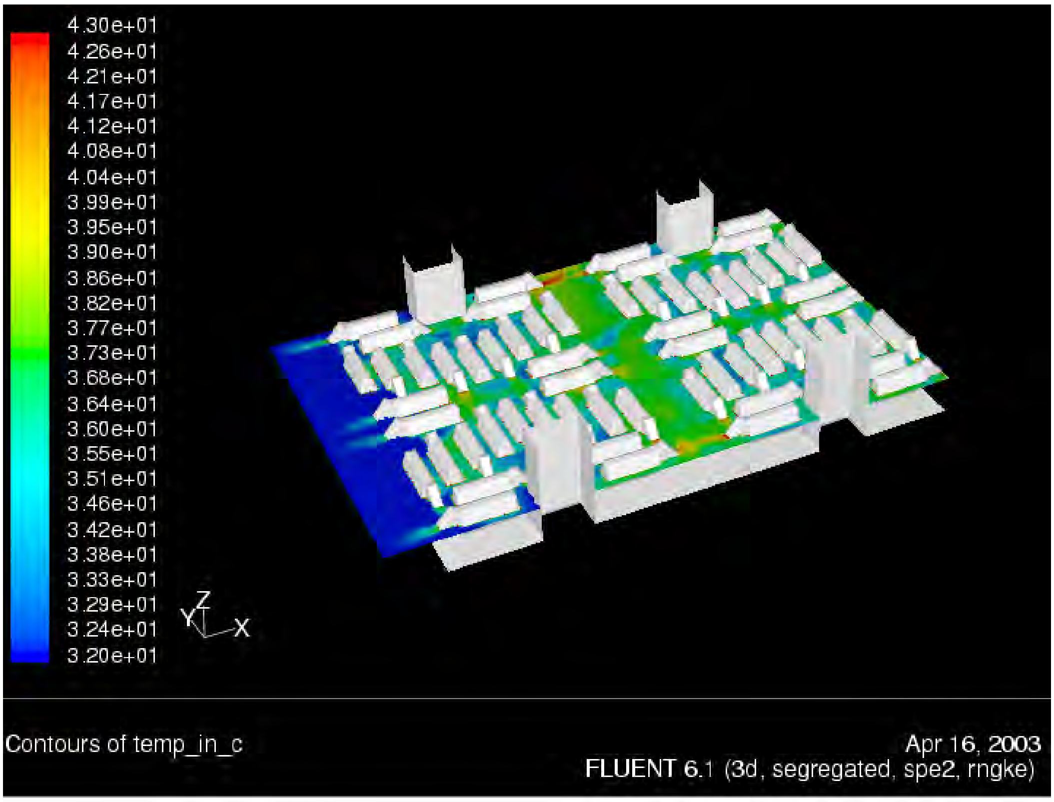
Figure C.5 Dry Bulb Temperature Vertical Plane



Cattle 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

The view shown is looking from sea (to the left) to the centreline of the ship (right). Columns and roof are not shown for clarity. Four vertical ventilation risers are clearly seen around the perimeter. No flow from these risers is modelled. A hot plume (red) is seen to be exiting the seaward pen (left) with a maximum dry bulb temperature of approximately 39°C. Dry bulb temperatures close to the cattle backs are typically 37°C to 38°C with the highest temperature occurring at the centreline of the ship.

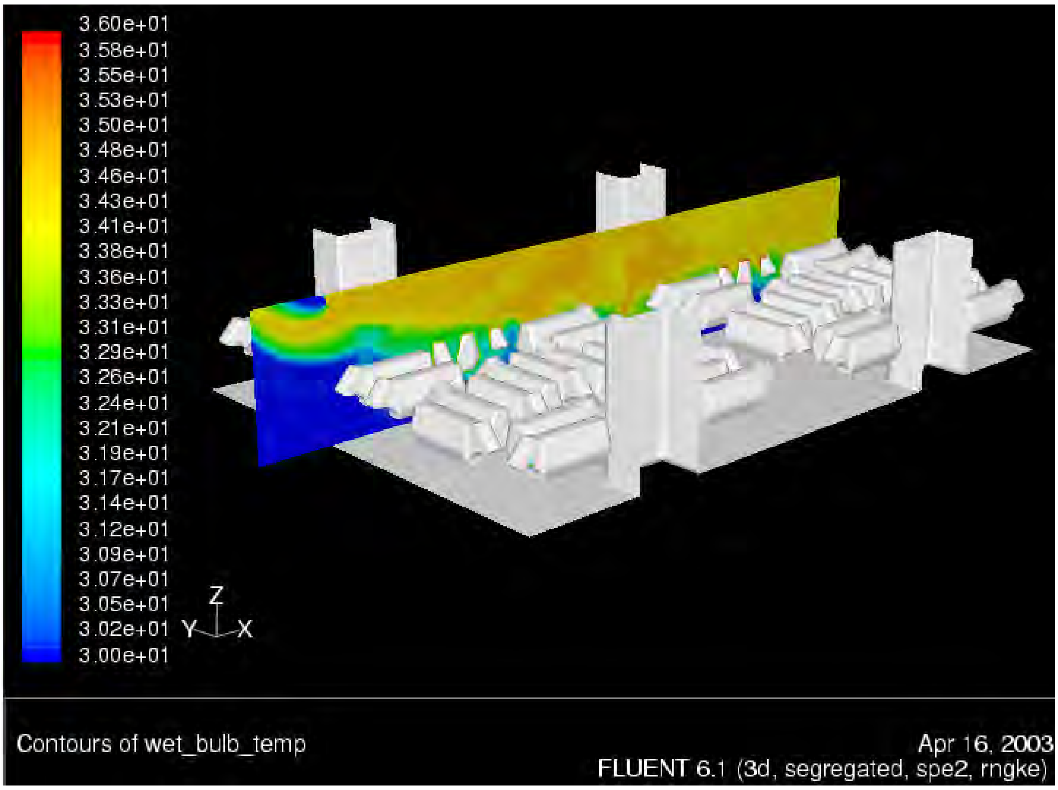
Figure C.6 Dry Bulb Temperature Horizontal Plane



Cattle, 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This view is from front of ship seaward to the centreline for the ship (right). Symmetry was implemented at this centreline face. The contours shown are in a horizontal plane through the deck at the approximate height of the cattle mouths. Heated breath jets are clearly seen issuing from most animals. The walkway or aisle is seen in the middle of the plot.

Figure C.7 Wet Bulb Temperature Vertical Plane

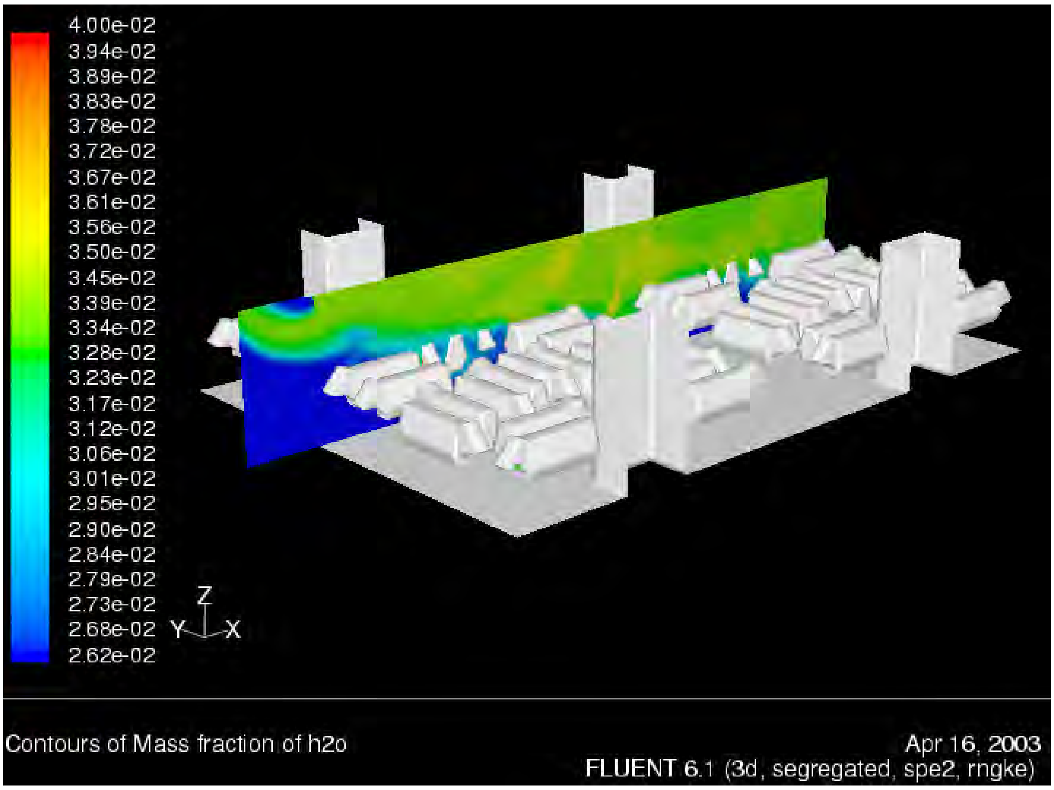


Cattle 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This plot has a similar view to Figure C.5 (sea to left). Contours are shown in a vertical plane through the pen. Maximum wet bulb temperatures towards the roof are seen to approach 35°C to 36°C while at the animal backs the value typically exceeds approximately 34°C.

Based on a tenability limit of approximately 32.5°C wet bulb temperature, the CFD simulation predicts a mortality rate of approximately 75% to 100% of animals in the inward pen on the ships centreline (right).

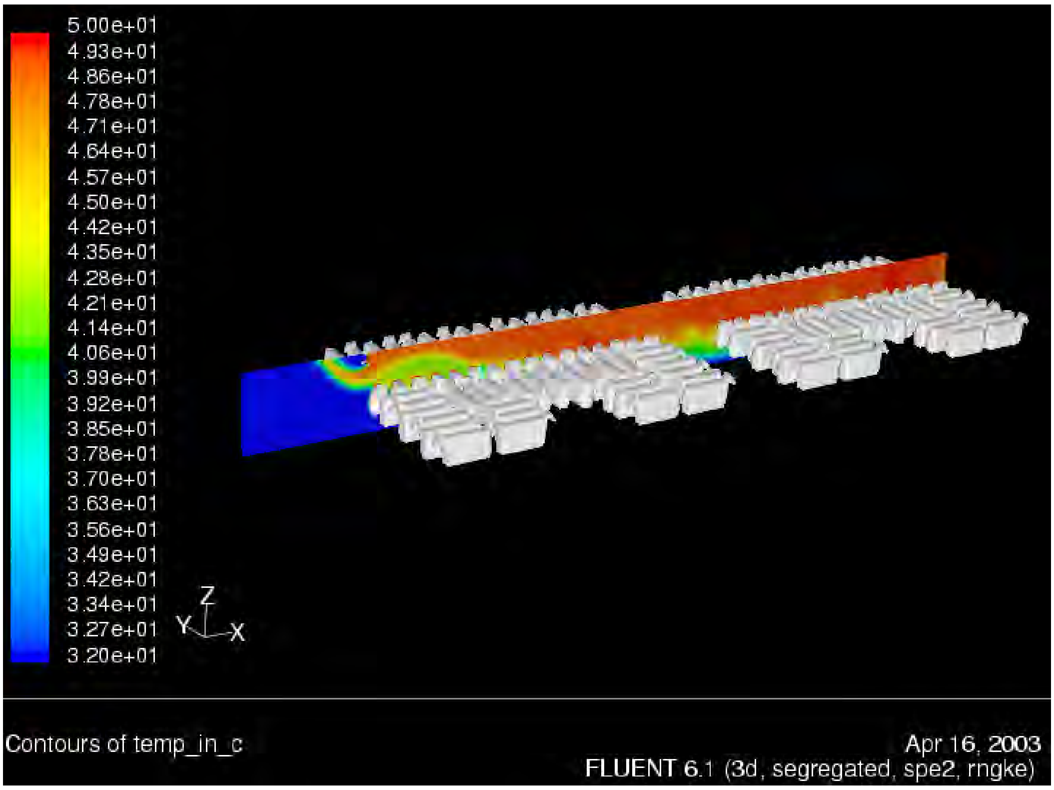
Figure C.8 Mass Fraction of Water Vertical Plane



Cattle 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m Deck.

This plot shows the level of humidity attained within the deck. The ambient value is noted to be 0.02622 corresponding to a relative humidity of approximately 85% and dry bulb temperature of 32.25°C.

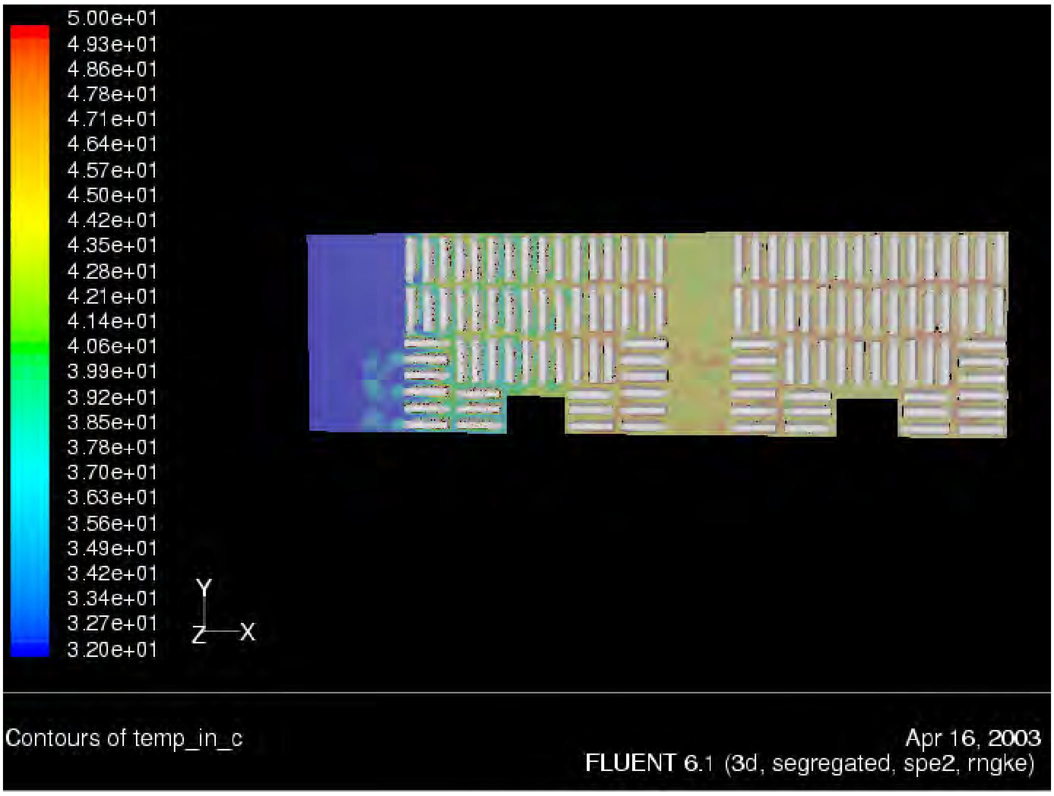
Figure C.9 Dry Bulb Temperature Vertical Plane



Sheep 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

Again the view is from sea (left) to the centerline of the ship (right). Wall, riser and flooring surfaces are not shown for clarity of image. Contours are displayed in a vertical plane through the pens. For this model, the centerline of the pen was also treated as a symmetric plane (edge in far view). In this case the dry bulb temperature towards the pen ceiling is typically between 49°C and 50°C. Dry bulb temperatures at the animal backs are seen to typically reach between 47.5°C and 49°C particularly towards the ship centerline (right).

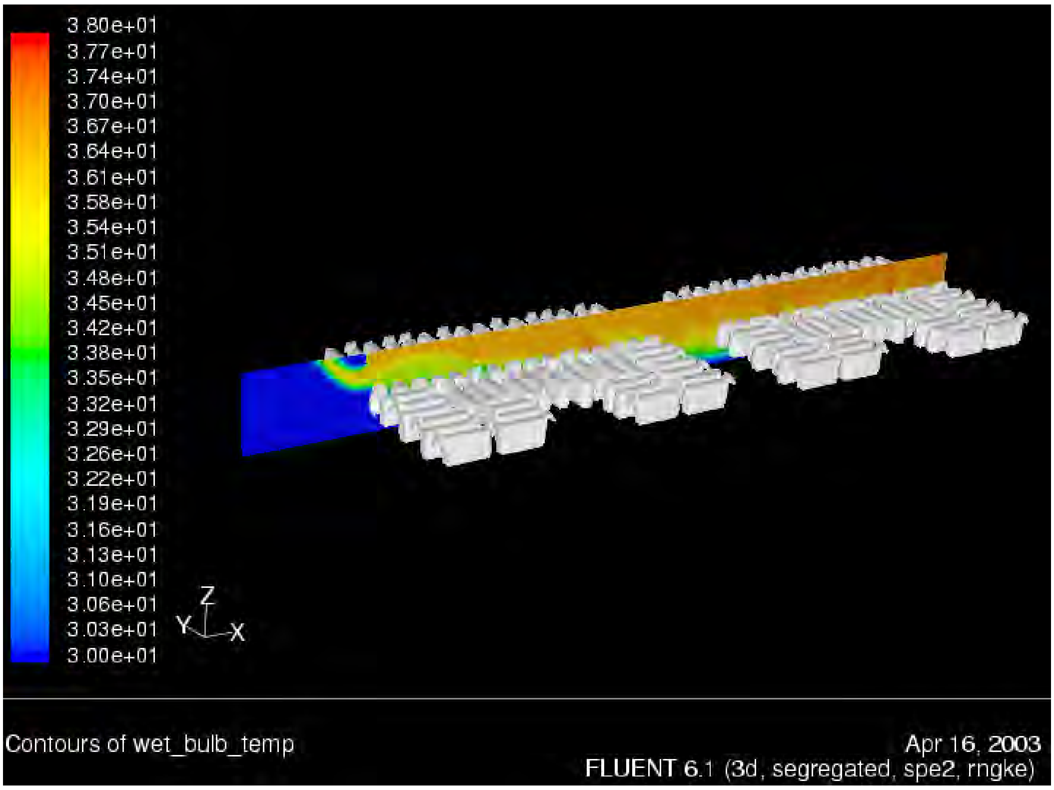
Figure C.10 Dry Bulb Temperature Horizontal Plane



Sheep 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This is a plan view of the single tier sheep model. Contours are taken through a plane at the height of the animal mouths. The cooler ambient seaward side is to the left while the ships centreline is to the right. The dry bulb temperature is seen to gradually decrease from right to left. Isolated heated breath jets are seen issuing from all animals. The dry bulb temperature in the aisle is seen to reach approximately between 42°C and 45°C.

Figure C.11 Wet Bulb Temperature Vertical Plane

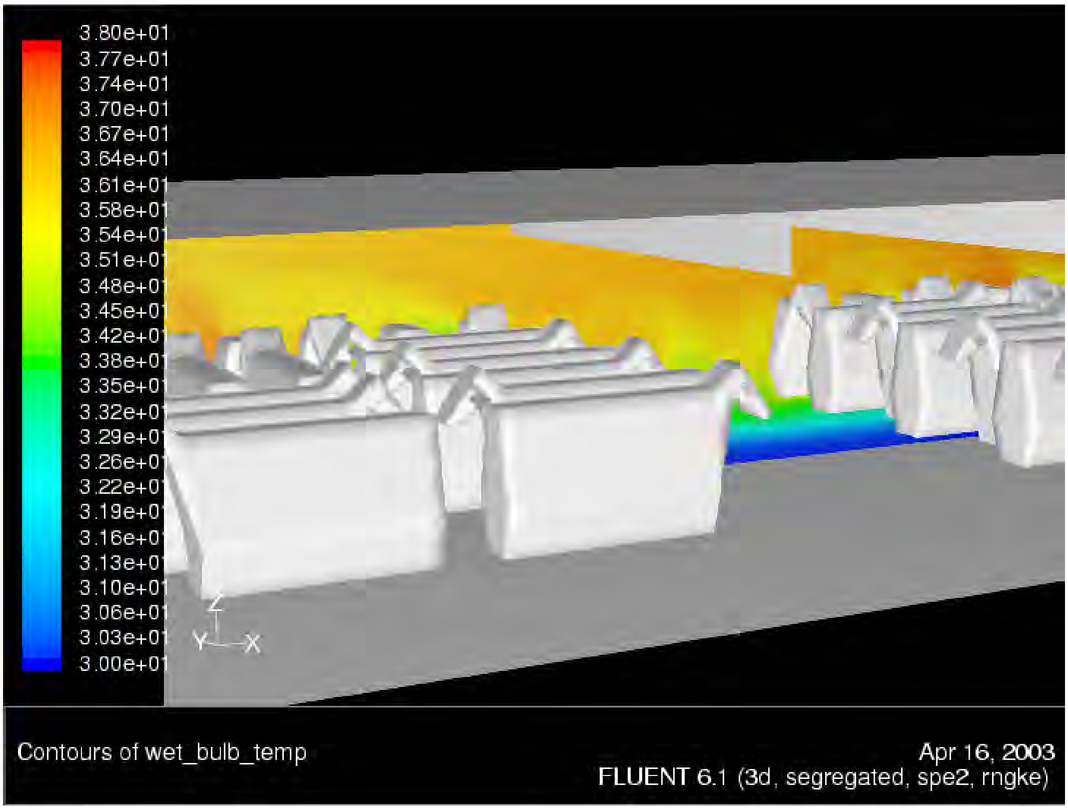


Sheep 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This is from a similar view as Figure C.9. Contours of wet bulb temperature are shown in a vertical plane through the pen. In this case, values between 37°C and 38°C are reached underneath the ceiling while typically 35.5°C to 37.5°C was achieved at the animal backs.

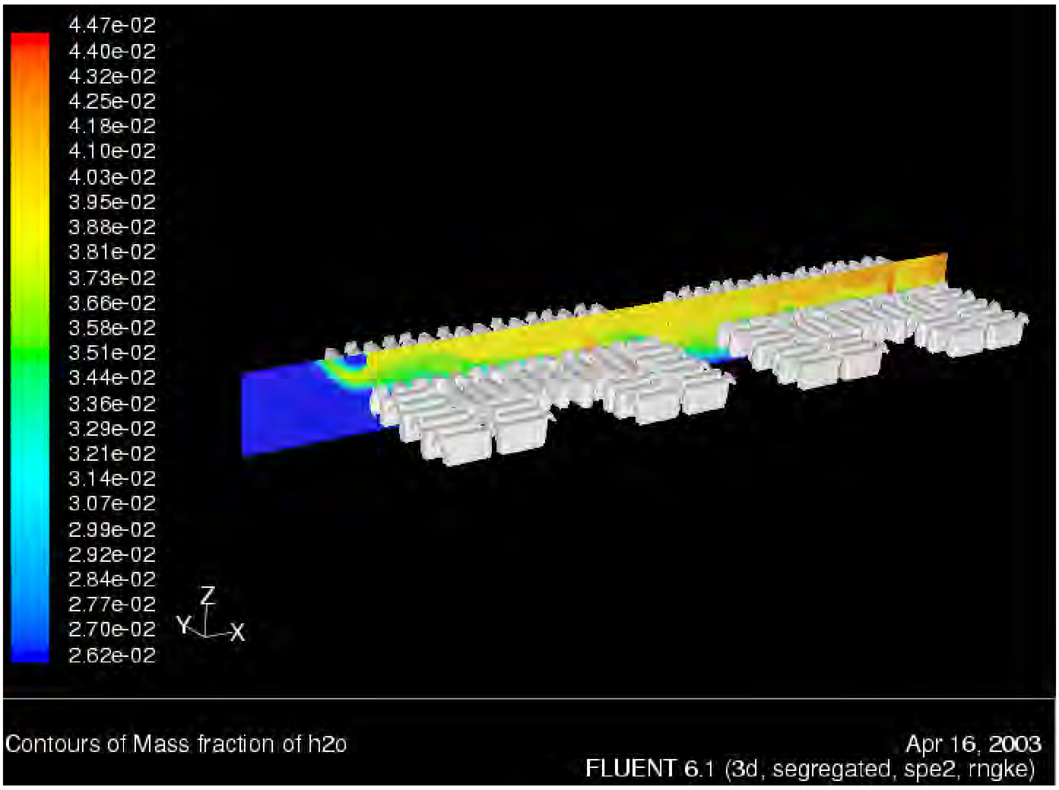
Based on a tenability limit of approximately 35°C wet bulb, the CFD simulation predicts a very high mortality rate of animals in all pens.

Figure C.12 Wet Bulb Temperature Vertical Plane



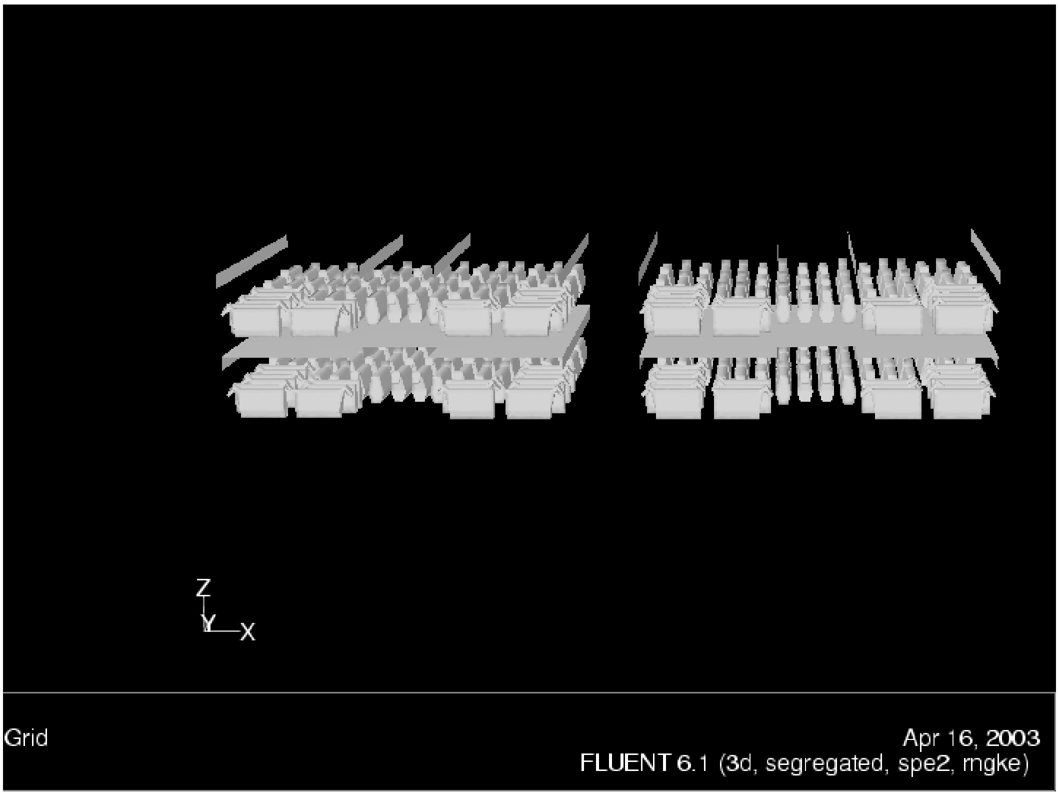
Sheep 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck. Close up of aisle between two pens.

Figure C.13 Mass Fraction of Water Vertical Plane



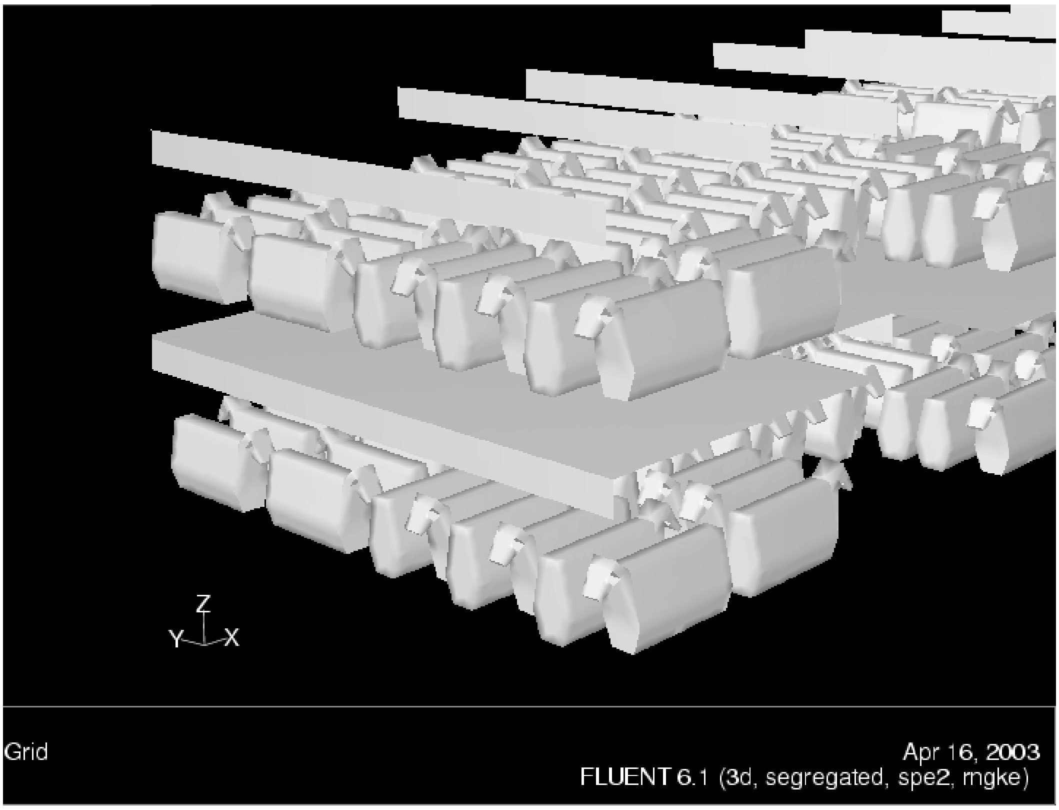
Sheep 1 Tier in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

Figure C.14 Layout of 2 tier sheep model - 24m deck



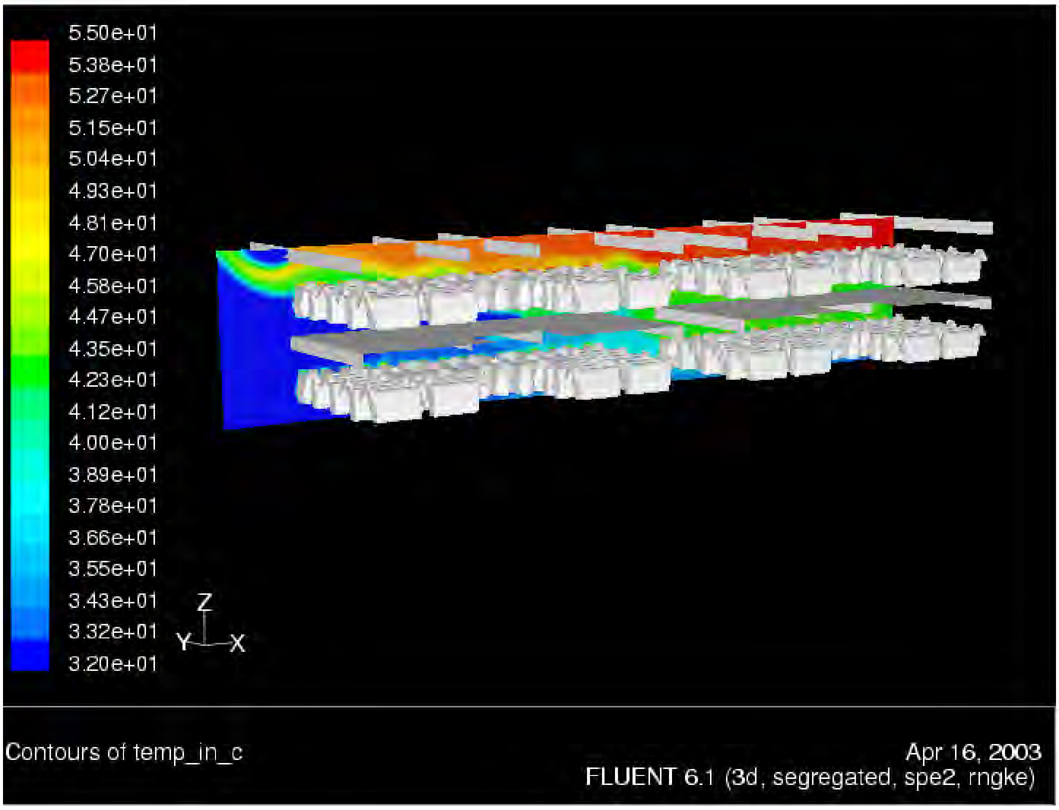
This plot shows the generic layout of the two tier sheep models. The animals are shown, along with middle floor, and columns. In this plot 240 animals are incorporated into the model.

Figure C.15 Layout of 2 tier sheep model



Close-up of Figure C.14. 24m deck.

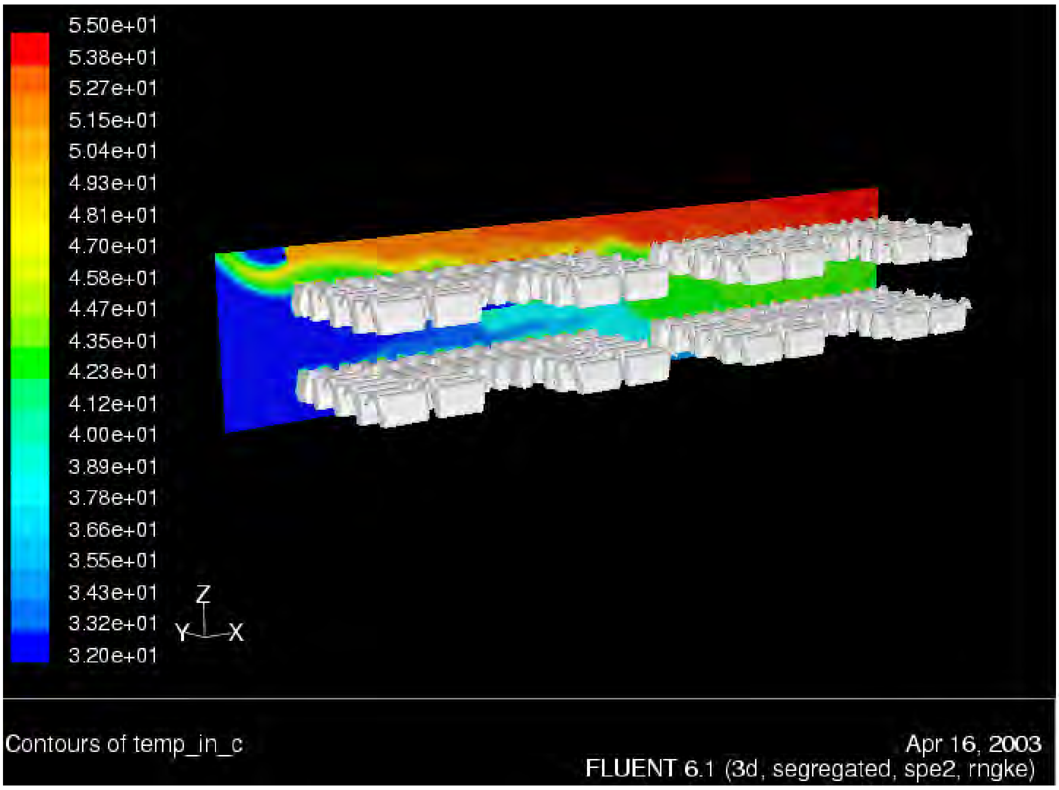
Figure C.16 Dry Bulb Temperature Vertical Plane



Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This view is from sea (left) looking to the centreline of the ship (right). In this case the highest dry bulb temperature reached was approximately 55°C in the upper most inward pen (top right of plot). The lower seaward pen remained the coolest with ceiling temperatures not exceeding 35°C. A hot plume is clearly seen leaving the uppermost seaward pen. No plume is present for the lower seaward pen due to the stack effect caused by the central walkway or aisle. Hot, moist air flowing from the lower inward pen (bottom right) flows directly up, predominantly feeding the lower half of the uppermost inward pen driving hot humid air over those animals.

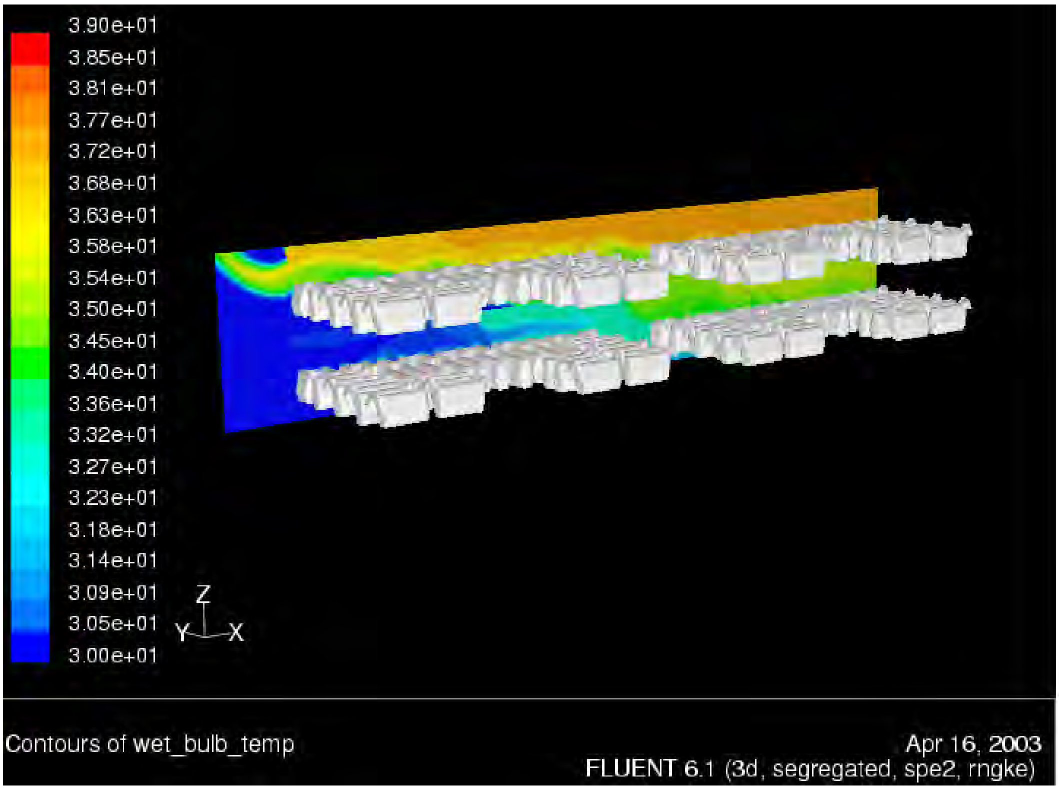
Figure C.17 Dry Bulb Temperature Vertical Plane



Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This is the same as Figure C.16 but with wall and floor surfaces removed for clarity.

Figure C.18 Wet Bulb Temperature Vertical Plane

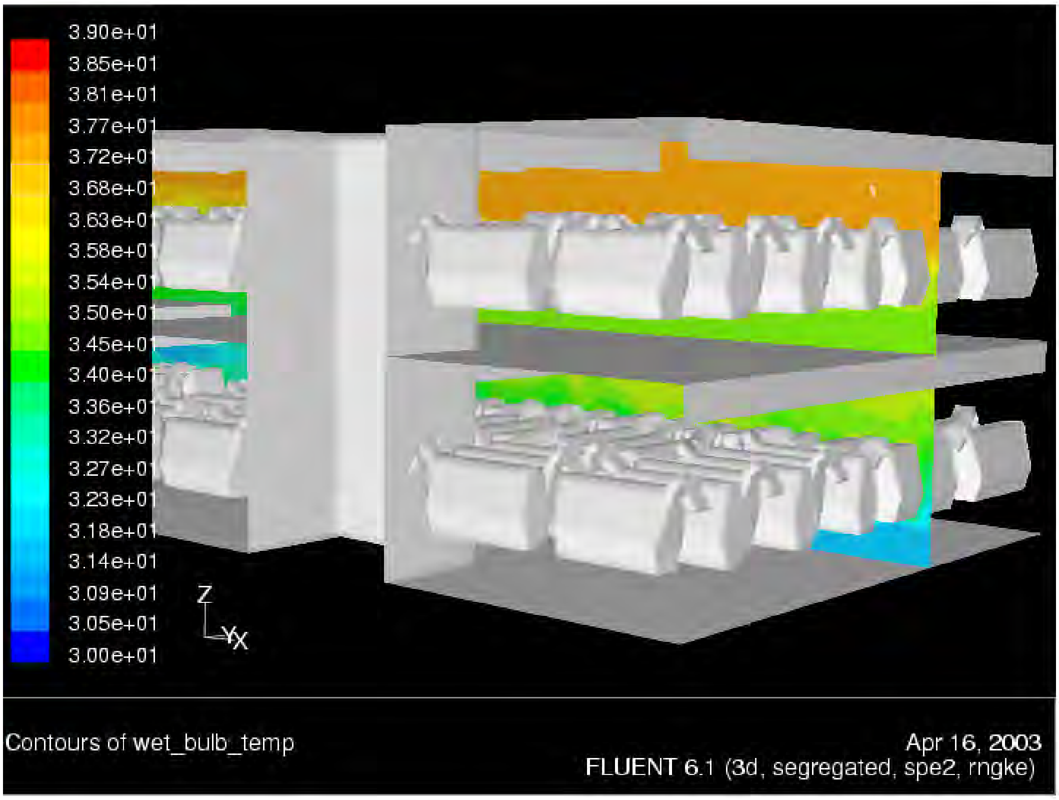


Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This view is from sea (left) looking to the centreline of the ship (right). The maximum values of wet bulb temperature achieved are in the uppermost inward pen (top right). At that location, typical temperatures at the animals are of the order of 37°C to 39°C. The lower seaward pen maintains a continuous flow of fresh drier air due to the stack effect at the central walkway.

Based on a tenability limit of approximately 35°C, the model predicts a 100% mortality rate in the uppermost inward pen and approximately 50% to 75% mortality in the lower inward pen (bottom right) and upper seaward pen (top left).

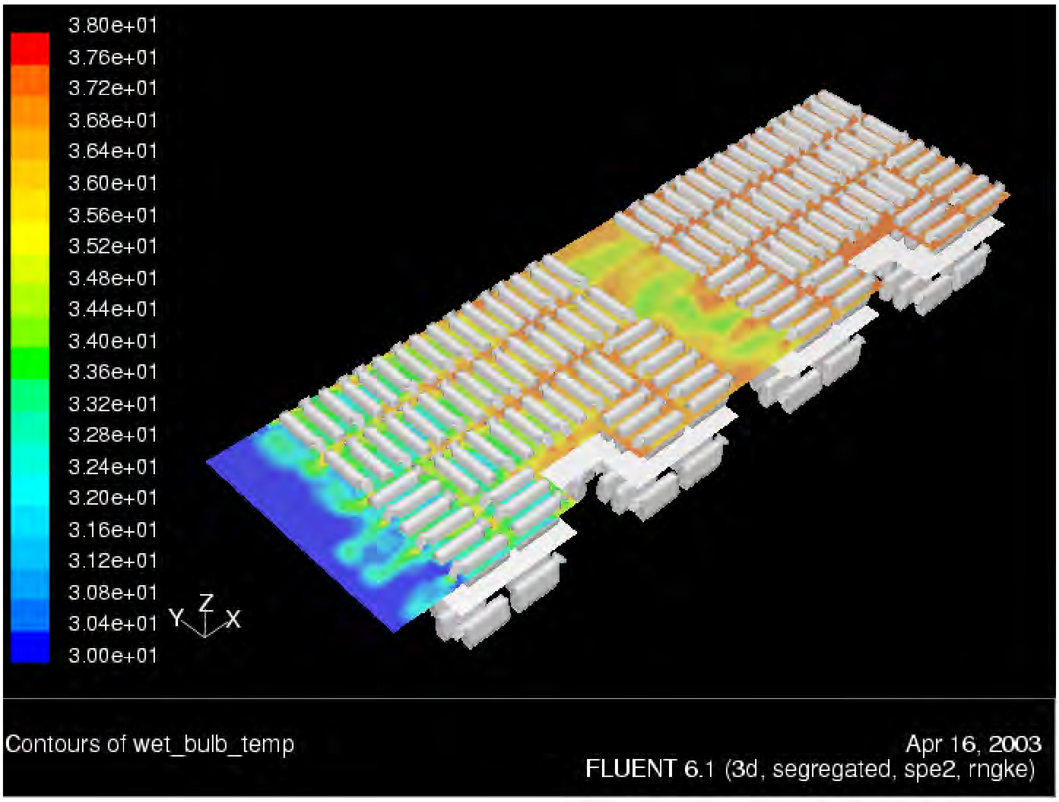
Figure C.19 Wet Bulb Temperature Vertical Plane



Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This plot shows a close-up view of wet bulb temperatures at the centreline of the ship in a vertical plane through all pens. Very high temperatures (of the order of 37°C to 39°C) at the animal mouths in the upper tier pen can be clearly seen.

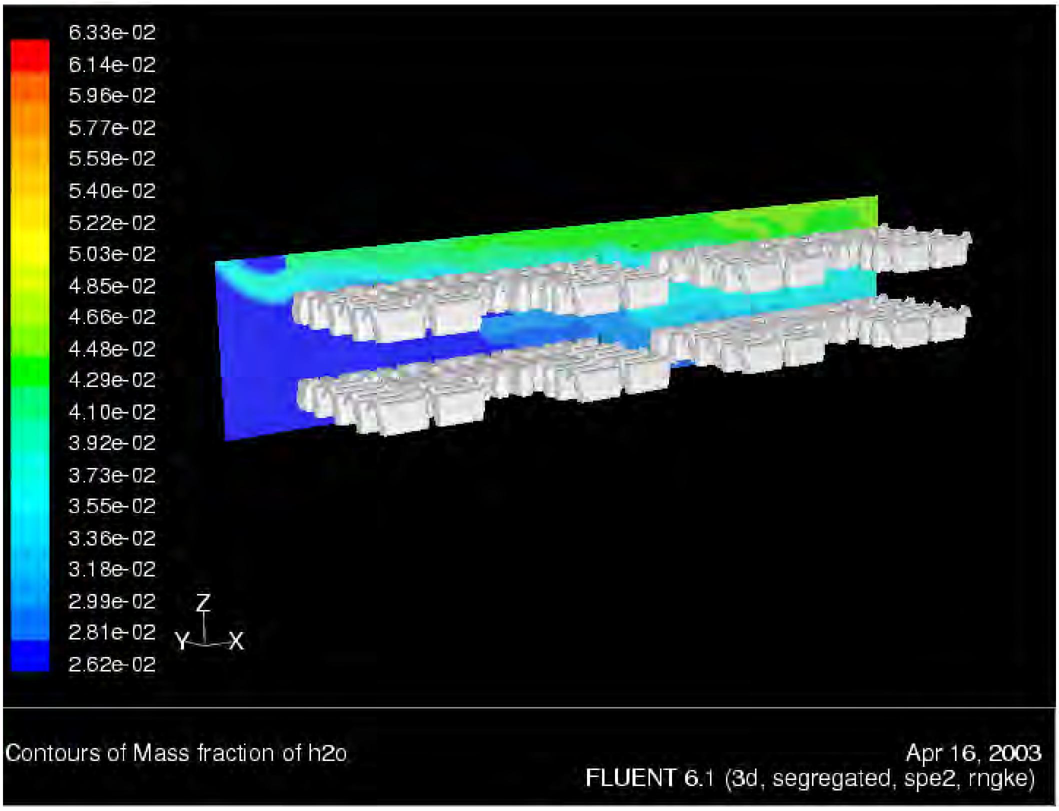
Figure C.20 Wet Bulb Temperature Horizontal Plane Through Top Tier



Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

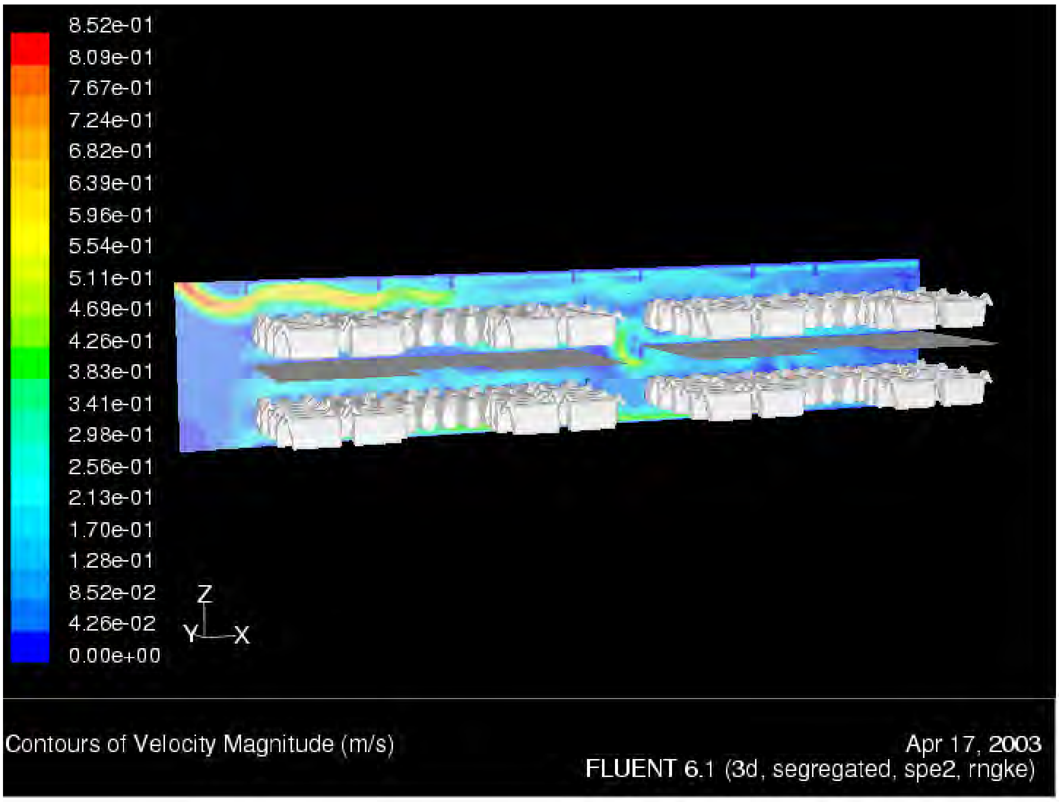
This plot shows contours of wet bulb temperature in a horizontal plane taken through the top tier at animal mouth level. It is seen that the temperature is greatest towards the centreline of the ship and least at the side open to the sea.

Figure C.21 Mass Fraction of Water Vertical Plane Through Top Tier



Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

Figure C.22 Air Velocity Vertical Plane Through Top Tier



Sheep 2 Tiers in still ambient conditions and no mechanical ventilation. Ambient temperature 32.25° with relative humidity 85%. 24m deck.

This plot shows air velocity contours through the 2 tier sheep model. Two features to note are the rapid hot plume (peak 0.85m/s) issuing from the top tier to sea (top left) and the "short-circuiting" occurring between the innermost lower and innermost upper pens (middle of plot). Higher velocity cooling air is also seen flowing beneath the sheep in the lower seaward pen.

Figure C.23 Wet Bulb Temperature Sample Point Location

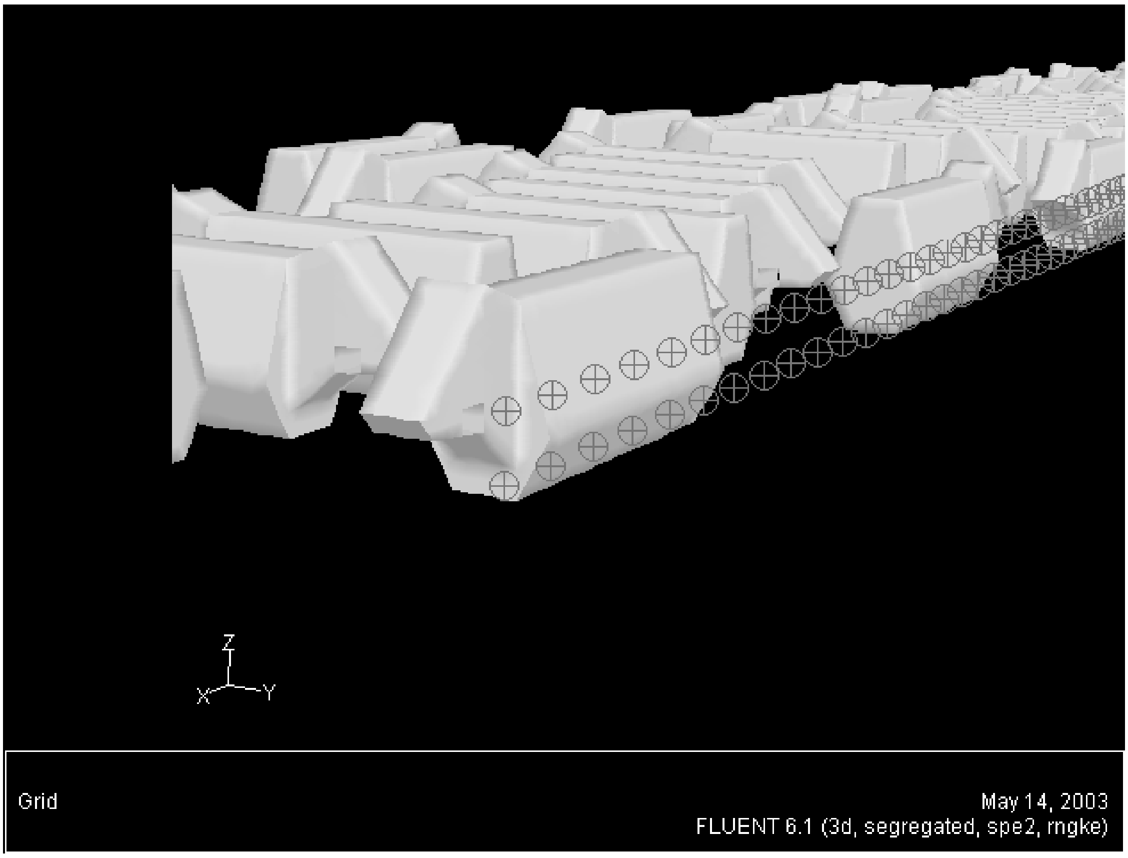


Figure C.24 Contours of Wet Bulb Temperature along Pen Centreline – Forced 30 PAT, 0.0m/s Crosswind, 24m Wide Deck

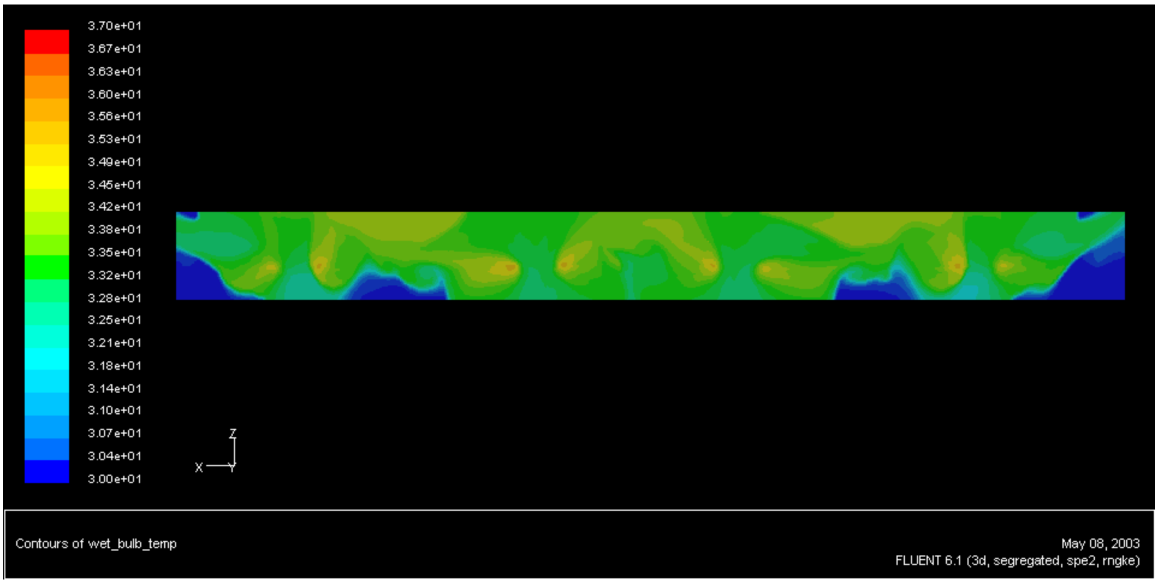


Figure C.25 Contours of Wet Bulb Temperature along Pen Centreline – Forced 40 PAT, 0.0m/s Crosswind, 24m Wide Deck

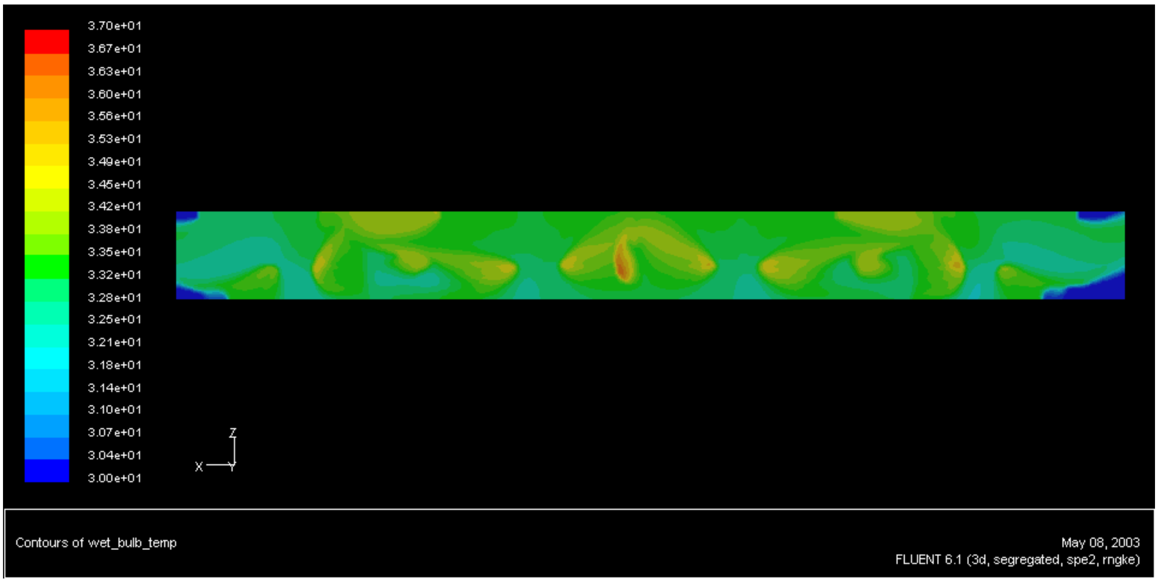


Figure C.26 Contours of Wet Bulb Temperature along Pen Centreline – Forced 40 PAT, Closed Deck, 24m Wide Deck

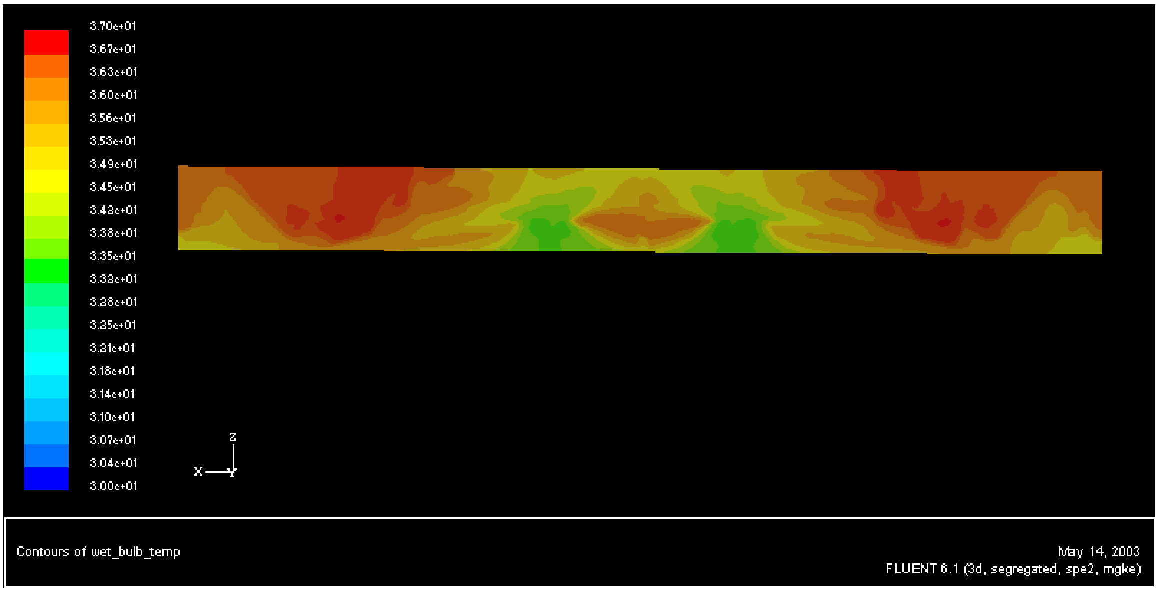


Figure C.27 Contours of Wet Bulb Temperature along Pen Centreline – Forced 40 PAT, 1.0m/s Crosswind, 24m Wide Deck

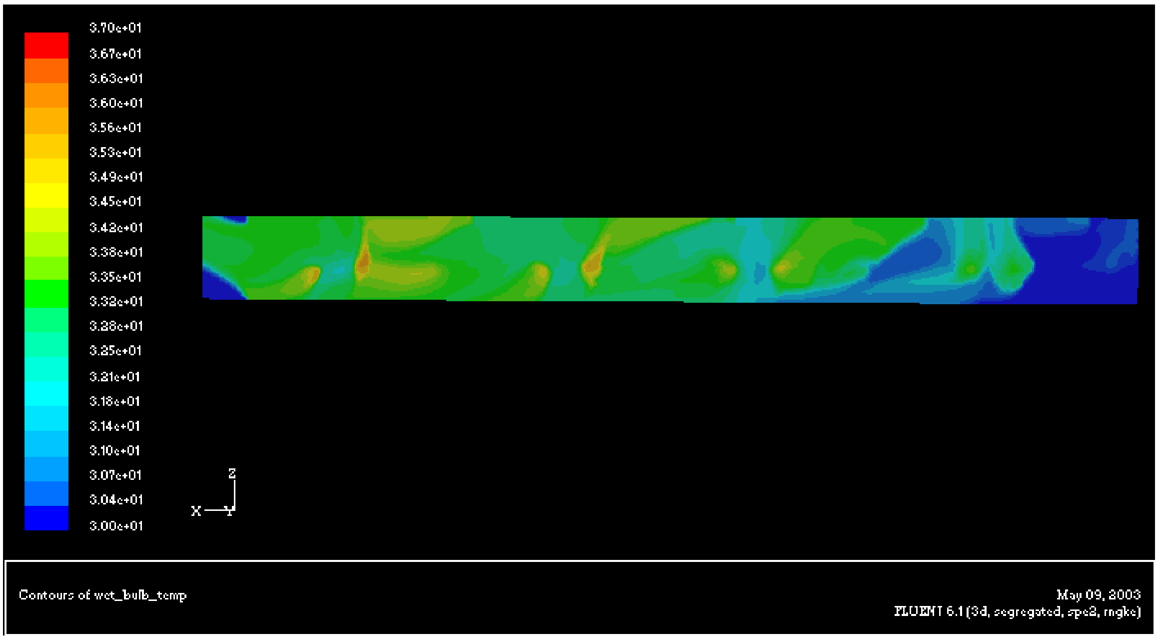


Figure C.28 Contours of Wet Bulb Temperature along Pen Centreline – Forced 40 PAT, 1.0m/s Crosswind, 36m Wide Deck

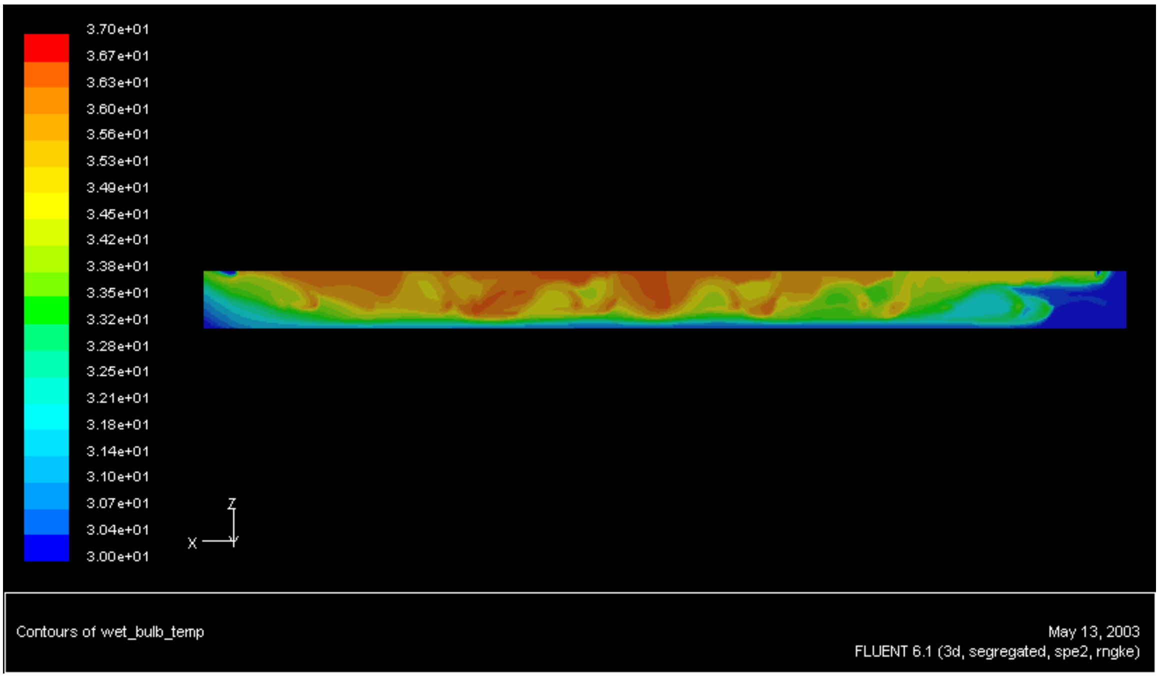


Figure C.29 Contours of Wet Bulb Temperature along Pen Centreline – Forced 60 PAT, 0.0m/s Crosswind, 24m Wide Deck

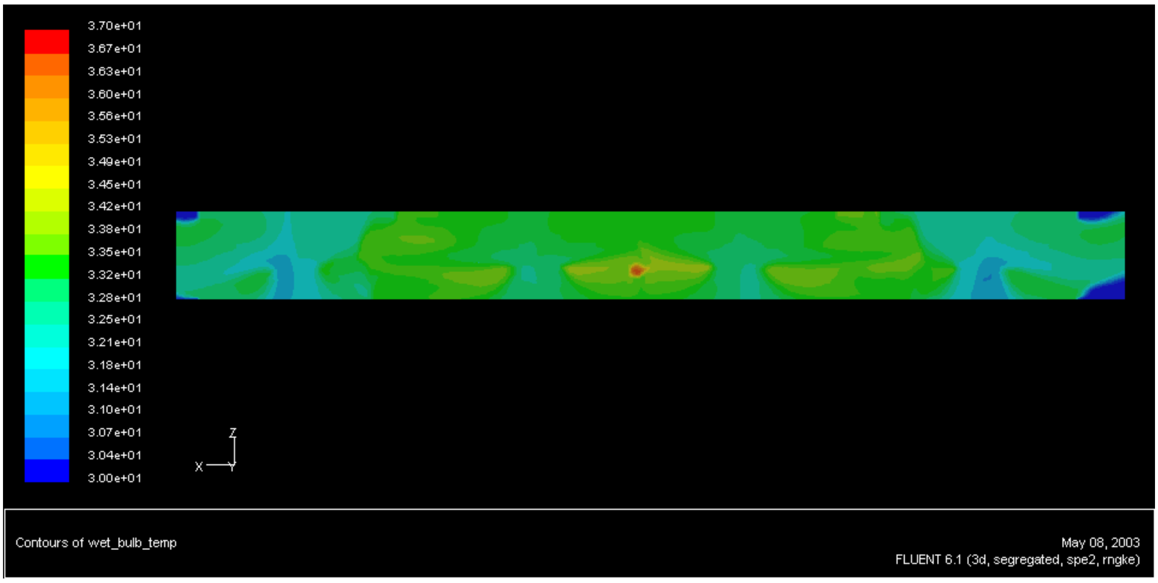


Figure C.30 Contours of Wet Bulb Temperature along Pen Centreline – Forced 60 PAT, Closed Deck, 24m Wide Deck

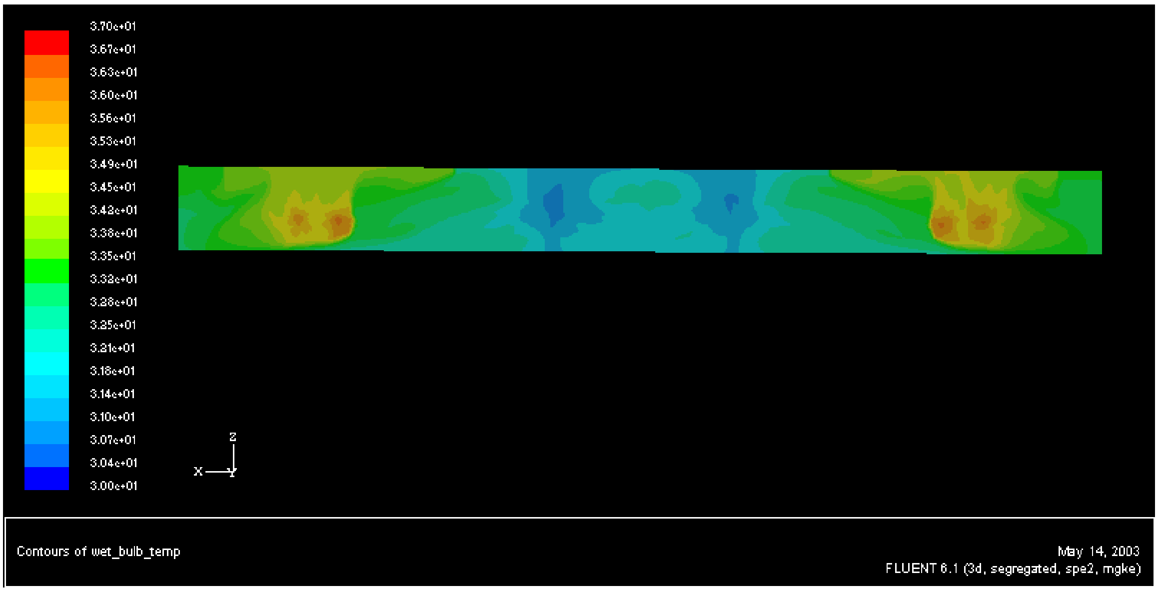


Figure C.31 Contours of Wet Bulb Temperature along Pen Centreline – Forced 60 PAT, 1.0m/s Crosswind, 24m Wide Deck

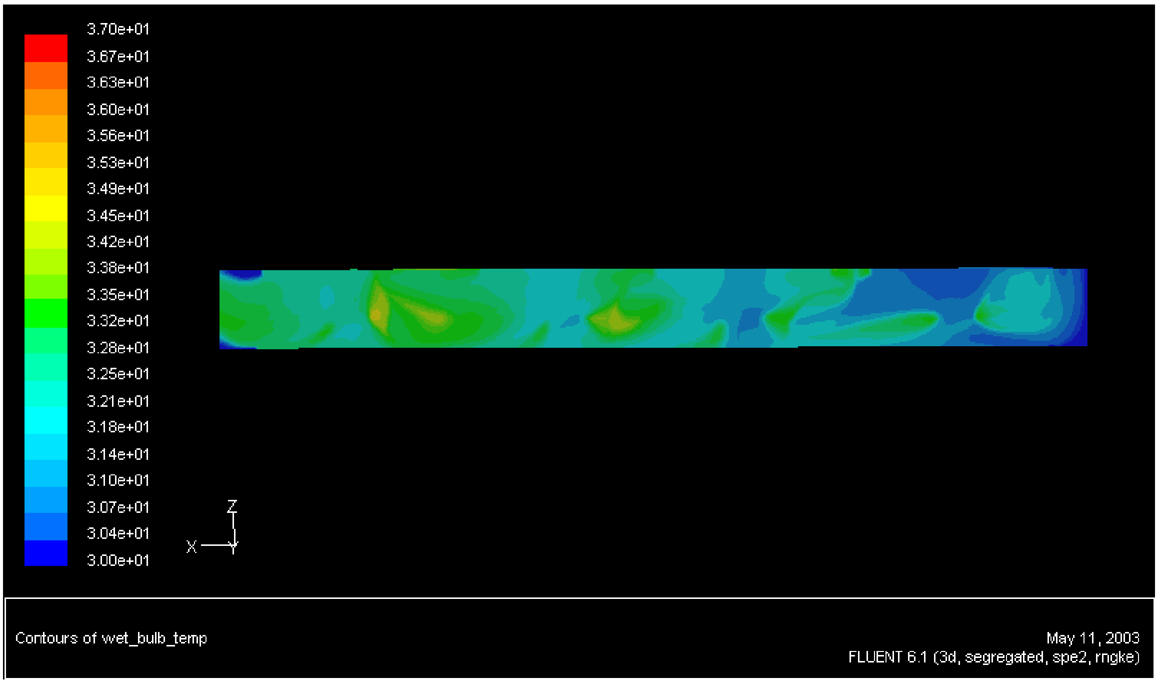


Figure C.32 Contours of Wet Bulb Temperature along Pen Centreline – Forced 60 PAT, vents directed 45° downwards , 0.0m/s Crosswind, 24m Wide Deck

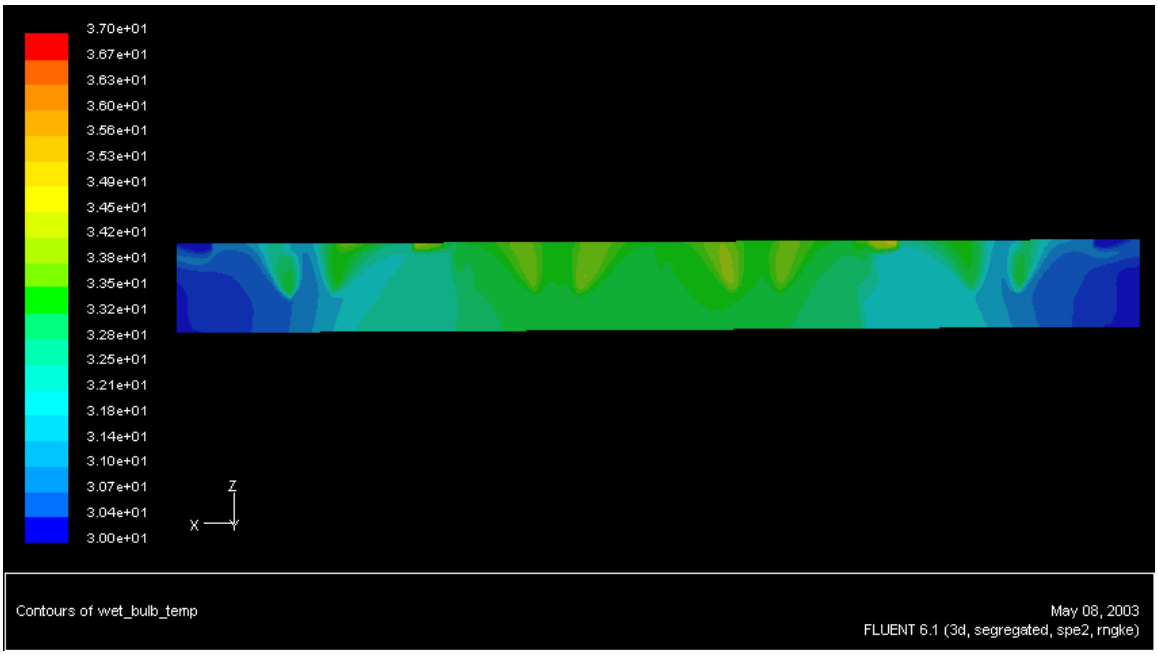


Figure C.33 Contours of Wet Bulb Temperature along Pen Centreline – Forced 90 PAT, 0.0m/s Crosswind, 24m Wide Deck

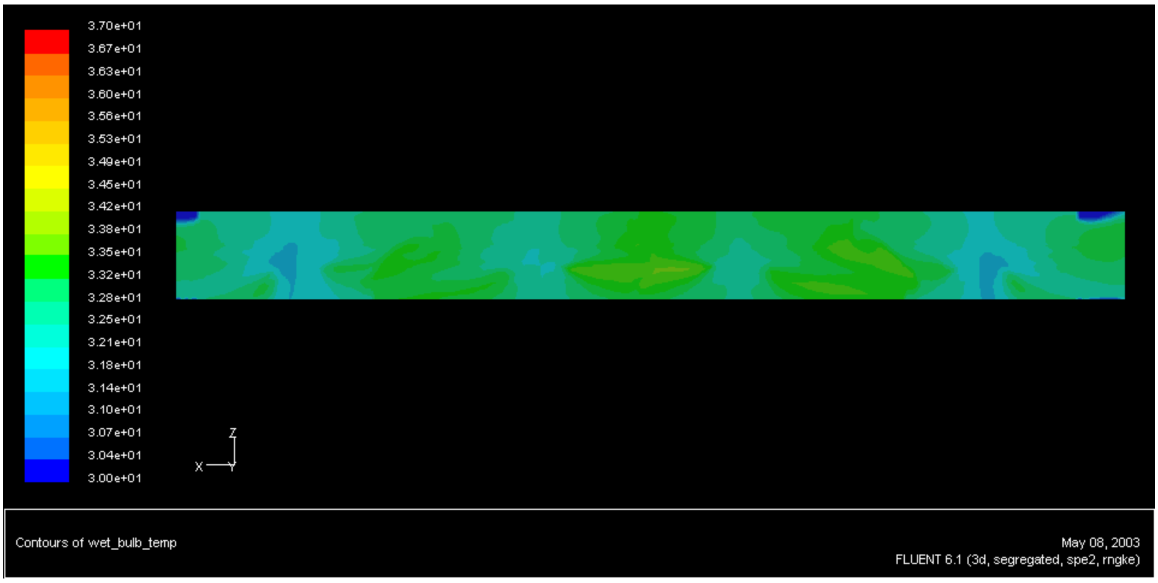


Figure C.34 Contours of Wet Bulb Temperature along Pen Centreline – Forced 150 PAT, 0.0m/s Crosswind, 24m Wide Deck

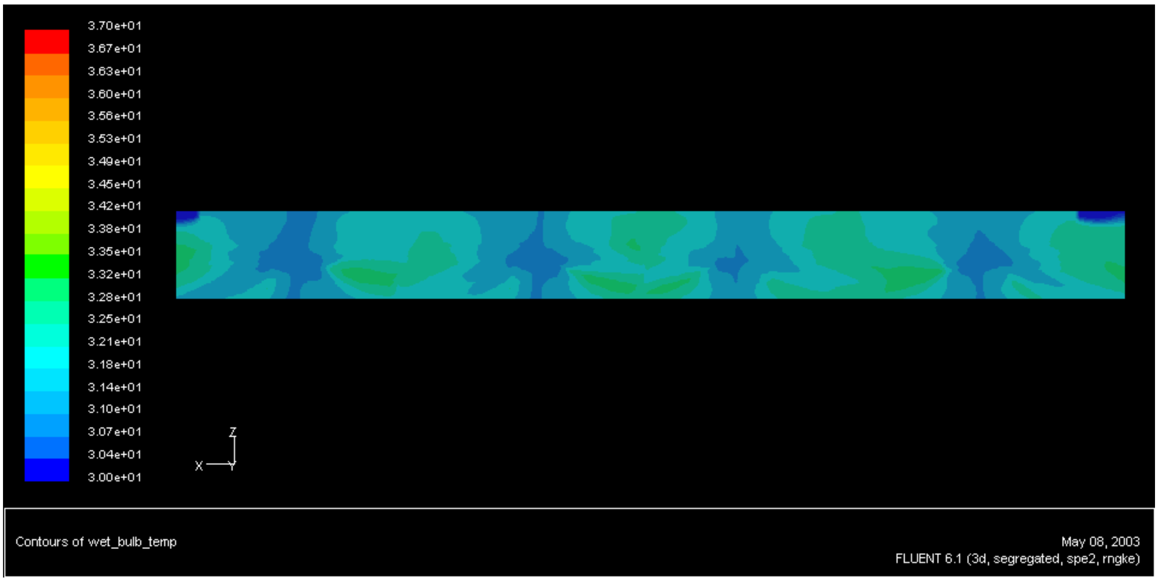


Figure C.35 Contours of Wet Bulb Temperature along Pen Centreline – 0m/s Crosswind (right to left), 24m Wide Deck

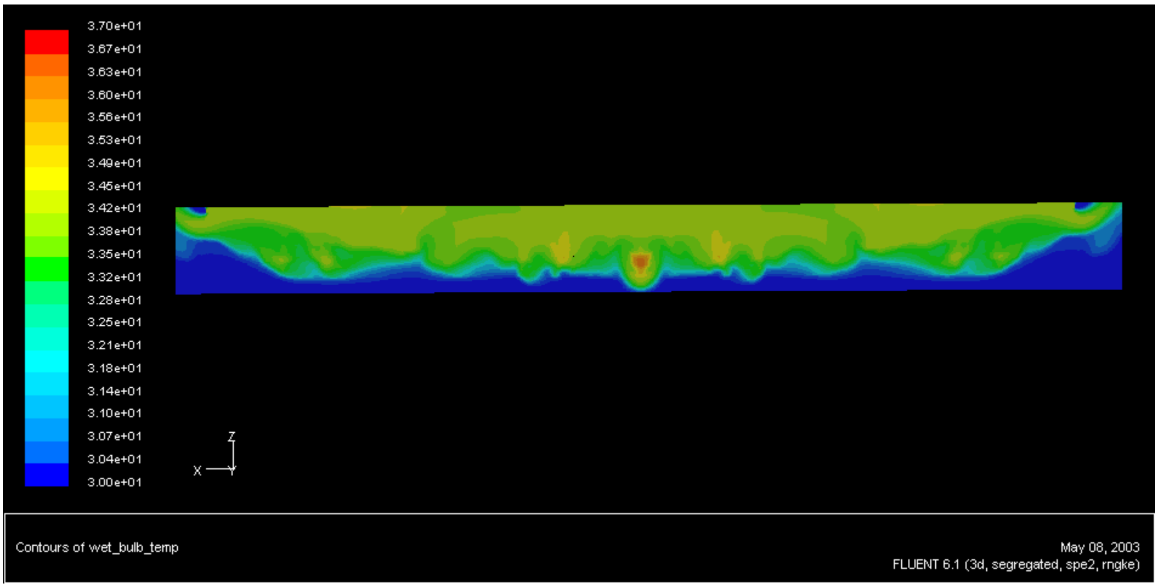


Figure C.36 Contours of Wet Bulb Temperature along Pen Centreline – 0m/s Crosswind (right to left), 36m Wide Deck

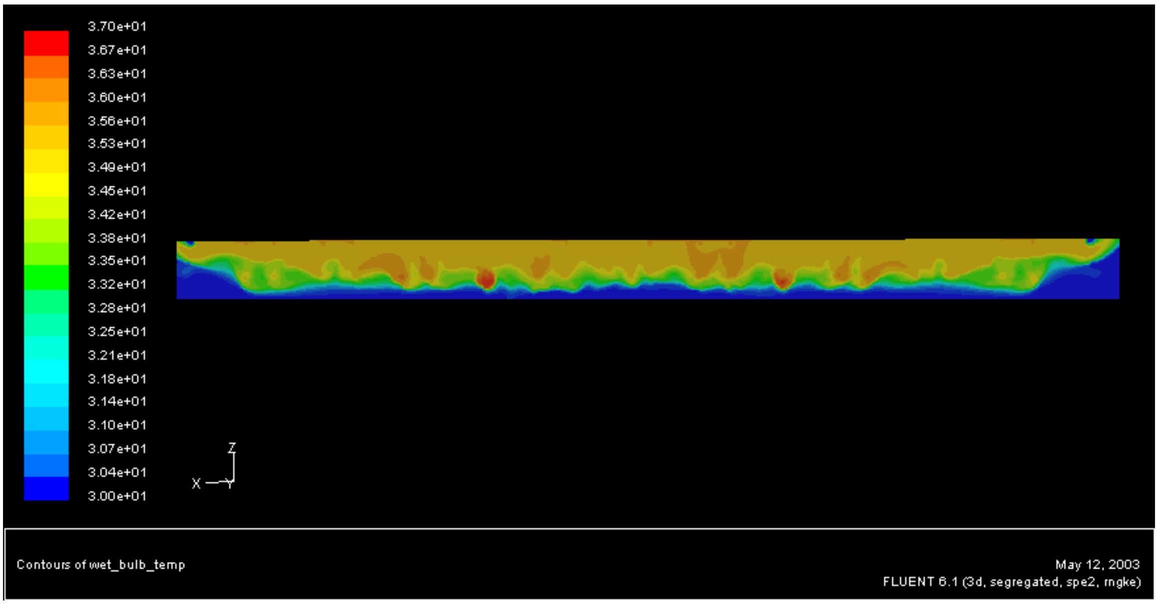


Figure C.37 Contours of Wet Bulb Temperature along Pen Centreline – 0.5m/s Crosswind (right to left), 24m Wide Deck

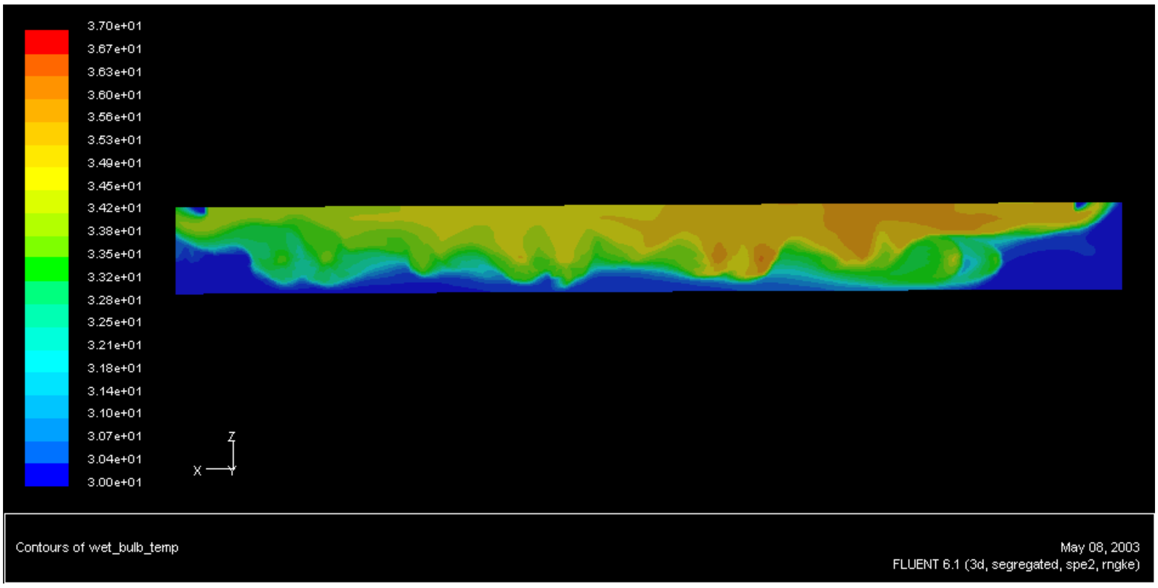


Figure C.38 Contours of Wet Bulb Temperature along Pen Centreline – 1.0m/s Crosswind (right to left), 24m Wide Deck

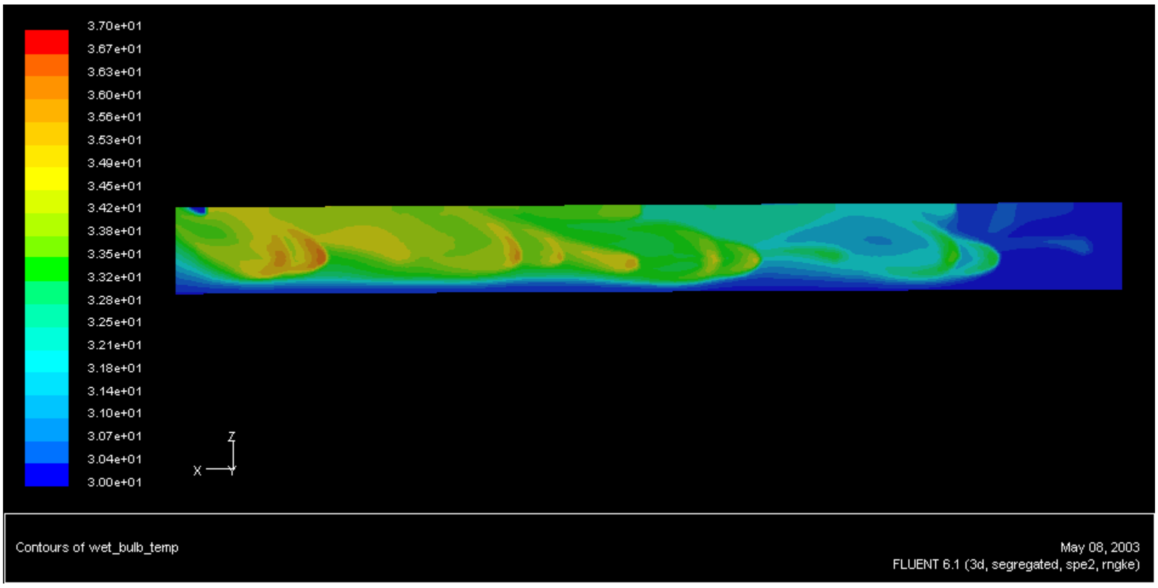


Figure C.39 Contours of Wet Bulb Temperature along Pen Centreline – 1.5m/s Crosswind (right to left), 24m Wide Deck

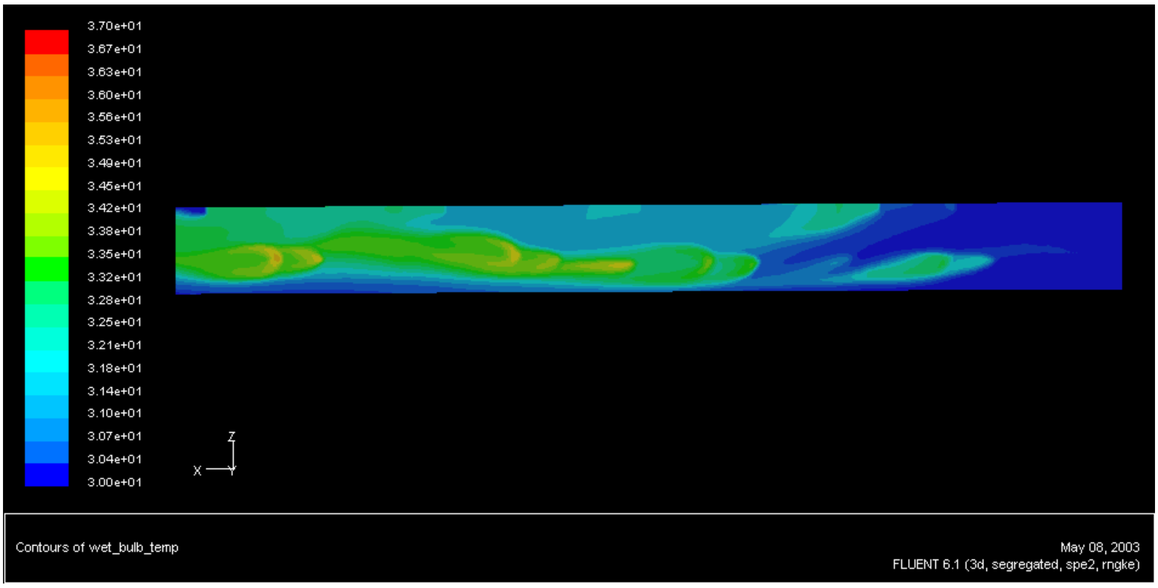


Figure C.40 Contours of Wet Bulb Temperature along Pen Centreline – 2.0m/s Crosswind (right to left), 24m Wide Deck

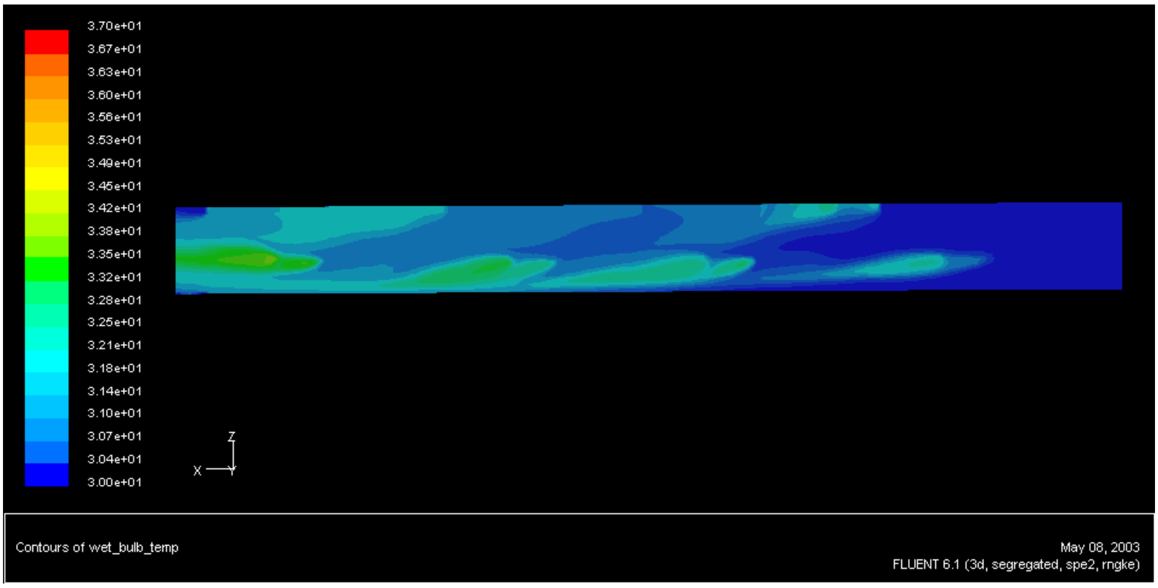


Figure C.41 Contours of Wet Bulb Temperature along Pen Centreline – 3.0m/s Crosswind (right to left), 24m Wide Deck

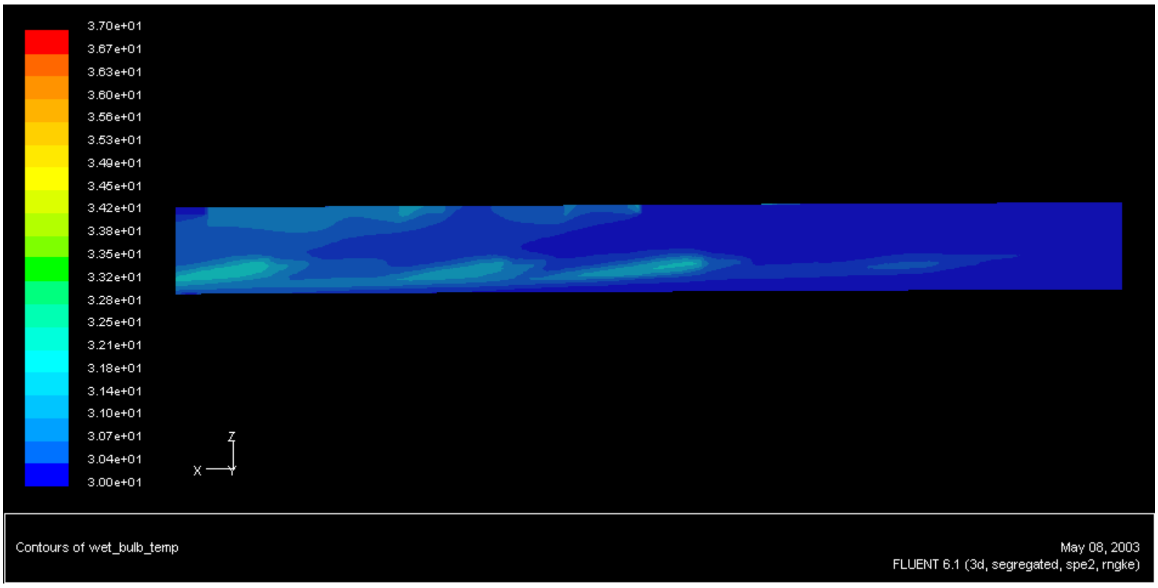
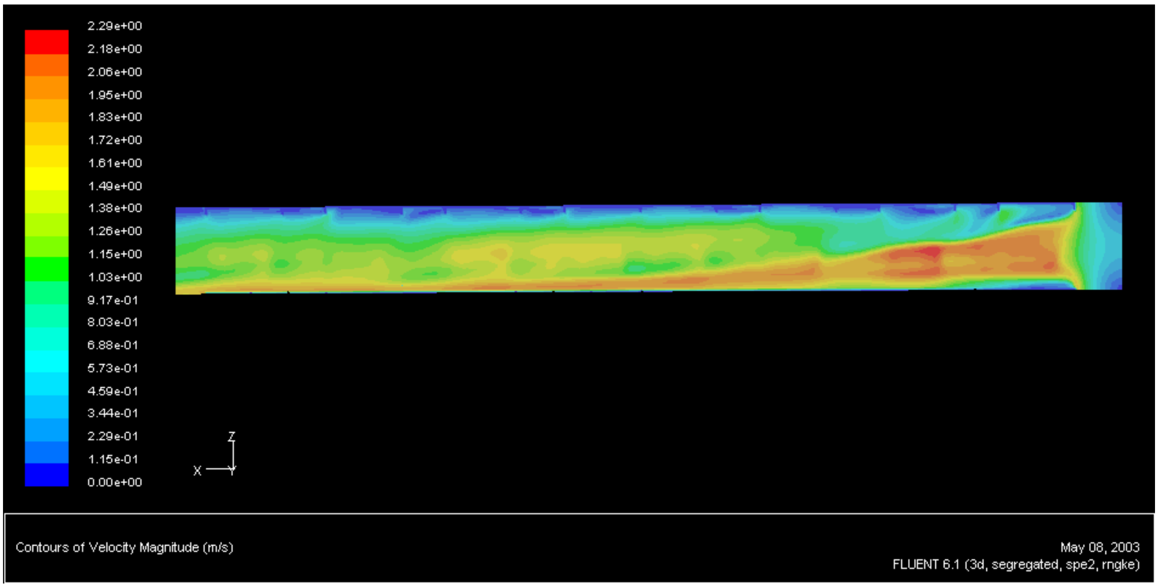


Figure C.42 Contours of Air Velocity along Pen Centreline – 3.0m/s Crosswind (right to left), 24m Wide Deck



Appendix D Scaling Open Deck Results

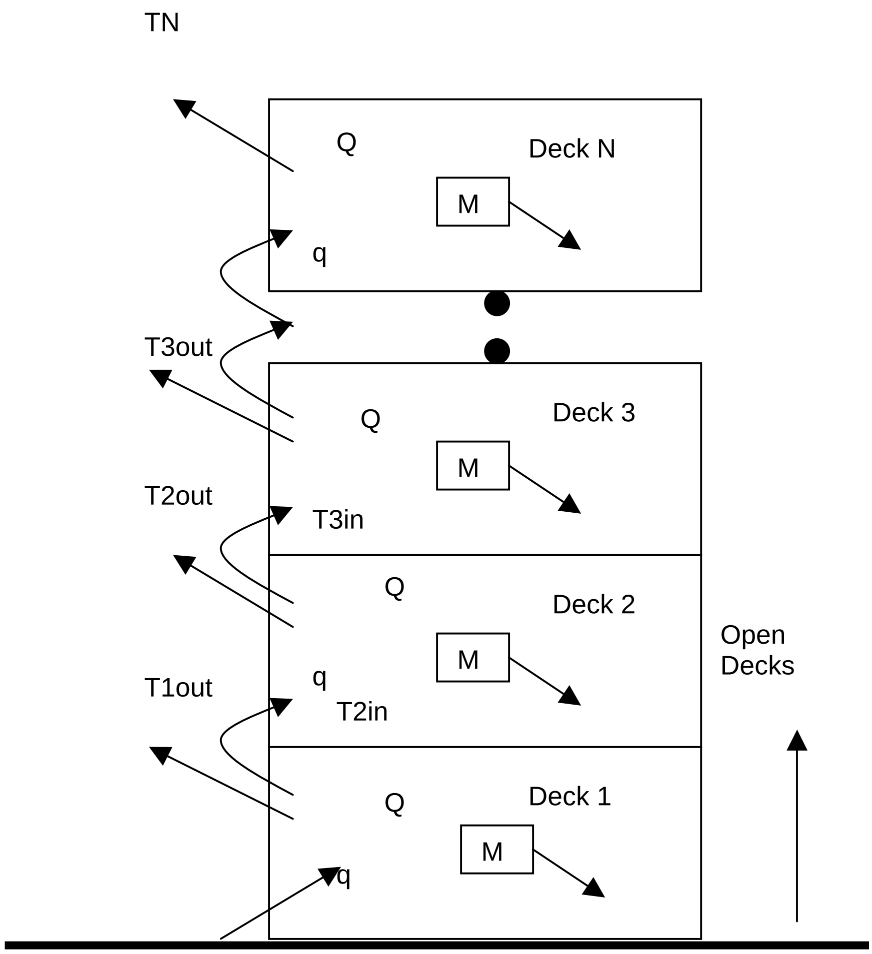
D.1 Reingestion

This section describes the mathematical development of a model of the effects of reingesting exhaust air from lower decks when the wind is still.

Re-ingestion Scaling Parameters

Heat input per deck	Q
Flow rate from mechanical supply	M
Flow rate into deck from sides	q
Deck height (m)	H
Deck width (m)	W
Temperature	T (all temperatures are taken as the rise above ambient temperature)
Constant factors	K, C
Re-ingestion fraction	R

Figure E.1 Reingestion on Open Decks



For deck 1, the exhaust temperature rise is;

$$T1out = \frac{C}{(q+M)}$$

Assuming that deck convection characteristics are similar, side inflows into each deck are the same, and there is full mixing on the decks, then;

$$T2in = T1out\left(\frac{q}{M+q}\right) = \frac{Cq}{(q+M)^2} \text{ and;}$$

taking T2in and adding the same temperature rise as for the lowest deck, we get:

$$T2out = \frac{C}{(q+M)} + T2in = C\left[\frac{1}{(q+M)} + \frac{q}{(q+M)^2}\right]$$

At this stage we define a reingestion fraction R which is the fraction of the airflow onto the deck that comes from the sides:

$$R = \frac{q}{q+M} \quad \text{then;}$$

$$T1out = \frac{C}{q}R \quad \text{and;}$$

$$T2out = \frac{C}{q}\left[R+R^2\right]$$

following the same process, we get T3out

$$T3out = \frac{C}{q}\left[R+R^2+R^3\right]$$

or;

$$TNout = \frac{C}{q}\left[R+R^2+R^3+...+R^N\right]$$

We now evaluate the effect on PAT by noting that PAT is inversely proportional to the outlet temperature;

i.e. $PAT1 = \frac{K}{T1out}$, $PAT2 = \frac{K}{T2out}$ etc.

$$PAT1 = \frac{Kq}{C}\Big/R$$

$$PAT2 = \frac{Kq}{C}\Big/\left(R+R^2\right)$$

$$PAT3 = \frac{Kq}{C}\Big/\left(R+R^2+R^3\right) \quad \text{and;}$$

$$PATN = \frac{Kq}{C} \Big/ \left(R + R^2 + R^3 ... + R^N\right)$$

Since we can always make an estimate of PAT for the bottom deck, we really need to know the ratio of PAT for each deck to that of the bottom one:

$$\frac{PAT2}{PAT1} = \frac{R}{\left(R + R^2\right)} = \frac{1}{(1 + R)}$$

$$\frac{PAT3}{PAT1} = \frac{R}{\left(R + R^2 + R^3\right)} = \frac{1}{\left(1 + R + R^2\right)}$$

$$\frac{PATN}{PAT1} = \frac{R}{\left(R + R^2 + R^3 + ... + R^N\right)} = \frac{1}{\left(1 + R + R^2 + ... + R^N\right)}$$

However, $1 + R + ... + R^{(N-1)} \quad = \quad \frac{\left(1 - R^{(N-1)}\right)}{(1 - R)}$

so; $\frac{PATN}{PAT1} = \frac{(1 - R)}{\left(1 - R^{(N-1)}\right)}$

The reingestion fraction obviously lies between a value of zero and one, but is not known from such scaling arguments alone. We noted that the average velocity out through the deck sides is proportional to the mechanical PAT and the deck width, and inversely proportional to deck height. We then used the limited CFD analysis of three deck geometries to correlate the reingestion fraction to the average outflow velocity. The resulting correlation is;

$$R = 0.405 - 0.000294 \frac{MPAT \times W}{H}$$

D.2 Natural Convection

The following notes outline the mathematics necessary to arrive at a dimensional scaling rule for the PAT driven by natural convection alone.

Natural Convection Scaling Parameters

Heat input	Q
Velocity Into Deck	V
Flow Rate Into Deck	q
Mass Flow into Deck	m
Deck Height	H
Deck Width	W
Deck Length	L
Pressure Loss Across Deck	DP
Constants	K1, K2, K3, K4
Gravity	g

Air Density	ρ
Air Density Within Deck	ρi
Height of Neutral Plane	Hn
Ambient Temperature	T
Temperature of Hot Layer	Ti
Gas Pressure	P
Gas Constant	R
Specific Heat	C_p

For a buoyant plume out of a vertical vent, it can be shown that:

m is proportional to L * SQRT (g * ρ * (ρ-ρi)) * $(H – Hn)^{1.5}$

Assuming a neutral plan height of say $\frac{H}{2}$ and P, R constant

$m = K_1 \times L \times \left(\frac{1}{T} - \frac{1}{T_i}\right)^{0.5} H^{1.5}$ then;

$$= K_1 \times L \times \left(\frac{T_i - T}{TT_i}\right)^{0.5} H^{1.5}$$

Since T_i will have a very small range (within a few degrees Celsius over 300K or so) we make the approximation that, relative to other effects, T_i is constant.

=> m is proportional to L $(T – Ti)^{0.5}$ $H^{1.5}$

or

$$m = K_1 \times L(T_i - T)^{0.5} H^{1.5}$$

from the heat balance of the airflow, we know that:

$$Q = mC_p(T_i - T)$$

Combining these two expressions, we get:

$$m = K_1 L\left(\frac{Q}{mC_p}\right)^{0.5} H^{1.5}$$

We also know that for standard stocking arrangements, the heat generated is proportional to deck area, and so;

$$Q = K_2 LW$$

This gives:

$$m^{1.5} = K_1 L\left(\frac{K_2 LW}{C_p}\right)^{0.5} H^{1.5}$$

=> $m = K_3 L^{\frac{2}{3}} (LW)^{1/3} H$

$$K_3 L^{\frac{2}{3}} (LW)^{\frac{1}{3}} H$$

From the definition of PAT, and assuming that pens take a fixed fraction of deck area;

$$PAT = \frac{K_3 m}{(pLW)} \quad => \quad PAT = \frac{K_4 H}{W^{2/3}}$$

That is; PAT induced by natural convection is scalable by $\frac{H}{W^{2/3}}$

D.3 Crosswind Scaling

The following notes outline the mathematics necessary to arrive at a dimensional scaling rule for the PAT driven by significant crosswinds.

Cross Wind Scaling Parameters

Wind velocity	v
Average Velocity Across Deck	V
Flow Rate Into Deck	q
Deck Height	H
Deck Width	W
Deck Length	L
Pressure Loss Across Deck	DP
Loss Factor	K
Friction Factor	f
Reynolds Number	Re

The pressure loss for any wind driven flow across the deck is approximately:

$$DP = K \times V^2$$

But K is proportional to $\frac{W}{H} \times f$ (from the Darcy Weisbach formula)

And DP is fixed by the cross wind, so

⇨ V is proportional to $\left(\frac{1}{K}\right)^{1/2}$

⇨ V is proportional to $\left(\frac{H}{fW}\right)^{1/2}$

The total deck flow is given by:

$$q = L \times H \times V$$

⇨ q is proportional to $L \times H \left(\frac{H}{fW} \right)^{1/2}$

But PAT is proportional to $\frac{q}{(WL)}$

⇨ PAT is proportional to $L \times H \left(\frac{H}{fW} \right)^{1/2} \Big/ WL$

⇨ PAT is proportional to $\left(\frac{H}{W} \right)^{1.5} \times \frac{1}{f^{0.5}}$

Reynolds number (Re) is proportional to $H \times V$ and f is approximately proportional to $Re^{-0.25}$. Within the anticipated range of changes in H and V, changes in f are likely to be small and will be ignored.

Therefore, PAT induced solely by crosswind is scalable by $(H/W)^{1.5}$.