MEAT & LIVESTOCK AUSTRALIA

On farm

Investigation of the Ventilation Efficacy on Livestock Vessels

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EXECUTIVE SUMMARY

This report is the culmination of a study “Investigation of Ventilation Efficacy on Livestock Vessels” funded jointly by Meat and Livestock Australia and LiveCorp.

The study commenced with a review and summary of the available literature in order to collect current knowledge and guide shipboard work. The work then moved shipboard with a research veterinarian accompanying six voyages between Australia and the Middle East, making observations and recording parameters as guided by the study engineering team. Each voyage gave new information, either due to the vessel design, the livestock type and history, or the voyage conditions.

As with many research projects, the significant conclusions were not always those anticipated. While information was gained on the physiological comfort of livestock in a range of ventilation related environmental conditions below decks and some correlations were apparent, it was also clear that breed effects and acclimatisation had major effects on livestock comfort.

The principal findings of this study are:

- Wet bulb temperature is as good as any other index of cattle comfort on livestock vessels. In particular, wet bulb temperature is preferred to the established THI.
- Air movement is very important and airspeed could be used to give an ‘adjusted wet bulb’.
- If AMSA MO43 ventilation requirements are to be updated, the figures in air changes per hour should be replaced with requirements expressed as minimum pen air turnover (airflow per pen area in $m^3/hr/m^2$), or perhaps minimum airflow per live weight or even a maximum ‘contamination integral’.
- On a ‘per deck area’ basis, current industry ventilation practice generally exceeds the minimum AMSA MO43 air change rates for 2.3m deck heights by a significant margin (a factor of 2.2 to 6.9 for the ships studied).
- Recirculation of exhaust air is a serious issue. Measured recirculation could be applied to downgrade the surveyed air turnover, through measurement of a contamination integral or other means.

Other significant outcomes are:

- Cattle generate metabolic heat at a rate of at least 1.6W per kg liveweight.
- Sheep generate metabolic heat at a rate of approximately 3.2W per kg liveweight.
- Cattle breed differences (*Bos indicus* vs *Bos taurus*) account for variations in heat tolerance equivalent to a change in wet bulb temperature of at least 2^0C and possibly up to 4^0C.

- In cattle, acclimatisation accounts for variations in heat tolerance equivalent to a wet bulb temperature change of 2 to 3^{0}C.
- Cattle weight and age account for variations in heat tolerance equivalent to at least 1^{0}C and perhaps 3^{0}C change in wet bulb temperature.
- Intake air systems operating inefficiently can add heat equivalent to up to 15% of the livestock heat.
- CO_2 is a useful tracer gas in assessing effective ventilation rates (or contamination integrals).
- It is beneficial to provide supply air 'jets' at frequent spacing to give airspeeds of 0.5m/s or more over a significant fraction of each pen area.
- Dead spots can best be avoided by mixing air in all areas using supply air 'jets'.
- Washdown has no effect on conditions beyond the washing time but does appear to offer respite to cattle through splash cooling.
- Ship course alteration when sailing is an effective strategy for controlling open deck air exchange.
- A risk management approach is required for operations involving open deck pens with no mechanical ventilation.
- There may be scope for cost-effective ductless mechanical ventilation of stacked open decks.

A number of recommendations are made for adoption of changes as expressed above or for further work to give information not available from the work so far completed.

In summary, the study produced a number of practical findings not only on the immediate topic of ventilation efficacy but also covering other livestock parameters and effects of some management activities (eg washdown, course alteration).

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1. INTRODUCTION

The purpose of ventilation in livestock vessels is to maintain environments appropriate to the physiological needs of the livestock. Stakeholders in the livestock export industry have long recognised the importance of ventilation in maintaining livestock health and welfare. This report is the culmination of a study initiated by the livestock export industry to improve the scientific and engineering knowledge base on matters of livestock vessel ventilation. The work was undertaken by MAMIC Pty Ltd jointly for LiveCorp and Meat and Livestock Australia.

This study specifically focussed on the long haul voyages to the Middle East. Voyages to Asia are not only shorter but also cross the equator more directly and don't appear to have the same ventilation related issues.

The study commenced with a literature review, submitted in May 2000, aimed at identifying and summarising prior knowledge and defining the requirements for shipboard work. The shipboard work involved monitoring ventilation, environment and animal health indicators in selected pens on six voyages from Australia to the Middle East. The voyages took place from May to December 2000. The literature review and six voyage reports are stand-alone documents. This final study report refers to the particular and general findings of the literature review and voyage reports and reproduces some of the figures and tables from those reports. A number of new figures and tables are also presented as a result of both analysis of the total data set and of revisiting voyage data in new contexts. Whereas the literature review was thoroughly referenced and the voyage reports included numerous plots of all data, this final report simply puts our views with illustration of points made rather than exhaustive justification. Of course our views on the science and engineering behind livestock vessel ventilation have been moulded by observations and analysis from the literature and from all six voyages. No attempt is made to summarise the earlier reports. It is hoped that this approach makes the findings more readily understandable and accessible to the industry.

2. PROJECT FINDINGS

2.1 Pollutant Sources

The term pollutants are used here to describe all airborne contaminants (including heat) which can adversely affect livestock health. Refer to Table 1 for a summary of the generated pollutant levels for each of the voyages.

Table 1: Summary of Cattle and Sheep Generated Pollutants for one control volume on each voyage

	Voyage 1[%]	Voyage 2[%]	Voyage 3	Voyage 4	Voyage 5	Voyage 6
	Cattle	Cattle	Cattle	Cattle	Cattle	Sheep
Average weight of beasts* (kg)	430	390	432	421	285	57
Air changes per hour	61	79	34	49	45	52
Air flow per beast (m^3/hr)**	411	589	190	374	316	0.92
Air flow per pen area (m/hr)	229	319	101	208	153	150
Stocking density (m^2/hd)	1.543	1.443	1.629	1.519	1.181	0.352

	Voyage 1%	Voyage 2%	Voyage 3	Voyage 4	Voyage 5	Voyage 6
	Cattle	Cattle	Cattle	Cattle	Cattle	Sheep
ΔT_{wb} (deg C) (in to out)	2	1.2	4.4	1.7	4.3	3.2
ΔTHI (in to out)	3	1.8	5.8	3.2	6.6	5.3
ΔETI (in to out)	4	2.1	7.2	3.6	7	5.8
Heat generated per kg (W/kg)	2.5	2.0	2.2	1.6	2.8	3.2
Latent/Total Heat	85%	85%	94%	84%	91%	89%
Vapour generated (g/s) **	0.45	0.34	0.42	0.28	0.51	0.0012
CO_2 generated (m^3/s) **	9.29E-05	5.86E-05	7.55E-05	5.96E-05	6.91E-05	1.75E-07
CO_2 generated (m^3/hr per kW)	0.26	0.21	0.25	0.27	0.18	0.2
NH_3 generated (m^3/s) **	2.82E-06	1.67E-06	1.03E-06	8.47E-07	1.09E-06	1.52E-09
NH_3 generated (mg/hr)**	7208	4269	2633	2165	2786	3.9

* Parameters for calculations performed. In particular, numbers are for the control volume and not necessarily the whole ship.
** Quantities per 500kg (cattle), per kg (sheep) live weight
% No fan powers available

2.1.1 Heat

Heat has long been recognised as the major variable driving livestock vessel ventilation. By far the major source of heat below decks is livestock derived. Assessments of livestock metabolic heat production were made on all voyages by measuring the overall heat balance between exhaust air and intake air. This process was complicated by multiple inlet and exhaust points and highly non uniform flows. The assessment was done most carefully for cattle on voyage 4, with the assessed metabolic heat generation being 800W per 500kg live weight (1.6W/kg) (the value expected from the literature was 700 to 1000W/500kg). The cattle on voyage 4 were *Bos indicus*. Other less careful assessments gave generally higher numbers, probably partly due to the difficulty of accurately measuring flowrates in the very complicated geometries, as well as to differences in heat production.

At maximum stocking densities (~275kg/m^2 refer Table 2a), minimum air changes (20 per hour) and a 2.3m deck height, a metabolic heat rate of 1.6W/kg gives an increase in wet bulb temperature of approximately 6^0C between inlet and exhaust.

There appears to be a variation in metabolic heat with breed (*Bos indicus* are slightly ‘cooler’ than *Bos taurus*) and with diet. The diet effect is not completely clear. While the high energy feeds may increase metabolic rate, the low energy, high roughage feeds liberate considerable heat when fermenting in the gut and hence may be no better, or even worse, in generating body heat.

The second biggest heat source was generally the intake air fans. It is obvious that the heat from motor and fan inefficiencies is carried down with the intake air. What is less obvious is that the useful energy applied in boosting air pressure also appears as heat through frictional losses and turbulent mixing in the ductwork and supply jets. For a deck with approximately neutral pressure relative to the atmosphere (generally the case), 100% of the input electrical power to the supply fans will appear as heat below decks. Airstream heat gains calculated as due to supply fans were typically 5 to 15% of the airstream heat gains from livestock metabolic heat.

This fan power issue has long been recognised in the mining industry with hot mines being ventilated by exhaust fans only. With the sea-tightness requirements on ships and the desire to limit airspeed in gangways and through doorways, supply fans are likely always to be a necessity for livestock vessels.

The temperature increase due to the supply fans can be minimised by keeping velocities (and hence pressure losses) low in the ducting and through supply vents. The latter is at odds with the benefits of providing a jetting airstream to pens. A sensible maximum jet speed for this purpose is perhaps 10 to 12m/s. For the example case above and with careful design of ducting, this could give an airstream heat gain only approximately 0.4% of that from the livestock.

The third largest source of heat for some pens was radiated heat from adjacent walls or ceilings. The hot walls observed were engine room bulkheads and fuel oil tanks. The hot ceilings were only on the uppermost deck with the sun shining on the top cover deck.

The highest wall/ceiling temperature observed in cattle housing was approximately 36^0C. This would add around 8W to a typical 500kg beast. This represents an increase of approximately 1% on the total heat to be rejected by radiation, sweating and panting. The highest wall/ceiling temperature measured was approximately 50^0C. This was measured under the top cover deck over a sheep deck. This would increase by approximately 15% the total heat to be rejected by cattle. The relevant fraction for sheep is less certain due to the radiation shielding of the wool.

The decomposing manure pad was also suggested as a heat source. Measurements of internal temperature in normal manure pads showed that the heat generation was not significant relative to the sources above. However, it is quite possible that when a thick dry pad suddenly becomes moist due to a change in conditions, the rapid decomposition could contribute significant heat for a period of one or two days.

2.1.2 Water Vapour

While not a pollutant in the general environmental sense, an increase in the moisture dissolved in the air decreases the rate of evaporative heat loss and so we can regard water vapour as a pollutant in hot conditions. With generally warm sea temperatures, the ambient humidity levels were generally fairly high (typically 65 to 85%RH). Adding to this the sweat and respiratory tract moisture evaporated in removing metabolic heat. As a general average for hot weather, approximately 85% of the heat gained by the air moving through the livestock pens appeared as additional water vapour.

We cannot see any economic way of altering ambient humidity and of course we don't seek to reduce the water vapour released by livestock cooling. The only other sources are drinking water (thought to be small), urine and wash down. Evaporation of urine and wash down water absorbs sensible heat from the air and water and while it may increase relative humidity, cooler wash down water may also decrease the wet bulb temperature and improve other comfort indices. The one detailed observation of washdown (see Figure 11 and Section 2.11) showed that with warm seawater, the impact on conditions was minor and the air stream returned to prior conditions very quickly when washdown finished.

The increase in wet bulb temperature and other indices due to evaporating urine is largely due to the body heat which left the animal with the urine. Once the urine has cooled to ship structure temperature, further evaporation of urine makes little difference to comfort levels.

2.1.3 Carbon Dioxide (CO2)

The atmosphere is approximately 0.03% CO_2 by volume. The emission of CO_2 by livestock is directly related to metabolic activity. The ratio of CO_2 to heat produced is governed by the heats of reaction of the biochemical reactions which power muscle activity in the livestock. Fermentation of roughage in the gut produces additional heat and additional CO_2 although possibly in a slightly different ratio. The overall result is a narrow band for the expected ratio between CO_2 and heat release. The literature review gave the CO_2 ratio as 0.17 to 0.20m^3/hr per kW of metabolic heat. The most careful of the voyage measurements gave a figure of 0.27m^3/hr/kW while the range overall was 0.18 to 0.27m^3/hr/kW.

Using 20 air changes per hour, standard stocking limits and a 2.3m ceiling, the expected CO_2 level in exhaust air is 0.26%. By comparing CO_2 levels to this value, assessment can be made as to whether local pockets of decks have air exchange significantly lower than the mandated average. The allowable limits for CO_2 are unclear. European Community standards give a limit of 0.3% for road transport vehicles. With this limit, CO_2 levels on livestock vessels are unlikely to affect animal health or comfort.

Because of its proportionality to heat generated and hence live weight of livestock, CO_2 is a very useful indicator pollutant. The level of CO_2 in an airstream is a direct measure of the ratio of upstream live weight to airflow rate.

2.1.4 Ammonia (NH3)

Negligible ammonia is emitted by the animals themselves. It is generated in the bedding by urease activity in breaking down urine, faeces and bedding material. The factors affecting generation rates are the subject of a separate ‘ammonia study’. We simply note here that the ammonia levels measured were higher than expected from calculations based on data from the literature and in many instances were higher than recognised allowable limits for animal housing. Allowable limits vary with jurisdiction but are typically 10 to 50ppm with 25ppm being a common figure. Typical levels below decks were 15ppm with readings commonly reaching 20 - 30ppm.

As ammonia is a strong irritant of mucosal tissue (eyes, respiratory tract etc.) it seems likely that it might be a contributing stressor in the reactions to heat stress and that lower ammonia levels through higher ventilation rates might reduce overall risk of disease. It is hoped that the ‘ammonia study’ will make some progress on these issues.

2.1.5 Methane

Methane is not toxic below the explosibility limit (36g/m^3). At the generation rates predicted in the literature, likely concentrations below decks will be orders of magnitude below the explosibility limit. Consequently no experimental time was devoted to measuring methane concentrations.

2.1.6 Noise

Noise is not a pollutant in the sense of being diluted by ventilation. It is related to ventilation only in that the ventilation fans are by far the strongest noise source in most areas. While no noise measurements were taken, the levels were high in empty, reverberant ships and caused discomfort for the authors when spending several hours below decks taking ventilation readings. The noise level reduces appreciably when the ships are loaded with sound absorbing livestock and no observations or anecdotal evidence was gathered indicating any adverse effect of the noise on livestock.

2.2 Stocking Density

The current AMSA regulations (Marine Orders 43) give allowable stocking densities (number of head per square metre) as a function of weight per head (refer Table 2). Multiplying the stocking numbers by the weights per head, it is seen that, for all cattle sizes, the regulations allow an almost constant density of liveweight per area (approximately 275kg/m^2). The figure for sheep varies more with size. These constant limits make sense not only in terms of providing sufficient space for livestock to move about and access feed and water, but also in terms of ventilation capacity.

Since heat is the principal pollutant to be removed and diluted by airflow, and since heat generation is proportional to liveweight, it follows that a reduction in stocking density will be just as effective as a similar relative increase in ventilation rate. This is demonstrated by the approach in Section 2.14. The effect of stocking density on heat and pollutant generation is recognised in the current stockman's practice of de-stocking hot areas or pens where animals become stressed.

If stocking rates are high and freedom of movement is restricted, the ability of some animals to access jets of supply air may be reduced, requiring additional jets to achieve the same benefit.

The previous section discussed the proportionality of metabolic heat to liveweight. When combined with a constant liveweight stocking density, this effectively limits the heat production to a constant value per square metre of deck. Using data given elsewhere in the report, and allowing for pens to be 80% of the deck area, the limits are effectively 440W/m^2 for cattle and 540W/m^2 for sheep.

A corollary of the relationship between stocking density and pollutant generation is the argument that exceptional ventilation performance should allow current AMSA stocking densities to be exceeded. It is recognised that there are many animal behaviour and health issues, including access to feed and water, which are not related to ventilation but are critically affected by stocking density. As this report concentrates on ventilation, it should not be read as supporting an increase in current stocking densities.

Table 2a: AMSA Cattle weight / floor area requirements

Average mass of cattle (kg)	**Minimum permissible floor area per head of cattle** (m^2)	**Average mass of cattle per square metre of flooring** (kg/m^2)
200	0.770	260
250	0.940	266
300	1.110	270
350	1.280	273
400	1.450	276
450	1.620	278
500	1.790	279

Table 2b – AMSA Sheep weight / floor area requirements

Average mass of sheep (kg)	**Minimum permissible floor area per head of sheep** (m^2)	**Average mass of sheep per square metre of flooring** (kg/m^2)
20	0.240	83
40	0.290	138
60	0.340	176
80	0.440	182
100	0.540	185
120	0.640	188

2.3 Air Exchange

The current AMSA MO43 regulations give the required ventilation in terms of the ratio of the supply air flowrate to the deck space volume. This is expressed as air changes per hour. For deck heights of 2.3m and above, the figure is 20 air changes per hour. Because high ceilings give a high volume to the deck, specifying air changes per hour for the deck volume means that the higher the ceiling, the more air is specified to be provided. The previous sections established that heat (and CO_2) production is fairly directly related to the total liveweight of beasts, which through the stocking density, is related to deck area and not to deck volume. Why then does MO43 require airflow proportional to deck volume? Higher ceilings do not allow higher stocking rates as livestock must still be free to move regardless of ceiling height. It seems more logical to specify the minimum ratio of air flowrate to deck area. The required 'pen air turnover' would then be in units of velocity; m/hr or m/s (m^3/hr divided by m^2). In part MO43 does do this. Required air changes are increased for deck heights below 2.3m. At 2.3m, the 20 air changes per hour gives a pen air turnover of 46m/hr. At 1.8m deck height, the requirement is 30 air changes per hour, giving a pen air turnover of 54m/hr.

We propose that the flowrate requirement in MO43 should be altered to specify the turnover flow per pen area in m/hr rather than flow per deck volume in air changes per hour. This would relate the ventilation capacity more directly to the need for pollutant removal and would treat high decks more equitably than at present. The turnover level to be specified is subject to assessment of cost and risk by industry stakeholders. The trade-offs are discussed elsewhere. For consistency with current regulations, the turnover capacity would be between 46 and 54m/hr.

The vessels observed mostly have air exchanges well in excess of the current AMSA minimum. In so far as this has arisen for sound economic and business reasons, it is likely to be maintained and any push for more stringent requirements could be seen as unnecessary. Alternatively, if all current ship owners are comfortable with more stringent requirements, they would serve as a guide to new entrants or designers who may not have a full appreciation of the benefits of maintaining higher ventilation rates.

2.4 Residence Time and Other Measures

There are many cases where two different airstreams mix into a deck space. This happens typically when air from one deck or deck area exhausts through another which also has its own supply air. Where airflow is specified in air changes per hour, the effective air change rate of the downstream volume is not immediately clear. The answer is found by inverting the flowrate in air changes per hour to give a residence time. For example; if deck 1 has 60 air changes per hour, the residence time is 1 minute. If 100m^3/s from deck 1 exhausts to deck 2 and mixes with another 50m^3/s of supply air, the average residence time entering deck 2 is:

(100 x 1min. + 50 x 0min.) / (100 + 50) = 2/3 min or 40 seconds

If the requirement is for a maximum 2 minutes residence time (30 air changes per hour), then the air must have no more than another 80 seconds (on average) before exiting from deck 2. The concept of residence time puts physical interpretation into the intermediate calculations required to work out effective air changes for mixing inlet streams with different histories.

However, as seen above, air changes per hour and hence residence time are volume based and don't relate directly to pollutant load in the air. Following the previous section, we should probably be measuring airflow relative to pen area and not volume, giving a pen air turnover figure in m^3/hr/m^2 or m/hr. The equivalent of residence time in this system could perhaps be called specific residence time and would have units of s/m or hr/m. Rolling the stocking density back into the specific residence time, we get a number which indicates the cumulative time for which each m^3 of air has provided the environment for the liveweight mass. This number, called perhaps a contamination integral, is the inverse of the ratio of flowrate to liveweight in a given deck area. The contamination integral has units of kg.s/m^3.

2.5 Recirculation

In specifying ventilation rates, it is assumed that the supply air is fresh outside air. When air exhausted from the decks is captured by intake air vents, the ventilation rate is effectively reduced. The recirculation of pollutants was a significant issue on a number of voyages, with up to 50% of the intake air in some deck areas being recirculated exhaust. If a particular space has 50% recirculation of its own exhaust, the effective ventilation rate or pen air turnover is halved and pollutant levels doubled. The situation is never this clear cut mathematically, with deck areas ingesting varying fractions of exhaust from other deck areas. Fortunately, as described in the section on pollutants, livestock CO_2 emissions can be used as a tracer gas to determine the effective age (or contamination integral) of any airstream. While the design of ventilation systems should aim at minimising the extent and probability of recirculation under all weather conditions, the CO_2 tracing technique can be used to assess any resulting recirculation.

Only one of the six vessels involved in the study had high inlets and one other vessel discharged exhaust vertically at high velocity. These two vessels had minimal recirculation.

2.6 Air Distribution

It is self evident that pockets of deck spaces which are ventilation dead zones will have lower air changes, lower pen air turnover, longer residence times and, using a new measure, higher contamination integrals. Why dead zones occur and what to do about eliminating them is less obvious for some geometries.

While the supply air may enter with a significant local velocity (‘jetting’), the general drift or average velocity along a deck towards the exhaust point will in general be very low (of the order of 0.1m/s or less). The dynamic pressure of this airspeed is 0.006Pa, about one hundredth of the pressure applied by a sheet of photocopy paper lying flat. Alternatively, a temperature rise of only 0.07^{0}C in one area of a 2.3m high deck space provides the same driving pressure as is required to generate 0.1m/s flow in circulation around the deck. From this, it is clear that very slight influences can cause ‘channelling’ or ‘short circuiting’ in which inflows pass more directly than intended to exhaust points, leaving dead zones. As it is not practical to avoid such slight influences, the design strategy must be to generate specific strong influences (jetting) which ensure good turbulence and mixing of the airflow within all areas. In doing this, there seems little point in designing to a scale smaller than say 2 or 3m as the pollutant sources and wind breaks (livestock) are free to move around much further than this.

One concern expressed to the authors is that highly humid air will ‘block’ the airflow. In fact, humid air has a lower density than dry air and will move just as freely for our purposes. However, where there is no strong jetting or mixing, humidity variations around a deck could be a ‘slight influence’ causing mal-distribution of slowly moving air as above.

2.7 Airspeed Effects

Several vessel owners place emphasis on distributing the supply air through many jetting nozzles so that livestock in each pen have access to one or more streams of fresh air with a noticeable airspeed. This strategy is supported by observations from vessels which have some pens provided with ‘jetting’ fresh air and other pens provided with fresh air only through the overall exchange. Figure 1 shows data from closed decks on Voyage 2 in which pens were categorised from A to D depending on air movement as follows:

- Category A - pens with ventilation outlets in more than one corner providing at least half the cattle with direct jets of air at any one time.
- Category B - pens with ventilation outlets in one corner providing at least one quarter of the cattle with direct jets of air at any one time.
- Category C - pens with no direct ventilation outlets relying on air to drift through the pen.
- Category D - pens with virtually no air movement or circulation.

Animals in category A pens never showed elevated respiration rates and respiration rates increased with decreasing air movement through the other categories. While other voyages showed similar data, they cannot be superimposed as the airspeed effects are swamped by other effects such as acclimatisation etc. Note the category D point in Figure 1, at a wet bulb temperature of approximately ~ 32^0C, the respiration rate is 35 breaths per minute. Normally at this wet bulb temperature the respiration rate would be highly elevated. This particular measurement was taken after a washdown event, indicating the respite provided by washing.

Airspeed effects were studied in previous animal house work by Baeta et al (1987). Figure 8 shows the effect of airspeed on their equivalent temperature index (ETI). As airspeed increases, hotter conditions give the same 'equivalent temperature'. They show each successive increase in airspeed having a bigger effect. This was not considered physically reasonable and so the fundamental heat transfer was revisited as below.

An example 500kg acclimatised beast normally generates approximately 800W of metabolic heat. The fraction of that heat rejected through respiratory tract evaporation is not affected by airspeed and is ignored. Allowing for increased metabolic heat when panting, the heat transfer through radiation, evaporation and convection from the external skin might be in the range of say 400 to 900W depending on conditions. The hide is taken as fully wet (sweaty). Rather than looking at the heat transferred from a fixed skin temperature, we looked at the skin temperature required to reject fixed metabolic heat. The skin temperature is plotted as a function of airspeed in Figure 2. For radiation purposes, the environment is taken as 33^0C and the beast is thermally black. Natural convection is included for realism at very low airspeeds.

Increasing airspeed decreases the skin temperature required to reject given metabolic heat. This simple model indicates that a modest 0.5m/s airspeed could significantly decrease the skin temperature required to reject the metabolic heat. Even if the simple model is only half right, 0.5m/s would give relief to the circulatory system and allow panting to be delayed and/or attenuated. Of course a jet of air will not reach all the skin surface at the same velocity and so the effect is likely to be lower than shown. Never the less, the plot clearly indicates the significance of providing some air movement. It also shows the diminishing returns with further increases in airspeed. The 'skin temperature savings' in going from 0.5m/s to 1m/s or 1m/s to 2m/s are only around 1^0C. Of course, the stronger jets are able to generate a wider zone of influence at the lower airspeeds and hence cover a useful fraction of a pen.

In colder conditions, the improvement in heat transfer with jetting may be detrimental, however, the air exchange is still important for the removal of ammonia and CO_2. To avoid chilling the livestock, the air should be introduced with low velocity. This could possibly be done using large removable panels or end plates on ducts which are also fitted with jetting nozzles for warm conditions.

2.8 Breed and Size Effects

The response of cattle to hot conditions varies with breed, with *Bos indicus* cattle performing generally better than *Bos taurus* cattle. The literature review identified several significant factors including increased surface area through skin folds, significantly different sweating response and differences in fat layers. On the voyages, breed effects can become confused with acclimatisation and prior handling as different lines of cattle will in general have had somewhat different history prior to loading. Voyage 4 demonstrated clearly that southern cattle, mainly of *Bos taurus* breeding (with no observable *Bos indicus* infusion), loaded in Fremantle had generally much higher respiration rates than the high *Bos indicus* content cattle loaded in Darwin on the same voyage (see Figure 9). To clearly separate breed from other effects requires distinct breed types of the same age and size to be loaded from the same port and holding situation.

Voyage 5 sailed from Fremantle with several breeds on board. While the lines were somewhat different in age, size and origin, any acclimatisation differences would have been attenuated by being marshalled in the Fremantle area over a period of 1 month. The respiration rate observations are summarised in Figure 3. The clear outcome is that the Friesian bulls, although quite light, had generally higher respiration rates than others. There is little difference discernible between the brahmans and other braham infused ex-pastoral bulls. These non-braham cattle were of shorthorn background with approximately 15% of the animals appearing to have at least 25% *Bos indicus* infusion. They were sourced from the Pilbara, Gascoyne and Murchison regions and were assembled over a 1 month period. It should also be noted that Voyage 5 was relatively cool and so breed differences in the hotter conditions could not be assessed. There is evidence in the literature to support the contention that even a minor *Bos indicus* infusion may have assisted the ex-pastoral cattle to cope better with heat.

It was anecdotally reported that younger cattle appeared more comfortable than heavier older cattle. Figure 3 also gives information on this. It is clear that the mixed breed weaner bulls at 175kg liveweight had lower respiration rates in very hot conditions than the heavier cattle. The lighter of the adult ex-pastoral lines (320kg) were generally in hotter conditions than the slightly heavier lines (370-400kg) and so direct comparison is difficult.

2.9 Acclimatisation

It became apparent during the study that the response of cattle to ventilation performance is influenced by acclimatisation prior to boarding and by acclimatisation during the voyage. Figure 4 shows respiration rate as a function of wet bulb temperature for monitored pens on Voyages 1 to 4. All cattle were northern *Bos indicus* breeds (Voyage 4 included some southern cattle which have been omitted from Figure 4).

The data sets are surprisingly different for apparently similar beasts. While the data from Voyages 1 and 2 are quite close and follow a trend, the data from Voyages 3 and 4 are clearly well above and well below the trend respectively. At any particular respiration rate, the Voyage 3 and 4 data are displaced from each other by at least 2^0C in wet bulb temperature. Following checking of instruments etc, the only logical explanation for the spread was prior acclimatisation.

Figure 5 shows the ambient wet bulb temperatures in the ports of departure for the 21 days prior to boarding. For 10 days prior to the departure of Voyage 4 on 3 September, the wet bulb temperature in Darwin rose steadily from around 22^0C to reach 25^0C. By contrast, the mean wet bulb temperature in Townsville in the 10 days prior to Voyage 3 was generally around 12^0C, rising to around 17^0C in the last two days before departure.

An example of acclimatisation occurring during the voyage is shown in Figure 6. The wet bulb temperature increased quickly during the initial stages of the voyage and then remained fairly constant for most of the voyage. The cattle monitored had elevated rates of respiration during this phase of the voyage. A peak in the ambient wet bulb temperature occurred during the last couple of days of the voyage and it would be expected that the respiration rate should increase significantly. However, the respiration rates were no higher than those experienced earlier in the voyage. Apparently the cattle were better able to tolerate the 'hotter' conditions towards the end of the voyage, due to their exposure to the 'hot' conditions earlier in the voyage.

2.10 Comfort Indices

The traditional approach has been to use ambient temperature (T_a) alone as the indicator of thermal stress. This fails to acknowledge the influence of humidity and airspeed.

The 'temperature-humidity index' (THI), widely used to estimate potential production losses in livestock, originated in 1959 as a human discomfort index produced by the US Weather Bureau (Thom, 1959). THI can be calculated using the following equation:

$$THI = 0.8DBT + RH\,(DBT - 14.4) + 46.4$$

where DBT is dry bulb temperature (^oC) and RH is percent relative humidity in decimal form (Bosen 1959; Thom 1959).

The THI values are then assigned to category levels of stress based on the United States Livestock Weather Safety Index. The normal condition is less than or equal to 74, alert condition is 75 to 78, danger status is 79 to 83, and an emergency exists when THI exceeds or is equal to 84 (LCI 1970) (It is noted that these numbers apply to *Bos taurus* cattle. Healthy non-stressed *Bos indicus* cattle would not normally be in the alert category until THI exceeds 84).

Other environmental factors, such as airflow and thermal radiation affect heat loading without necessarily being directly reflected in the THI.

The most thorough attempt so far identified to relate an environmental index to animal physiology is that by Baeta et al (1987). They started with algebraic models of the heat transfer by each of the available heat rejection mechanisms and then calibrated their model to observations of stress parameters on Holstein cows in carefully controlled environments. There are four significant features of their work;

- It has a basis in the fundamental heat transfer of cattle.
- It does not include solar radiation as a heat input.
- It includes airspeed.
- It was calibrated for 20 combinations of temperature, relative humidity and air velocity.

The exclusion of solar radiation was inevitable given their indoor laboratory but it was also convenient for this study as solar radiation is not relevant to shipboard heat transfer. The inclusion of air velocity is also useful for the forced draught environment below decks. The expression given by Baeta et al for their "Equivalent Temperature Index" (ETI) is:

$$ETI = 27.88 - 0.456t + 0.010754t^2 - 0.4905h + 0.0088h^2 + 1.1507v - 0.126447v^2 + 0.019876t(h) - 0.046313t(v)$$

where t is dry-bulb temperature (^{0}C)
d is relative humidity as a percentage figure, and
v is airspeed (m/s)

There are many ways of plotting such indices. We have chosen to plot them on a psychometric chart as it is standard in the heating, ventilation and air conditioning industry. Figures 7 and 8 are based on the standard psychometric chart. The horizontal axis is dry-bulb temperature. The vertical axis is the mass ratio of water vapour in the air, known as the humidity ratio. Relative humidity is the volume ratio of the water vapour content in the air to the water vapour content in saturated air at the same dry-bulb temperature. The plot is bounded at the top left by the 100% relative humidity line. Lines of constant wet-bulb temperature slope down to the right and intersect the dry-bulb of the same value on the 100% humidity line.

Contours of ETI at zero airspeed are compared with contours of the better-known THI and with wet bulb temperature in Figure 7. Based on the voyage data, the range of environmental conditions likely to be experienced during voyages to the Middle East during the Northern summer is also shown. The region of relevance is bounded by relative humidities of 65% and 85% and a wet bulb temperature of 25^{0}C. It is evident that ETI and THI represent quite different views about the relative importance of dry bulb and wet bulb temperatures. The THI is very nearly just the arithmetic mean of the wet and dry bulb temperatures whereas the ETI is determined mostly by wet bulb temperature with a small influence from the dry bulb temperature.

Figure 8 shows the predicted effect of airspeed for one ETI contour (ETI = 40). At moderate airspeed (2m/s), the ETI=40 line coincides very closely with the 29^{0}C wet-bulb line. As airspeed increases, the ETI line becomes a constant humidity ratio line. This suggests that at very high airspeeds, when convective boundary layers are not a limiting factor, only the vapour pressure of water in the local air is important. This is consistent with South African literature on the forced convection cooling of miners, which relates evaporative cooling to the difference between the saturated vapour pressure at skin temperature and the ambient vapour pressure. The airspeed influence is discussed further in Section 2.7.

Evaporative heat loss from the skin and respiratory tract accounts for the great majority of heat loss in hot conditions (up to 94%). The wet bulb temperature will then clearly be far more important than dry bulb temperature in determining the available cooling power from evaporative heat loss. As a human comfort indicator (or air conditioning load indicator) THI will not have been so concerned with wet bulb temperature as ‘discomfort’ occurs when office workers need to loosen their ties. Wet bulb temperature does not dominate the heat transfer until the ‘stress’ stage when clothing is soaked with sweat. Hence the ETI would seem to be a more realistic index for the conditions. There is then an obvious question as to why THI has apparently been such a useful predictor of stress and gained widespread acceptance. The answer possibly lies in the effect of radiation.

Days of high ambient dry bulb temperature which are likely to cause problems in feedlot or pasture-fed cattle are very likely to be associated with high solar radiation (clear skies give high ground temperatures). The apparently excessive weighting given to dry bulb temperature in the formulation of THI may in fact correct for the lack of accounting for solar heat load. That is; an experimental study such as that done by Baeta et al but including radiation may well give an index similar in effect to THI. In any case, solar radiation is of less interest on board ships. The ETI given by Baeta et al is probably more appropriate than THI for assessment of shipboard conditions.

In the region of interest, it can be seen that lines of constant ETI are nearly parallel to the wet bulb contours. Prior to the shipboard work, the small distinction between ETI and wet bulb temperature seemed important. Given the scatter of data due to acclimatisation, breed, individual variability etc, the distinction now seems too small to be concerned with. The respiration rate correlated with wet bulb temperature, THI & ETI are shown in Figures 9 and 10 for all voyages and for both cattle and sheep respectively. This dramatically shows the effects of data scatter due to acclimatisation, breed, etc.

The index of wet bulb temperature alone is not only a well established climatic property, it is also easy to measure with inexpensive, readily available equipment and requires no further calculation or charts. Hence we propose that wet bulb temperature replace both ETI and THI as a practical measure of shipboard conditions. Should wet bulb temperature not be readily available, it can be found from dry bulb temperature and relative humidity in any reference with information on psychometry. Table 3 overleaf was generated to give wet bulb temperatures for the range of dry bulb temperatures and humidities relevant to this study.

Table 3: Wet Bulb Temperature (^{0}C) from Dry Bulb Temperature and Relative Humidity

Dry Bulb Temperature (^{o}C)	**Relative Humidity**										
	50%	**55%**	**60%**	**65%**	**70%**	**75%**	**80%**	**85%**	**90%**	**95%**	**100%**
15	9.7	10.2	10.8	11.4	11.9	12.5	13.0	13.5	14.0	14.5	15.0
16	10.5	11.1	11.7	12.3	12.8	13.4	13.9	14.5	15.0	15.5	16.0
17	11.3	11.9	12.5	13.1	13.7	14.3	14.9	15.4	16.0	16.5	17.0
18	12.1	12.8	13.4	14.0	14.6	15.2	15.8	16.4	16.9	17.5	18.0
19	13.0	13.6	14.3	14.9	15.5	16.1	16.7	17.3	17.9	18.5	19.0
20	13.8	14.5	15.1	15.8	16.4	17.1	17.7	18.3	18.9	19.4	20.0
21	14.6	15.3	16.0	16.7	17.3	18.0	18.6	19.2	19.8	20.4	21.0
22	15.4	16.2	16.9	17.6	18.2	18.9	19.6	20.2	20.8	21.4	22.0
23	16.2	17.0	17.7	18.5	19.1	19.8	20.5	21.1	21.8	22.4	23.0
24	17.1	17.8	18.6	19.3	20.1	20.8	21.4	22.1	22.7	23.4	24.0
25	17.9	18.7	19.5	20.2	21.0	21.7	22.4	23.1	23.7	24.4	25.0
26	18.7	19.5	20.3	21.1	21.9	22.6	23.3	24.0	24.7	25.4	26.0
27	19.5	20.4	21.2	22.0	22.8	23.5	24.3	25.0	25.7	26.3	27.0
28	20.3	21.2	22.1	22.9	23.7	24.5	25.2	25.9	26.6	27.3	28.0
29	21.2	22.1	22.9	23.8	24.6	25.4	26.1	26.9	27.6	28.3	29.0
30	22.0	22.9	23.8	24.7	25.5	26.3	27.1	27.8	28.6	29.3	30.0
31	22.8	23.8	24.7	25.6	26.4	27.2	28.0	28.8	29.6	30.3	31.0
32	23.7	24.6	25.6	26.5	27.3	28.2	29.0	29.8	30.5	31.3	32.0
33	24.5	25.5	26.4	27.3	28.2	29.1	29.9	30.7	31.5	32.3	33.0
34	25.3	26.3	27.3	28.2	29.1	30.0	30.9	31.7	32.5	33.3	34.0
35	26.1	27.2	28.2	29.1	30.1	31.0	31.8	32.7	33.5	34.2	35.0
36	27.0	28.0	29.1	30.0	31.0	31.9	32.8	33.6	34.4	35.2	36.0
37	27.8	28.9	29.9	30.9	31.9	32.8	33.7	34.6	35.4	36.2	37.0
38	28.6	29.7	30.8	31.8	32.8	33.8	34.7	35.5	36.4	37.2	38.0
39	29.5	30.6	31.7	32.7	33.7	34.7	35.6	36.5	37.4	38.2	39.0
40	30.3	31.5	32.6	33.6	34.6	35.6	36.6	37.5	38.3	39.2	40.0

In the literature review and voyage reports prepared for this study, ETI was offered as the preferred comfort index. It is important to reiterate that the preference expressed here for wet-bulb temperature as the key index does not mean that ETI is not accurate or useful. It is simply that in the region of interest, the two indices have almost the same effect and wet bulb temperature is by far the simpler of the two.

Accounting for airspeed still deserves further work on hide wetness and heat transfer by sweating. However, the simple model given in the section on airspeed effects is preferred to that given by Baeta et al. The airspeed can be seen as effectively lowering the wet bulb temperature to give an ‘airspeed adjusted wet bulb’.

Using the simple model numbers, the adjustment could be plotted, or tabulated, as below. Note that the model assumes the whole beast to be in uniform cross-flow with a fully wet (sweaty) hide. The effect is likely to be less than indicated when subject to jetting of the given speed in a pen with other animals.

Table 4: Effective Wet Bulb Temperature Adjustment with Airspeed
(This table should be treated as tentative until confirmed by subsequent data and analysis)

Airspeed (m/s)	**Wet Bulb Adjustment (^{0}C)**
0*	0
0.1*	0
0.17	1^0
0.26	2^0
0.42	3^0
0.75	4^0
1.6	5^0

* Airspeeds below 0.2m/s are difficult to measure practically and highly variable in the shipboard environment. Natural convection, or residual momentum of inlet air may drive flows of the order of 0.1m/s and the very low speed flow heat transfer is not clear. Consequently 0.1m/s is suggested as the base for adjustment.

2.11 Washdown Events

Environmental parameters were recorded at frequent intervals during two washdown days in Voyage 5, refer to Figure 11. The washdown used seawater with temperatures of 27^{0}C for the first washdown and 29^{0}C for the second washdown. Because the seawater temperature was close the prevailing wet bulb temperature, little effect is seen on the conditions. In fact, the wet bulb temperature may even have increased slightly during the washing. This may have been due to heat transfer effects or, more likely, to redistribution and short-circuiting of ventilation with many doors open to allow access for the stockmen. After washing was completed, conditions returned very rapidly to steady values.

The cattle were observed to have lower respiration rates after washdown events on other voyages. It is likely that the removal of sensible heat by splashing water allows a reduction in skin temperature and a period of respite for the cattle. Figure 1 shows a Category D pen with low respiration rate at a high wet bulb temperature following washdown.

Concern has been expressed to the authors that washdown causes very high humidity which is detrimental to the cattle. It is true that relative humidity will be increased by spraying water around, however relative humidity by itself is not a controlling parameter in cooling of the cattle. As explained in the section on comfort indices, wet bulb temperature is the important parameter. It seems that washdowns generally bring the dry bulb temperature down towards the wet bulb temperature (which may also elevate slightly). In doing so, relative humidity is necessarily increased. Relative humidity will increase in these circumstances even if the wet bulb temperature is unaltered. With constant wet bulb temperature and lowered dry bulb temperature, conditions would clearly be more comfortable.

Washdown would also be expected to decrease NH_3 levels through removal of bedding, faeces and urine. The decrease is real but only short lived with levels returning to pre-wash levels within a day or so.

Overall, we do not believe that washdown causes problems of cattle cooling and it appears to give benefits in splash cooling of the cattle. In fact, the intentional splashing of stressed cattle seems likely to have merit. This could be done manually or using sprinklers. The use of sprinklers has more implications for feed wastage and would need careful design, however it is a possibility. Splash cooling does not seem so useful for sheep as they lose relatively less heat through the skin. The major problem with wetting sheep is that the moisture may trigger rapid composting of an otherwise dry manure pad.

2.12 Open Deck Ventilation

Ventilation of closed decks must always be by mechanical means, and with no doors being opened or closed or grilles blocked, the air flowrates will stay constant.

Ventilation of open decks with no forced ventilation is not so predictable. When the wind blows strongly past the ship, air exchanges will be high. With a following breeze, or still air when in port, the ventilation can be very poor. An experiment was conducted during Voyage 6 to demonstrate the effect of prevailing breeze on open decks. The ship was sailing with a following breeze such that the relative wind (apparent airspeed) was very low. The course was altered for 15 minutes so as to generate a net breeze of 8-9m/s. Measured airspeeds in the alleyways were then 4-5m/s, with 1-2m/s in the sheep pens. Conditions were recorded near the centres of the four quadrants of the penned deck area. The environmental parameters changed markedly for the duration of the deviation then returned rapidly to ‘normal’ when back to original heading. Figure 12 plots the measurements taken. Wet bulb temperature fell by 2 to 4^0C. NH_3 concentrations almost halved and CO_2 concentrations fell by a similar ratio.

This points to a protocol appropriate for following breezes as follows. By making slight deviations off-course (up to 30^0) significant apparent cross winds can be generated with only a minor slowdown in effective progress. The deviations could last from 10 minutes to a day or more, with the ship zig-zagging around the intended course. The new apparent wind speed and effective progress reduction can be readily calculated using trigonometry. The algebra can also be turned into a spreadsheet to give a ready reference management tool for use by ship’s captains in making course alteration compromises given the breeze requirements of particular open decks, the weather, and schedule constraints. Appendix C gives a sample printout from such a spreadsheet.

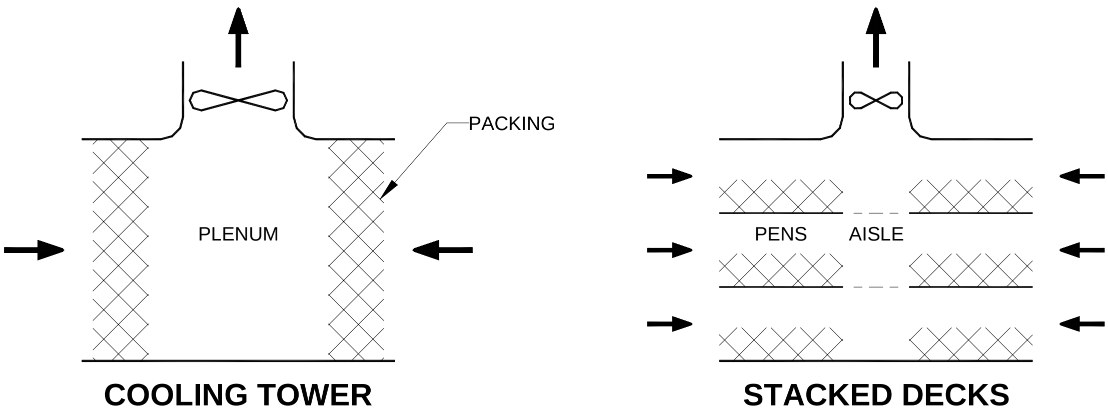
No still conditions were experienced while in port.

The AMSA MO43 regulations require mechanical ventilation of open decks only when the breadth is greater than 20m. It is considered that for some pen and deck geometries, a breadth of 20m would give unacceptable conditions in still air. Assessment of the air flow patterns and overall air exchange in stacked open decks is a complicated and lengthy activity and because it must be done uniquely for each ship, it could not form part of this study. There is the added problem that very low wind speeds may be just as bad as, or worse than, zero wind and an assessment needs to be made for a range of wind directions.

With the unpredictability of weather, a more practical approach may be to consider risk in the context of past events. It is well known that some ports in the Middle East (notably Muscat) are prone to periods of very hot, very still weather. On occasions, a significant number of animals have perished in open decks while awaiting discharge in still conditions. With no mechanical ventilation, the problem is an exercise in risk management. The shipowner and exporter must assess the risk of weather conditions which would cause untenable conditions in open decks on their ships. This risk will vary with the season and, when approaching port, it may be reassessed with short term weather predictions. Contingency plans would also be appropriate such as making preparations to quickly cast off and motor away to create breeze. All of these precautions, the operational restrictions, and the implementation of contingencies have a significant cost. The exporter and shipowner must decide if the cost of reducing risk in this way to acceptably low levels is more or less than the cost of reducing risk by mechanical ventilation. Again, with the many variables involved, including discharge time, the answers will be unique for each ship.

For existing ships, the cost of conventional mechanical ventilation of open decks, with the fabrication required to fit ductwork into what are often low sheep decks, may also be too great. Unless the original risk can be accepted, either inconvenience cost or capital cost must be borne.

As a practical approach to minimising the cost of mechanically ventilating open decks, we offer the following suggestion for development by the industry. The stacked open decks are similar in many ways to the packing in a conventional water cooling tower. Whereas cooling towers have an internal plenum between the packing on either side, the stacked decks have narrow gridmesh walkways. By collecting the flow into a plenum, the cooling towers are able to use a single, large, low pressure, high efficiency fan. The narrower walkways in the stacked decks may prevent flow collection into a single fan, with several smaller fans being required along the walkway. Cooling tower style low pressure fans are now available in small sizes and are being recommended by the authors in other industrial applications. A simple diagram of the concept is given overleaf:



The vertical discharge of the fans would also assist to minimise exhaust recirculation into systems for ventilating closed decks. The fans need not be operated except during still conditions and for testing when approaching port. Of course the flow calculations would be specific to the layout of each ship and the concept may not suit all ships with open decks.

2.13 Summary of Heat Stress Influences

Table 5 below gives a summary of the orders of magnitude of the effects possible through each of the influences on heat stress. It should be noted that as the existing fleet is already ventilated at well above the AMSA minimum flowrates, much of the range of some influences has already been gained. The range then indicates the scale of problem which could be created by falling back to the minimum requirements.

Table 5: Order of Magnitude Impacts of Various Influences Expressed as Equivalent Wet Bulb Temperature Change

Influence	Degree of Impact as Equivalent Wet Bulb Change
Improving ventilation above AMSA minimum	Decrease by up to 5^0C
Stocking density from AMSA maximum down to zero	Decrease by up to 6^0C*
Recirculation from 50% down to zero	Decrease by up to 6^0C**
Prevailing breeze in open decks	Many degrees depending on deck layout
Breed	$2^0 – 4^0$C
Weight/Age	$1^0 – 3^0$C
Acclimatisation	$2^0 – 3^0$C
Air Velocity (jetting)	0^0 to 5^0C (refer to Table 3)

* based on AMSA minimum air exchange.
** depends on ship air exchange rate, taken as AMSA minimum.

2.14 Planning and Risk Management

When livestock become stressed during a voyage, it is not particularly helpful to know that the wet bulb temperature indicates that they should be stressed. The effort will be to relieve the stress by all available means. The information on acceptable wet bulb temperatures and the effects of stocking density and ventilation may be of some immediate assistance, however, the real benefit of this information is in planning voyages and managing risk. We offer a framework as below for using the data from this study to look further at risk when planning voyages. For cattle, this is really an extension of the current practice of preferring northern *Bos indicus* cattle during the northern hemisphere summer. While we believe the approach is sound, the input data are based only on the data from the six voyages and may be varied when more data are available.

From the sections above, the heat input from the livestock divided by the air flowrate gives the increase in internal energy of the air stream as it crosses the deck. Internal energy is not so useful if wet bulb temperature is the driver of animal stress. Fortunately, wet bulb temperature rise can be closely related to internal energy rise for the conditions of interest. This means that by knowing the stocking densities, the livestock weight per head, the pen areas and the ventilation flowrates, we can estimate the rise in wet bulb temperature through each ventilated zone, according to:

$$\triangle Twb = 3.6 \times C \times M \times h/(\rho\, Q/A)$$

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 cattle and 3.2W/kg for sheep.
ρ is the density of air (1.2kg/m^3)
Q is the air flowrate (m^3/hr) into the ventilation zone.
A is the pen area in the ventilation zone.
Q/A is the pen air turnover discussed in Section 2.3.
The factor 3.6 at the front corrects units from W to kW and hours to seconds.

This calculation can also be readily tabulated for typical cargoes. Appendix D gives four tables of wet bulb temperature increase as a function of pen air turnover and stocking density. The four tables cover cattle and three sizes of sheep.

To find the wet bulb temperature increase through a deck space requires knowledge of the stocking density relative to the AMSA MO43 limits and the ventilation rate expressed as pen air turnover. Selecting the table appropriate to the cargo, the pen air turnover down the left column and the stocking density column headings leads directly to the table entry giving wet bulb temperature increase.

By adding the estimated wet bulb temperature rise to a prediction of ambient wet bulb temperature, the wet bulb temperature below deck can be predicted. This prediction can be compared with the bands given in Table 6 below for assessment of risk. We caution again that the bands in Table 6 are based on interpretation of the limited data with many other contributing variables and may vary with more information.

Table 6: Preliminary wet bulb temperature risk criteria for heat stress in several livestock lines

	Wet Bulb Temperature Risk Range		
Livestock Line	**Safe**	**Caution**	**Danger**
Bos indicus	< 28⁰C	28 - 31⁰C (non acclimatised) 30 - 33⁰C (well acclimatised)	> 31⁰C (non acclimatised) >33⁰C (well acclimatised)
Bos taurus	< 26⁰C	26 - 30⁰C	> 30⁰C
Sheep	< 26⁰C	26 - 29⁰C	> 29⁰C

It is noted that the risk assessment using THI traditionally involved a two dimensional table with dry bulb temperature and relative humidity as parameters. As expressed above, the risk assessment no longer requires a table, being dependent only on a single variable; wet bulb temperature.

In assessing risk, exporters and ship owners must consider the variability of weather, variability in acclimatisation and breed variability in individual animals. For example, ambient wet bulb temperature may be taken as the 95^{th} or 99^{th} percentile value for the particular time of year. Weather data available from the US Hydrographic Office may assist in estimating likely wet bulb temperatures.

If the risks are assessed as too high, exporters and ship owners can choose livestock which, due to breed, size and acclimatisation, are more tolerant of heat. They may also decrease stocking density. Air flowrate is hard to change for existing ships, however exporters have this option through chartering different ships. It is accepted that delaying the shipment several months for cooler conditions is not an option.

Ensuring availability of ventilation through maintenance and redundancy of plant is also part of the overall risk management which commences with vessel design.

3. RECOMMENDATIONS

- While an airspeed adjustment has been proposed for ‘adjusted wet bulb temperature’, more accurate data on this cannot come from shipboard work. It is suggested that careful animal house experiments, coupled with heat transfer modelling and analysis would define the adjustment better, particularly at very low airspeeds. This is important as the potential benefits are equivalent to several degrees reduction in wet bulb temperature.

- The stockmen should be trained in the use of hand held sensors to measure dry bulb and wet bulb temperature and CO_2 concentration, with representative measurements to be recorded whenever animal stress is noted. Ventilation arrangement and pen air speeds should also be noted.

  The data and animal observations should be recorded on a standard form and forwarded to MLA and LiveCorp to expand the available heat stress database. The data should include a photograph of the beasts and pens involved.

- If the industry decides to request that the statutory ventilation requirements be varied, it is recommended that the new regulations be based on deck area and stocking rates as described in Sections 2.2, 2.3 and summarised in Section 2.14.

APPENDIX A - MEASUREMENT TECHNIQUES

The following is a list of instrumentation used for the voyages:

Dry/Wet Bulb Temperature and Relative Humidity

Manufacturer: PCWI – Precision Instrumentation
Model: 8705 Digital Hygrometer

Air Velocity (Vane Type)

Manufacturer: PCI Precision Instrumentation
Model: 8904 Anemo-Thermometer

Air Velocity (Hot-Wire Type)

Manufacturer: Testo
Model: 405-V1 Velocity Stick with Temperature

CO_2 Sensor

Manufacturer: Airwatch
Model: PM1500 CO_2 Personal Gas Monitor

NH_3 Sensor

Manufacturer: Neotox
Model: MK5 Ammonia Monitor

Infrared Thermometer

Source: Australasia Livestock Services
Manufacturer: Linear Laboratories
Model: quickTEMP
Serial No: 04030

Various pens were selected to be monitored throughout each of the voyages. The pens were selected to be representative of the range of conditions experienced throughout each of the ships. Any known difficult pens (ie. hot spots) were also selected.

Twice daily monitoring (~6:00am and 1:00pm ship local time) was undertaken for each of the pens selected. The dry bulb and wet bulb temperatures, relative humidity and CO_2 and NH_3 concentrations were measured using the equipment listed above. The livestock were also observed using both individual and group assessment techniques. The respiration rate and character were measured for each of the pens, as pen average quantities.

Skin and rectal temperatures were also measured using the infrared thermometer.

The infrared thermometer was also used to measure the ship wall, ceiling, floor and pen bedding temperatures in order to assess possible additional heat sources.

The airspeed was measured using the hot wire velocity stick with audio magnetic tape to gauge wind direction. Several sites were measured in each pen and the average of these values was used in further analysis.

The livestock generated pollutant levels were also calculated. To do this, a discrete control volume was selected for each of the voyages. The supply and discharge air conditions were measured (dry bulb and wet bulb temperatures, relative humidity, CO_2 and NH_3 concentrations). The air flow rate to and from the control volume was also measured and checked with ship data. This was done by surveying the air intakes and exhausts and measuring the areas and air velocities.

Data were also obtained from the ships' personnel. This included bridge 4 hourly data (dry/wet bulb temperature and relative humidity) and livestock deck conditions (dry/wet bulb temperatures and relative humidity).

The project researcher also measured the ambient conditions (dry/wet bulb temperature, relative humidity, CO_2 and NH_3 concentrations) and these were compared with the ship data. The ambient conditions were also compared with the intake conditions to confirm the effects of recirculation of exhaust air.

Other experiments were conducted throughout the voyages (eg. monitoring washdown events, course alterations). The dry/wet bulb temperatures, relative humidity, CO_2 and NH_3 concentrations were monitored during these experiments.

APPENDIX B - GLOSSARY

Acclimatisation	Gradual adjustment of bodily functions and metabolism to cope with new environmental conditions.
Air Exchange	The volume throughput of air through a given volume (eg. volume of $5m^3$, flow rate of $100m^3$/hr would give 20 air changes per hour).
Air Turnover	Ratio of air flow rate to area being ventilated (eg. flow rate 100 m^3/hr, area 10 m^2 would give an air turnover of 10 m/hr).
Comfort Indices	Indices to describe succinctly the environmental conditions, eg wet bulb temperature, THI, ETI.
Deck Volume	Total volume enclosed within each deck.
Dry Bulb Temperature	Normal ambient temperature.
ETI	Equivalent Temperature Index (comfort index based on the dry bulb temperature, relative humidity and airspeed. See Section 2.10).
Humidity Ratio	Ratio of the mass of water vapour content to the mass of dry air.
Jetting	Relatively high velocity stream of air introduced into ambient air.
Latent Heat	Heat absorbed in the evaporation of liquids (water in this case).
Metabolic Heat	Heat produced due to metabolic breakdown of nutrients and oxygen within the body.
Push-Pull	Ventilation scheme using both supply and exhaust fans.
Recirculation	Re-ingestion of exhaust air with the intake air.
Relative Humidity (RH)	Volume ratio of water vapour content to the water vapour content in saturated air at the same dry bulb temperature. At RH=100%, precipitation will occur.
Residence Time	Time spent by a parcel of air in a given volume (eg. 60 air changes per hour would give a residence time of 1 minute).
THI	Temperature Humidity Index (comfort index based on the dry bulb temperature and relative humidity. See Section 2.10).
Wet Bulb Temperature	Temperature as measured by a thermometer with a damp ‘sock’ around the sensing element. Calculable also from the dry bulb temperature and relative humidity.

APPENDIX C - SAMPLE COURSE ALTERATION SPREADSHEET FOR MANAGEMENT OF OPEN DECKS IN FOLLOWING BREEZES

Speed of ship	**18**	knots	9.26	m/s	1 nautical mile =	1850 m
Angle of turn (to s'board)	**30**	degrees	0.524	radians	1 knot =	0.514 m/s
Delay factor (1 = no delay)	1.155					
Vs*(1-cosALPHA)	1.241		(Vs is ship speed in m/s ; ALPHA is the turn angle)			
Vs*sin(ALPHA)	4.63					

TABLE OF NEW APPARENT WIND STRENGTH AFTER A TURN (m/s)

(shaded) Apparent cross wind > 4m/s before turn

Apparent wind direction before turn (starboard of bow)	Apparent wind speed (m/s) before turn											
	m/s	0	1	2	3	4	5	6	7	8	9.26	10
Degrees	knots	0	1.946	3.892	5.838	7.784	9.73	11.68	13.62	15.57	18.02	19.46
0		4.8	4.6	4.7	5.0	5.4	6.0	6.6	7.4	8.2	9.3	9.9
30		4.8	5.1	5.7	6.3	7.0	7.8	8.6	9.5	10.3	11.5	12.2
60		4.8	5.5	6.4	7.2	8.1	9.0	10.0	10.9	11.9	13.1	13.8
90		4.8	5.8	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.9	14.7
120		4.8	5.8	6.7	7.7	8.7	9.7	10.7	11.7	12.7	13.9	14.7
150		4.8	5.5	6.4	7.2	8.1	9.0	10.0	10.9	11.9	13.1	13.8
180		4.8	5.1	5.7	6.3	7.0	7.8	8.6	9.5	10.3	11.5	12.2
210		4.8	4.6	4.7	5.0	5.4	6.0	6.6	7.4	8.2	9.3	9.9
240		4.8	4.1	3.7	3.4	3.4	3.8	4.3	5.0	5.7	6.8	7.4
270		4.8	3.8	2.9	2.0	1.4	1.3	1.8	2.7	3.6	4.8	5.5
300		4.8	3.8	2.9	2.0	1.4	1.3	1.8	2.7	3.6	4.8	5.5
330		4.8	4.1	3.7	3.4	3.4	3.8	4.3	5.0	5.7	6.8	7.4
360		4.8	4.6	4.7	5.0	5.4	6.0	6.6	7.4	8.2	9.3	9.9

TABLE OF NEW APPARENT WIND DIRECTION AFTER A TURN (degrees starboard of bow)

Apparent wind direction before turn (starboard of bow)	Apparent wind speed (m/s) before turn											
	m/s	0	1	2	3	4	5	6	7	8	9.26	10
Degrees	knots	0	1.946	3.892	5.838	7.784	9.73	11.68	13.62	15.57	18.02	19.46
0		75	63	51	39	29	21	14	9	4	360	358
30		75	64	55	48	41	37	33	29	27	24	22
60		75	68	62	58	55	52	50	48	47	45	44
90		75	72	71	69	68	67	67	66	66	65	65
120		75	78	79	81	82	83	83	84	84	85	85
150		75	82	88	92	95	98	100	102	103	105	106
180		75	86	95	102	109	113	117	121	123	126	128
210		75	87	99	111	121	129	136	141	146	150	152
240		75	85	98	113	130	145	158	167	174	180	183
270		75	79	85	97	123	167	198	212	220	225	227
300		75	71	65	53	27	343	312	298	290	285	283
330		75	65	52	37	20	5	352	343	336	330	327
360		75	63	51	39	29	21	14	9	4	360	358

APPENDIX D - TABLES OF WET BULB TEMPERATURE INCREASE

Increase in Wet Bulb Temperature from Inlet to Outlet
(for cattle 200 to 500kg)

Pen Air Turnover* m^3/hr per m^2	Percentage of AMSA MO43 Stocking Density									
	20%	**40%**	**60%**	**70%**	**80%**	**85%**	**90%**	**95%**	**100%**	**105%**
40	1.9	3.8	5.7	6.6	7.6	8.1	8.5	9.0	9.5	10.0
50	1.5	3.0	4.6	5.3	6.1	6.5	6.8	7.2	7.6	8.0
60	1.3	2.5	3.8	4.4	5.1	5.4	5.7	6.0	6.3	6.6
70	1.1	2.2	3.3	3.8	4.3	4.6	4.9	5.2	5.4	5.7
80	0.9	1.9	2.8	3.3	3.8	4.0	4.3	4.5	4.7	5.0
90	0.8	1.7	2.5	3.0	3.4	3.6	3.8	4.0	4.2	4.4
100	0.8	1.5	2.3	2.7	3.0	3.2	3.4	3.6	3.8	4.0
120	0.6	1.3	1.9	2.2	2.5	2.7	2.8	3.0	3.2	3.3
140	0.5	1.1	1.6	1.9	2.2	2.3	2.4	2.6	2.7	2.8
160	0.5	0.9	1.4	1.7	1.9	2.0	2.1	2.3	2.4	2.5
180	0.4	0.8	1.3	1.5	1.7	1.8	1.9	2.0	2.1	2.2
200	0.4	0.8	1.1	1.3	1.5	1.6	1.7	1.8	1.9	2.0
220	0.3	0.7	1.0	1.2	1.4	1.5	1.6	1.6	1.7	1.8
240	0.3	0.6	0.9	1.1	1.3	1.3	1.4	1.5	1.6	1.7
260	0.3	0.6	0.9	1.0	1.2	1.2	1.3	1.4	1.5	1.5
280	0.3	0.5	0.8	0.9	1.1	1.2	1.2	1.3	1.4	1.4
300	0.3	0.5	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.3
320	0.2	0.5	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.2
340	0.2	0.4	0.7	0.8	0.9	0.9	1.0	1.1	1.1	1.2
360	0.2	0.4	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.1
380	0.2	0.4	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0
400	0.2	0.4	0.6	0.7	0.8	0.8	0.9	0.9	0.9	1.0

* Air flowrate (m^3/hr) divided by the pen (m^2) area in the ventilation zone
Liveweight per pen area at 100% stocking density - 275 kg/m^2
Metabolic heat - 2 W/kg of liveweight

Increase in Wet Bulb Temperature from Inlet to Outlet
(for sheep >60kg)

Pen Air Turnover* m^3/hr per m^2	Percentage of AMSA MO43 Stocking Density									
	20%	**40%**	**60%**	**70%**	**80%**	**85%**	**90%**	**95%**	**100%**	**105%**
40	2.0	4.0	6.0	7.0	7.9	8.4	8.9	9.4	9.9	10.4
50	1.6	3.2	4.8	5.6	6.4	6.8	7.2	7.6	7.9	8.3
60	1.3	2.6	4.0	4.6	5.3	5.6	6.0	6.3	6.6	7.0
70	1.1	2.3	3.4	4.0	4.5	4.8	5.1	5.4	5.7	6.0
80	1.0	2.0	3.0	3.5	4.0	4.2	4.5	4.7	5.0	5.2
90	0.9	1.8	2.6	3.1	3.5	3.8	4.0	4.2	4.4	4.6
100	0.8	1.6	2.4	2.8	3.2	3.4	3.6	3.8	4.0	4.2
120	0.7	1.3	2.0	2.3	2.6	2.8	3.0	3.1	3.3	3.5
140	0.6	1.1	1.7	2.0	2.3	2.4	2.6	2.7	2.8	3.0
160	0.5	1.0	1.5	1.7	2.0	2.1	2.2	2.4	2.5	2.6
180	0.4	0.9	1.3	1.5	1.8	1.9	2.0	2.1	2.2	2.3
200	0.4	0.8	1.2	1.4	1.6	1.7	1.8	1.9	2.0	2.1
220	0.4	0.7	1.1	1.3	1.4	1.5	1.6	1.7	1.8	1.9
240	0.3	0.7	1.0	1.2	1.3	1.4	1.5	1.6	1.7	1.7
260	0.3	0.6	0.9	1.1	1.2	1.3	1.4	1.5	1.5	1.6
280	0.3	0.6	0.9	1.0	1.1	1.2	1.3	1.3	1.4	1.5
300	0.3	0.5	0.8	0.9	1.1	1.1	1.2	1.3	1.3	1.4
320	0.2	0.5	0.7	0.9	1.0	1.1	1.1	1.2	1.2	1.3
340	0.2	0.5	0.7	0.8	0.9	1.0	1.1	1.1	1.2	1.2
360	0.2	0.4	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.2
380	0.2	0.4	0.6	0.7	0.8	0.9	0.9	1.0	1.0	1.1
400	0.2	0.4	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0

* Air flowrate (m^3/hr) divided by the pen (m^2) area in the ventilation zone
Liveweight per pen area - 180 kg/m^2
Metabolic heat - 3.2 W/kg of liveweight

Increase in Wet Bulb Temperature from Inlet to Outlet
(for sheep 40kg)

Pen Air Turnover* m³/hr per m²	Percentage of AMSA MO43 Stocking Density									
	20%	40%	60%	70%	80%	85%	90%	95%	100%	105%
40	1.5	3.1	4.6	5.4	6.2	6.6	7.0	7.3	7.7	8.1
50	1.2	2.5	3.7	4.3	4.9	5.3	5.6	5.9	6.2	6.5
60	1.0	2.1	3.1	3.6	4.1	4.4	4.6	4.9	5.2	5.4
70	0.9	1.8	2.6	3.1	3.5	3.8	4.0	4.2	4.4	4.6
80	0.8	1.5	2.3	2.7	3.1	3.3	3.5	3.7	3.9	4.1
90	0.7	1.4	2.1	2.4	2.7	2.9	3.1	3.3	3.4	3.6
100	0.6	1.2	1.9	2.2	2.5	2.6	2.8	2.9	3.1	3.2
120	0.5	1.0	1.5	1.8	2.1	2.2	2.3	2.4	2.6	2.7
140	0.4	0.9	1.3	1.5	1.8	1.9	2.0	2.1	2.2	2.3
160	0.4	0.8	1.2	1.4	1.5	1.6	1.7	1.8	1.9	2.0
180	0.3	0.7	1.0	1.2	1.4	1.5	1.5	1.6	1.7	1.8
200	0.3	0.6	0.9	1.1	1.2	1.3	1.4	1.5	1.5	1.6
220	0.3	0.6	0.8	1.0	1.1	1.2	1.3	1.3	1.4	1.5
240	0.3	0.5	0.8	0.9	1.0	1.1	1.2	1.2	1.3	1.4
260	0.2	0.5	0.7	0.8	1.0	1.0	1.1	1.1	1.2	1.2
280	0.2	0.4	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.2
300	0.2	0.4	0.6	0.7	0.8	0.9	0.9	1.0	1.0	1.1
320	0.2	0.4	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0
340	0.2	0.4	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0
360	0.2	0.3	0.5	0.6	0.7	0.7	0.8	0.8	0.9	0.9
380	0.2	0.3	0.5	0.6	0.7	0.7	0.7	0.8	0.8	0.9
400	0.2	0.3	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.8

* Air flowrate (m^3/hr) divided by the pen (m^2) area in the ventilation zone
Liveweight per pen area - 140 kg/m^2
Metabolic heat - 3.2 W/kg of liveweight

Increase in Wet Bulb Temperature from Inlet to Outlet
(for sheep 20kg)

Pen Air Turnover* m^3/hr per m^2	Percentage of AMSA MO43 Stocking Density									
	20%	**40%**	**60%**	**70%**	**80%**	**85%**	**90%**	**95%**	**100%**	**105%**
40	0.9	1.8	2.6	3.1	3.5	3.8	4.0	4.2	4.4	4.6
50	0.7	1.4	2.1	2.5	2.8	3.0	3.2	3.4	3.5	3.7
60	0.6	1.2	1.8	2.1	2.4	2.5	2.6	2.8	2.9	3.1
70	0.5	1.0	1.5	1.8	2.0	2.1	2.3	2.4	2.5	2.6
80	0.4	0.9	1.3	1.5	1.8	1.9	2.0	2.1	2.2	2.3
90	0.4	0.8	1.2	1.4	1.6	1.7	1.8	1.9	2.0	2.1
100	0.4	0.7	1.1	1.2	1.4	1.5	1.6	1.7	1.8	1.9
120	0.3	0.6	0.9	1.0	1.2	1.3	1.3	1.4	1.5	1.5
140	0.3	0.5	0.8	0.9	1.0	1.1	1.1	1.2	1.3	1.3
160	0.2	0.4	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.2
180	0.2	0.4	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0
200	0.2	0.4	0.5	0.6	0.7	0.8	0.8	0.8	0.9	0.9
220	0.2	0.3	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8
240	0.1	0.3	0.4	0.5	0.6	0.6	0.7	0.7	0.7	0.8
260	0.1	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7
280	0.1	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.7
300	0.1	0.2	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6
320	0.1	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6
340	0.1	0.2	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5
360	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5
380	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5
400	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.5

* Air flowrate (m^3/hr) divided by the pen (m^2) area in the ventilation zone
Liveweight per pen area - 80 kg/m^2
Metabolic heat - 3.2 W/kg of liveweight