final report

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Closed livestock housing environments and ventilation systems – a literature review

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Summary

In 2018, LiveCorp called for proposals to identify new technologies and systems that would mitigate the risks of extreme heat stress for sheep exported to the Middle East. Dehumidification of the animal house on livestock vessels was included on a short list of proposals selected for further consideration and applied field trials.

Dehumidification is fundamentally different from the ventilation system on all livestock vessels currently operating from Australia. It involves a shift from using ambient air with high air exchange rates, to the use of dehumidified air with much lower air exchange rates.

This literature review was commissioned to provide a better understanding of closed livestock housing ventilation systems across a range of agricultural settings, with a particular focus on the use of dehumidification technologies. The review was also tasked to identify any risks and risk mitigation strategies associated with moving livestock acclimatized to a controlled housing environment to an uncontrolled housing environment.

Key findings

Based on a review of the scientific literature, industry research reports, guidelines and codes, key findings are as follows:

- Controlled environment housing with dehumidification is not a current commercial husbandry practice for sheep, goats, dairy cattle, beef cattle or pigs in any production system or geographical environment worldwide.

- Sheep and goat housing in hot climatic areas is typically designed to maximize natural ventilation, with features such as a raised slatted or mesh floor, side openings that allow cross-ventilation, roof vents, wide eaves and non-radiant construction materials. Mechanical ventilation is not a key design feature.

- For dairy farms in hot climates, provision of shade in outside areas, cattle shed orientation and roof insulation are important infrastructure considerations to minimize exposure to radiant heat. Cooling hot cows is almost entirely achieved by evaporative cooling, with water sprayed onto the cattle or into the air around them, and air blown over the animals causing convective heat loss. A variety of spraying, fogging and misting systems and wetting regimens are described in the literature. The engineering specifications differ (droplet size, fan sizes and speeds, air inlet and outlet locations etc.), but the basic principle of heat loss from evaporative cooling is the same.

- Despite clear animal productivity benefits from housing dairy cattle in a fully air conditioned barn during hot weather, refrigerant air conditioned housing has not been widely adopted by commercial dairies. This is presumably because the technology is not cost-effective.

- Small-scale studies have shown that conductive heat loss can reduce the impact of heat stress in dairy cattle barns, with chilled water circulated through a water mattress or below the surface of tie-stall bedding. However, this technology has not been adopted on a commercial scale.

- Temperature and humidity control with a hybrid desiccant dehumidification / air conditioning system in a pig shed has been demonstrated conceptually using computer simulation models. However, the models in the published literature do not consider the concentration of noxious gases in the shed and do not appear to have been proven in practice.

- There are fully air conditioned stables at horse racing and equestrian facilities throughout the tropics, the Middle East and in Australia. Air conditioned stables provide high performance horses with respite from the heat outside. However, they do not have to dissipate the quantity of metabolic heat or ammonia generated in the animal house on a live export vessel.

- Dehumidification is a well-established technology for environmental control of large public buildings and enclosed spaces, such as office buildings, hotels, supermarkets and indoor sporting facilities. The factors driving adoption of dehumidification in non-agricultural buildings include human comfort, preventing mould, preventing condensation on walls and ceiling fluid drips, eliminating frost on freezers, reducing metal corrosion and meeting the requirements for industrial processes and product storage that need low humidity. Hybrid environment control systems are common, with air conditioning and/or heating to manage temperature fluctuations and a desiccant dehumidification plant to control humidity. Hybrid ventilation systems offer significant energy savings compared with air conditioning alone. Dissipating the heat, moisture and noxious gases generated in the animal house on a livestock ship, when there is a high ambient temperature and humidity, is an environmental control challenge well beyond what is typically required of a non-agricultural building's ventilation system.

- The ventilation system on a livestock vessel must be able to dissipate the peak heat load in the animal house – metabolic heat generated by the livestock, plus radiant heat from the vessel, heat generated by the ventilation fans and heat from fermentation in the dung pad. A critical step when considering dehumidification for a livestock vessel must be calculation of the proposed system's ability to dissipate the peak heat load in the animal house.

- Ammonia is produced with microbial activity in a moist dung pad breaking down urea from urine and undigested protein in faeces. The concentration of ammonia in the animal house has been an issue of concern on some livestock export voyages, with levels recorded above the short-term exposure limit (STEL) for humans set by Safe Work Australia.

- At present, dispersion of ammonia from an animal house, on land or at sea, is entirely by air exchange. If the air exchange rate in an animal house is greatly reduced, an increased concentration of ammonia can be expected, with both animal welfare and workplace health and safety consequences. For the livestock export industry, keeping the concentration of ammonia in the animal house below an acceptable threshold will be a major challenge for dehumidification or any other environment control system that involves significantly reduced air exchange rates.

- If the ventilation system in an animal house can adequately disperse ammonia, then carbon dioxide, methane and hydrogen sulphide emissions are unlikely to be a problem.

- Ventilation fans are the main source of noise in the animal house on a livestock vessel. If the air exchange rate is reduced with a dehumidification plant, there is likely to be a concurrent reduction in noise emissions. However, noise generated by the dehumidification system must also be taken into account. A reduction in noise intensity would enhance the comfort of seafarers working in the animal house, but have little effect on the animals on board.

- There are two principal sources of dust in livestock housing – dust from a dry dung pad and fodder 'fines'. The relationships affecting the movement of dust within an animal house are complex - particle concentration, size, mass and buoyancy, type and location of the dust source, airflow characteristics, turbulence and animal activity all affect particle movement.

- Dust mitigation strategies for intensively housed livestock focus on reducing dust generation rather than removing airborne dust or dispersion with air exchange. It is not clear what effect a dehumidification system with reduced air flow rate would have on the concentration of airborne particulate matter in a ship's animal house.

- This review did not identify any original research on the acclimatization response for sheep after exposure to thermal stress, or the rate of de-acclimation after cessation of thermal stress. However, there is some information for cattle and a large body of original research on human acclimatization to heat stress, derived from sports medicine, military and occupational health and safety studies. In the absence of hard data for sheep, the findings from cattle and human studies may be cautiously interpreted in a live sheep export context.

- Acclimatization to heat stress is a relatively rapid process that begins on the first day of exposure, with about 75% of total adaption in the first seven days. It is reasonable to assume that, if sheep exported to the Middle East during the northern hemisphere summer are held on the vessel in anything other than a fully air conditioned animal house, they will arrive with at least modest if not strong acclimatization to heat stress. After discharge, thermal stress will be largely determined by the weather and by the design and management of the destination feedlot – ambient temperature and humidity, availability of shade, exposure to radiant heat, stocking density, air flow, availability of fresh water, stock handling etc. The ventilation system on the ship is unlikely to have a detrimental effect on sheep welfare after discharge.

1. Background

In 2018, the Australian Livestock Export Corporation (LiveCorp) called for proposals to identify new technologies and systems that would mitigate the risks of extreme heat stress for sheep exported to the Middle East. A short list of proposals was selected for more detailed consideration and applied field trials.

The technologies deemed worthy of further consideration included:

- dehumidification;
- route optimization using enhanced weather forecasting;
- enhanced data connectivity on livestock vessels;
- temperature / humidity loggers; and
- volatile gas sensors.

Dehumidification is a fundamentally different approach to shipboard ventilation from that used by the fleet of vessels currently exporting livestock from Australia. It involves a shift from using ambient air with high air exchange rates, to the use of dehumidified air with much lower air exchange rates.

This literature review was commissioned to provide a better understanding of closed livestock housing environment control and ventilation systems across a range of agricultural settings, and in particular the use of dehumidification technologies. The review was also tasked to identify any risks and risk mitigation strategies associated with moving livestock acclimatized to a controlled housing environment to an uncontrolled housing environment.

2. Closed housing environment control systems

2.1 Livestock housing

2.1.1 <u>Sheep and goats</u>

Although sheep and goat production for fibre, meat and milk occurs worldwide, across a wide range of environments, and under a multitude of production systems, there are relatively few references in the scientific literature to fully enclosed housing with a ventilation system that maintains a controlled environment for small ruminants.

Small ruminant housing designs are readily available as extension material from a range of reputable sources including Departments of Agriculture [31] [32], industry associations [3], [29] [79], university faculties of Agriculture [63] [123] [128] and aid organisations [1].

In hot, humid climates, sheep and goat housing is typically designed to maximize natural ventilation, with features such as a raised slatted or mesh floor, side openings that allow cross-ventilation, roof vents, wide eaves and non-radiant construction materials [79]. Mechanical ventilation is not a key design feature.

In northern Europe, sheep and goat housing is mainly designed to provide protection from the elements in winter [12]. Ventilation to disperse noxious gases may be entirely passive, with air warmed by body heat and water vapour rising and exiting the building through flues that create a vacuum and suck air out, or may be assisted with input and/or exhaust fans. Dispersal of body heat is not a key requirement.

Poly-tunnels are used to protect sheep from cold during the northern European winter. They are typically long, narrow buildings, constructed with heavy-duty polyethylene draped over a metal frame, with sufficient natural ventilation from the sides and/or ends that additional mechanical ventilation is not required.

In Mediterranean Europe, thermal stress in summer may be an issue for housed sheep and goats, requiring mechanical ventilation in addition to natural ventilation to dissipate heat and disperse noxious gases [19]. Depending on shed design, this may be cross-ventilation, tunnel ventilation or a pressure tube ducted ventilation system.

Superfine wool production from sheep kept in sheds (Sharlea sheep) was a boutique industry in Australia in the 1980s and 1990s. The sheep were kept continuously in sheds, to produce a very fine, high-value fibre. Most Sharlea sheep sheds were re-purposed farm buildings, particularly shearing sheds with a slatted or mesh floor and passive natural ventilation. Key management issues related to nutrition, foot conditions and behavioural problems associated with long-term residency in the shed. Ventilation was not a major management concern [66].

Repurposed farm buildings, including sheds designed and built for pre-export quarantine of live export sheep, are also used in Australia to grow out lambs for slaughter. These sheds typically rely on natural air flow to dissipate heat and disperse noxious gases, with mechanical ventilation not required.

Guidelines for the Housing of Sheep in Scientific Institutions [4] provides generic husbandry recommendations for sheep in scientific establishments. It provides guidance to institutional animal ethics committees, but does not recommend any particular environmental control system. As 'rules of thumb', the *Guidelines* recommend a temperature range of 10-24°C, a humidity range of 40-60% and an air exchange rate of at least 3m^3 air / kilogram bodyweight / hour.

Controlled environment housing with desiccant dehumidification is not a commercial husbandry practice in any of the production systems reviewed.

2.1.2 Dairy cattle

There is a large body of work in the scientific literature relating to heat stress in dairy cattle as a cause of production loss and animal welfare concern. Fournel et al. [40] provide a detailed review of the literature and a comprehensive reference list.

For dairy farms in hot climates, provision of shade in outside areas, cattle shed orientation and roof insulation are important infrastructure considerations to minimize exposure to radiant heat. The location and design of feed bunks and water troughs is also an important consideration [111].

Cooling hot cows is almost entirely achieved by evaporative cooling, with water sprayed onto the cattle or into the air around them, and air blown over the animals causing convective heat loss. A variety of spraying, fogging and misting systems and wetting regimens are described in the literature. The engineering specifications differ (droplet size, fan sizes and speeds, air inlet and outlet locations etc.), but the basic principle of heat loss from evaporative cooling is the same [40] [90] [106] [112] [129].

Cattle barns with a 'tunnel' ventilation system remove body heat by evaporative cooling, using a high air exchange rate and high velocity air flow. Tunnel ventilation is a popular design for intensive dairy farms in the tropics. The sheds are typically long, narrow buildings, with a passive ventilation opening at one end and exhaust fans at the other end that suck air into the shed. For most efficient air flow along the shed, resistance barriers need to be kept to a minimum and all doors, windows and openings along the side walls and roof kept closed [126] [129]. Tunnel ventilated dairy barns provide concentrated airflow over the animals inside, with fresh rather than recirculated air drawn into the shed, and heat from the fans transferred to the exhaust air, not into the barn. However, there are significant operational costs for energy, and if air flow stops because of power failure, a tunnel ventilated barn full of cattle heats up very quickly [126] [129].

Evaporative cooling pads are often added to the air inlets of tunnel ventilated barns. They are typically made with a woven fibrous material that is saturated with water. As air is drawn through the pad, liquid water is converted to water vapour, which lowers the temperature of the incoming air but increases its humidity [40].

A number of scientific research trials have investigated air conditioning as a means of alleviating the effects of heat stress on dairy cattle. Stott and Wiersma [121] [133] studied the effect of short-term air conditioning on conception rates in dairy cows on a farm in a hot, dry desert environment (Arizona USA). Cows that were normally housed in open corrals with overhead shade were kept in an air conditioned barn for one day before and up to seven days after artificial insemination. A modest improvement in conception rates occurred early in summer, but not later in summer. Thatcher [124] found that air conditioning increased milk production and enhanced reproductive performance during summer on a large-scale commercial dairy in a hot, humid environment (Florida, USA). Thatcher et al. [125] and Hahn et al. [49] also reported significant milk production and reproduction benefits from holding dairy cattle in air conditioned barns during hot weather. Bray et al. [16] recommended using an air conditioned 'transition barn' to enhance cow comfort for dairy cows calving in hot weather.

Despite the clear animal productivity benefits from housing dairy cattle in an air conditioned barn during hot weather, fully enclosed air conditioned housing has not been widely adopted by commercial dairies. This is presumably because the technology is not cost-effective.

This literature review identified a small body of work on conductive heat loss from cattle. Perano et al. [96] reported that with a water cooled mattress modified to circulate chilled water, and with environmental conditions of high heat, high humidity or both, lactating dairy cows had lower rectal temperatures, a decreased respiration rate, increased dry matter intake and increased milk yield compared with controls on a waterbed without additional cooling. Ortiz et al. [89] investigated the effects of heat exchangers buried 25 cm below the surface of tie-stall beds containing sand or dried manure. Water cooled to 7°C was circulated through the heat exchangers. Lactating cows lying on cooled bedding had lower core body and rectal temperatures, lower respiration rates and greater dry matter intake and milk production than control animals on similar bedding but without heat exchange cooling.

The Perano and Ortiz studies show that conductive heat loss can be used to reduce the impact of heat stress in dairy cattle barns. However, these are small-scale studies, with the technology yet to be adopted on a commercial scale.

In northern Europe, cattle housing is mainly designed to provide protection from the elements in winter [3] [83]. Ventilation to disperse noxious gases may be entirely passive, or may be assisted with intake and/or exhaust fans. Dispersal of body heat is not a key requirement.

This literature review did not identify any scientific studies or field reports of desiccant dehumidification technology used in a closed housing system for dairy cattle.

2.1.3 Beef cattle

The International Commission of Agricultural and Biosystems Engineering (CIGR) report *Design recommendations of beef cattle housing* [23] provides detailed design recommendations for beef cattle barns, from a European and North American perspective. Ventilation with air exchange is identified as critical to keeping noxious gases below an acceptable threshold. In hot climates, where heat loss from the animal house is required, an air flow rate of 1-3 m/sec over the cattle is recommended to facilitate convective heat loss from evaporative cooling.

There are many references in the scientific and extension literature to the design and management of beef cattle feedlots. Confinement is mostly in outdoor pens. Where enclosed housing is used, ventilation is typically by natural means [46] [132].

This literature review did not identify any scientific studies or field reports of desiccant dehumidification technology used in a closed housing system for beef cattle.

2.1.4 Pigs

There are a wide variety of pig production systems around the globe, but the vast majority of production occurs intensively, with pigs born and reared in sheds [15].

Pigs are quite sensitive to temperature stress. A pig’s zone of thermal neutrality is the temperature range in which the pig does not have to expend metabolic energy to keep warm or stay cool. The lower critical temperature (LCT) is the ambient temperature below which a pig diverts energy from growth to keep warm. The upper critical temperature (UCT) is the ambient temperature above which a pig diverts energy from growth to keep cool. Significant production and hence economic losses occur if the ambient temperature is outside the pig’s zone of thermal neutrality [24] [53].

Air flow rates are an important consideration for housed pigs. Growing pigs have a higher surface area to body mass ratio than mature pigs, with piglets particularly susceptible to wind chill. A pig’s lower and upper critical temperatures increase with air speeds faster than 0.15 m/s. So, whilst high air flow rates help alleviate heat stress in hot conditions, draughts increase susceptibility to chilling in cold weather [3].

Mayorga et al. [75] provide an up to date review of heat stress management for intensively housed pigs. They discuss a range of strategies to alleviate heat stress – shed design, evaporative cooling pads to lower the temperature of air entering the shed, fogging and misting systems for evaporative cooling, elevated airspeeds to enhance convective heat loss, floor conductive cooling and air conditioning. The Mayorga review says that although the air temperature in a pig shed can be controlled with a refrigerant air conditioning unit, this is not economically viable. The review does not mention desiccant dehumidification.

Banhazi et al. [10] report the findings of a survey of 48 piggery buildings in South Australia, investigating the factors affecting thermal control under hot climatic conditions. The paper includes a detailed analysis of pig housing design, ventilation and heat transfer systems, but does not mention desiccant dehumidification.

Nicolai et al. [86] produced a concept design for a cold climate 1,000 pig finishing barn, with a ventilation system that would filter exhaust air from the barn to remove ammonia, methane, hydrogen sulphide, volatile organic compounds and moisture, then recycle the same air back through the barn. Moisture was to be removed by cooling the air causing condensation, with the cool air warmed again by passing over a heat exchanger, so as to return to the barn at a constant temperature. The capital and operating costs of the proposed air recirculating barn were significantly higher than for a traditional mechanically ventilated barn. The payback period was estimated to be from 6.3 to over 16 years, depending on assumptions regarding feed costs, feed efficiency gains and the market price for finished pigs. This system does not appear to have been adopted commercially.

Gates et al. [43] developed a computer model to simulate environmental control in a conceptual swine facility in North Carolina USA. This model has greater relevance to current live export heat stress trials as it simulates livestock housed in a hot, humid environment. The Gates model compared three different air conditioning systems with a hybrid desiccant unit for dehumidification coupled with an air conditioner to provide cooling. The simulation found that a hybrid dehumidification and air conditioning system provided superior control of thermal stress (both temperature and humidity) at comparable operating cost. The Gates computer simulation does not consider the concentration of noxious gases in the animal house. Gates et al. recommended further investigation and field trials for possible use housing high-value pigs in breeding and genetic improvement programs.

Johnson et al. [60] also used computer simulation to assess desiccant dehumidification coupled with air conditioning for temperature and humidity control of pig sheds, and concluded the proposed system had merit, but did not consider control of noxious gases in the shed.

Temperature and humidity control in a pig shed with a hybrid desiccant dehumidification and air conditioning system has been demonstrated conceptually by the Gates and Johnson computer simulations, but these models do not consider the concentration of noxious gases in the shed, and do not seem to have been proven in practice and adopted commercially.

2.1.5 Horses

There are lots of references in the scientific and extension literature to ventilation and air quality in horse stables. Elfman et al. [37] provide a good summary of the issues. The main concerns relate to the respiratory health of the horses and grooms working in the stable. Key issues include control of airborne particulate matter (organic matter, potential allergens, microorganisms and endotoxins), minimizing proliferation of moulds, ammonia and odour control, bedding management and stable hygiene. Natural ventilation, with or without fans, is the norm in temperate and cold climate areas.

There are air conditioned stables at horse racing and equestrian facilities throughout the tropics, the Middle East and in Australia. Air conditioned stables provide high performance horses with respite from the heat outside, with a controlled indoor environment (temperature, humidity, noxious gases and particulate matter). However, they do not have to dissipate the quantity of metabolic heat or ammonia generated in the animal house on a live export vessel.

Desiccant dehumidification coupled with air conditioning is widely used for environmental control of large non-agricultural buildings (see section 2.3 below). Some air conditioned horse stables may well have a hybrid dehumidification and air conditioning system. This literature review did not identify any horse stables with desiccant dehumidification as the primary source of environmental control.

2.1.6 Livestock housing – reviews and technical reports

Banhazi et al. [9], Hoff [55] and Ugwuishiwu et al. [127] are contemporary reviews of environmental control, particularly heat stress, in livestock houses. These reviews discuss building design, ventilation and heat transfer systems, and speculate on the future direction of environmental control technology, but do not mention desiccant dehumidification.

Arcidiacono [5] provides another contemporary review of animal heat stress abatement in livestock buildings. It has one reference to desiccant dehumidification – a study by Samer et al. [114] into the use of desiccant pads to absorb moisture from the air before it passes through a conventional air intake. This study demonstrated that desiccant pads over the air intake could be used to enhance convective heat loss in an animal house. However, there were significant logistical and cost constraints to commercial adoption, as the desiccant pads needed to be reactivated every 150 minutes, and additional energy was required for the extractor fans to overcome the air flow resistance from the desiccant pads.

The Agriculture and Horticulture Board publication *Controlled environment for livestock* [3] is an up to date practical handbook on controlled environment housing for livestock in the UK. It does not mention dehumidification systems.

2.2 Livestock ships

In this review, livestock ships are considered separately from other types of animal housing, as a special case, with unique management challenges and constraints.

The ships that export livestock from Australia all have mechanical ventilation systems that rely on high air exchange rates with air flow across the livestock pens to remove excess heat load, water vapour and noxious gases.

A ship must have a current Australian Certificate for the Carriage of Livestock (ACCL) when loading livestock for export from Australia. This is a mandatory regulatory requirement. The Australian Maritime Safety Authority *Marine Order 43 (Cargo and cargo handling – livestock) 2018* [8] sets out minimum design and operational requirements needed for a livestock ship to hold an ACCL – including ventilation requirements. For an enclosed space, the vessel must have a mechanical ventilation system that can change the total volume of air in that space in accordance with Table 1 below.

Table 1. Air change required for livestock holds

Minimum clear head space	Time for complete air change
≤ 1.8 m	At least every 2 minutes
≥ 2.3 m	At least every 3 minutes
1.8 – 2.3 m	Proportionally between 2 and 3 minutes

AMSA Marine Order 43 contains grandfathering clauses that allow lower ventilation air exchange rates for ships with livestock holds that are not enclosed and also for older ships. However, the grandfathering clauses have a sunset date of 31 Dec 2019. From 1 Jan 2020, all ships exporting livestock from Australia will be required to have a mechanical ventilation system compliant with Table 1 for all livestock holds.

AMSA Marine Order 43 also sets minimum requirements for air distribution across livestock pens, carriage of spare parts, system power supply, redundancy and alarms in the event of ventilation system failure.

An exporter planning to export livestock to or through the Middle East must complete a heat stress risk assessment, showing the heat stress risk is below a critical threshold. This is a regulatory requirement needed to obtain approval to export. The heat stress risk assessment tool in use is the HotStuff computer model [118]. Hotstuff combines animal characteristics and their heat tolerance with weather statistics and vessel parameters to give an estimate of the heat stress mortality risk for each line of livestock loaded.

One of the critical factors in the HotStuff calculations is the pen area turnover (PAT) for each livestock hold on the vessel. The PAT is the air exchange in cubic metres, per square meter of livestock pen space, per hour. This is considered a better measure of ventilation than simply air exchange, as it links air flow to the pen space within the hold, and it factors in both the deck height and the proportion of pen space relative to the total deck area [76].

The ventilation design requirements in AMSA Marine Order 43 and the importance of high PAT values for HotStuff heat stress risk assessment have encouraged shipboard ventilation systems with high air exchange rates, distributed to provide an even air flow across the livestock pens as efficiently as possible.

The *OIE Terrestrial Animal Health Code Chapter 7.2 Transport of Animals by Sea* [88] includes a generic requirement that the ventilation system must be adequate to meet the thermo-regulatory needs of the animals being transported. It does not specify how that should be achieved or set minimum standards for air change rates, air flow rates over livestock pens or air quality parameters.

2.3 Non-agricultural buildings

Dehumidification is now a well-established technology for environmental control of large enclosed public spaces, such as office buildings, hotels, supermarkets, industrial premises and indoor sporting facilities. Also for buildings requiring highly controlled humidity levels, such as museums, sterile rooms and hospitals [98] [117]. There are multiple suppliers of commercial building dehumidification technology in Australia and worldwide.

The major factors driving adoption of dehumidification in non-agricultural buildings and large enclosed public spaces are human comfort, preventing mould, preventing condensation on walls and ceiling fluid drips, eliminating frost accumulation on freezer cabinets, reducing corrosion of metal components, and meeting the requirements for product storage and industrial processes that require low humidity (such as museum storage, food processing and manufacture of pharmaceuticals) [58] [84] [104].

Hybrid environment control systems are common, with air conditioning and/or heating to manage temperature fluctuations and a desiccant dehumidification plant to control humidity. Desiccant dehumidification in conjunction with a cooling system may significantly lower the total energy cost, compared with a cooling system alone [38].

The heating, ventilation and air-conditioning (HVAC) system for a public building must be able to keep the temperature, humidity and concentration of noxious gases within an acceptable range. The Dehumidification Handbook [84] sets out a process for determining system requirements for buildings and provides a series of case study examples.

Dissipating the metabolic heat, moisture and noxious gases generated in the animal house on a livestock ship, with a high ambient temperature and humidity, is an environmental control challenge well beyond what is typically required of a non-agricultural building's HVAC systems.

3. Risks and risk management

3.1 Scope

Risk mitigation strategies that do not involve ventilation or environmental control procedures are outside of scope and are not included in this literature review. Such strategies include reduced stocking rates, prohibition of exports during high risk times of the year, exclusion of high risk animals and dietary manipulation to reduce metabolic heat production.

3.2 Heat

3.2.1 <u>Livestock housing</u>

The literature on confined livestock housing in hot environments contains a raft of building design strategies to reduce solar heat load on the building and facilitate heat loss with efficient natural and/or mechanical ventilation. Considerations include building site and orientation, building size and geometry, construction materials, and a wide range of factors that affect air flow within the building – air inlet and exhaust sizes and locations, fan sizes and locations, roof slope and venting, internal features that impact air flow and/or distribution within the building, and pressure and thermal gradients [5] [83] [126].

Uneven distribution of air flow and local thermal hot-spots within a building are an issue for housed livestock, resulting in the concept of an 'animal occupied zone' with surrounding microclimate [5].

Modelling techniques, especially Computational Fluid Dynamics (CFD), are now used to analyse the effects of building design, with spatial and temporal mapping of temperature, air velocity and air contamination inside livestock houses and other buildings [87] [105] [136]. This allows new building designs to be fine-tuned and modification of existing buildings to optimize ventilation for dissipation of heat and noxious gases.

There is increasing interest in precision farming technology, with sensors and cameras that provide continuous monitoring of the physical environment (temperature, humidity, air speed), physiological activity (feed consumption, respiration rates, milk or egg production) and animal behaviour (animal movement, feed and water intake) to automatically adjust the environmental control system, to enhance animal comfort and reduce input costs [9] [41] [42]. This is an emerging area of new technology application.

Under heat stress conditions, housed livestock lose most of their excess body heat as a result of convection, with evaporative cooling. This occurs when sweat or water evaporates from the animal's skin, water vapour is blown off the animal's lungs, or there is evaporation in the animal's nearby environment. The major constraint is that heat loss with evaporation declines as humidity in the surrounding air increases, which makes evaporative cooling much less effective in a hot, humid climate [40].

3.2.2 <u>Shipboard environment</u>

Heat stress has long been recognized as a critical factor affecting animal and human comfort on livestock vessels travelling to the Middle East, and as a cause of shipboard reportable mortality incidents for sheep during the Middle East summer [20] [26]. It has been a key focus of live export industry research and risk mitigation efforts [11] [71] [72] [76] [118] [119] [120].

MAMIC Pty. Ltd. [70] monitored shipboard ventilation, environmental conditions on board and animal health indicators on six live export voyages from Australia to the Middle East, from May to December 2000. Following and based on that study, a supplementary report described a raft of practical measures which could be implemented to improve ventilation and/or reduce costs [71].

The MAMIC reports have a strong engineering focus. They provide the most comprehensive information in the published literature on ventilation of livestock vessels. Recommendations to enhance shipboard ventilation performance include:

- flaring of ventilation intakes and removal of mushroom caps (which impede air flow and increase power requirements);
- smoothing of duct corners and avoidance of duct elbows;
- removal of extraneous grills and baffles from air outlets;
- balancing supply and exhaust fan capacity;
- even distribution of air over the livestock, with avoidance of ventilation dead spots;
- insulating hot surfaces that radiate heat, such as bulkheads and cover decks; and
- avoiding recirculation, with intake air sourced well away from exhaust outlets and not alongside open decks.

In the MAMIC shipboard ventilation study [72], livestock metabolic heat production was calculated for five cattle voyages and one sheep voyage from Australia to the Middle East. This was done by measuring overall heat balance between exhaust air and intake air. The major source of heat generated in the livestock house was considered to be metabolic heat produced by the livestock on board.

The second biggest heat source was the air intake fans, with heat from the motor and fan inefficiencies carried down with the intake air. The energy applied to boost air pressure also generated heat with frictional losses and turbulent mixing in the ductwork and supply jets. MAMIC determined that airstream heat gains from the supply fans were typically 5 to 15% of the heat generated from livestock metabolic heat. MAMIC [71] includes a series of practical recommendations regarding the design of ventilation intakes, fans, ducts and exhaust outlets, to enhance their efficiency and reduce added heat load.

The third largest source of heat in the MAMIC study [72] was radiant heat from adjacent walls or ceilings. This varied depending on location of the pen.

Decomposing manure was also considered as a possible heat source. A dry sheep pad is unlikely to generate much microbial heat. However, if the dung pad stays moist as a result of hot humid conditions on board, fermentation in the dung pad could contribute significant heat load [72].

The MAMIC [72] estimates of the metabolic heat generated by sheep and cattle at sea whilst travelling to the Middle East are shown in Table 2.

Table 2. Metabolic heat generation – MAMIC [72]

	Metabolic heat generated *
Sheep (57 kg)	3.2 W / kg
Cattle (390-430 kg)	1.6 W / kg

* 1 Watt (W) = 1 joule / second

A key requirement of a livestock ship's ventilation system is removal of heat from the animal house, so the animals on board can maintain their core body temperature. The ventilation system must be able to dissipate the peak heat load in the animal house – metabolic heat generated by the livestock, plus radiant heat from the vessel, heat generated by the ventilation fans, heat from fermentation in the dung pad and any other source of heat.

A critical step when considering the use of dehumidification for a livestock vessel, with or without additional cooling, is calculation of the proposed system's ability to dissipate the peak total heat load in the animal house.

The HotStuff risk assessment model used by the live export industry is not suitable for assessing a dehumidification system, as HotStuff risk calculations assume ambient temperature and humidity of intake air with a high flow rate, not dehumidified air with a much lower flow rate.

Outschoorn [91] applied CFD software to produce a 2D model of air and heat transfer mechanisms within a livestock hold on the *MV Becrux*. This information was used to gain a better understanding of heat removal from the hold and explore ways to produce a more favourable outcome. For a new livestock vessel or new conversion, or with substantial re-design of a vessel in the existing fleet, CFD modelling would enable fine-tuning of the animal house design and ventilation system, to optimize air flow and distribution.

3.3 Ammonia

3.3.1 <u>Workplace health and safety</u>

Under the Australian Federal *Work Health and Safety Act (2011)*, and the subordinate Work Health and Safety Regulations, any person who conducts a business has a responsibility to *'ensure that no person at the workplace is exposed to a substance or mixture in an airborne concentration that exceeds the exposure standard for the substance or mixture'.*

Safe Work Australia is the authority responsible for setting workplace exposure standards for airborne contaminants in Australia [109]. There are two separate standards in place:

- *Eight-hour time weighted average (TWA).* This is a time-weighted average exposure limit for humans during an eight-hour working day, in a 40-hour working week.
- *Short-term exposure limit (STEL).* This is a time-weighted average exposure limit, measured over 15 minutes. It should not be exceeded, even if exposure during a full day is less than the eight-hour TWA exposure standard.

The TWA and STEL standards for ammonia set by Safe Work Australia are listed in Table 3. The United Kingdom has identical workplace exposure standards for ammonia [51]. Although these standards may not have legislative standing for a livestock vessel in international waters or in another overseas jurisdiction, they provide a benchmark for the livestock export trade.

Table 3. Workplace exposure standards for airborne contaminants
Safe Work Australia [109]

	TWA	**STEL**
Ammonia (NH_3)	25 ppm	35 ppm

The main symptoms in humans exposed to ammonia vapours are irritation of the eyes, nose and throat, coughing, increased production of phlegm and narrowing of the bronchi causing shortness of breath. The odour detection threshold in humans is about 5 ppm, but ammonia causes olfactory fatigue or adaption, making the gas more difficult to detect after exposure over an extended period [2].

Donham et al. [35] investigated the effects of concurrent exposure to ammonia and dust on the health of poultry workers. In this study 257 workers from various segments of the poultry industry (broiler production, egg laying, turkey growing and poultry processing) were tested for pulmonary function before and after a four-hour shift. Their work sites were also assessed for ammonia, total dust and respirable dust. The effects of simultaneous exposure to ammonia and dust on Forced Expiratory Volume and Forced Expiratory Flow were examined by correlation, logistic modelling and synergy index calculations. Simultaneous exposure to ammonia and dust caused a significantly greater decline in pulmonary function than the sum of ammonia and dust effects in isolation. This study suggests that a dusty working environment exacerbates the effects of exposure to elevated ammonia emissions.

3.3.2 Effects on animal health and welfare

Phillips [99] investigated the effects of ammonia concentration (0, 15, 30 and 45 ppm) on the physiology and behaviour of steers and wethers held for 12 days under micro-climate and stocking density conditions to simulate a voyage from Australia to the Middle East during the northern hemisphere summer. In this study, physiological changes caused by ammonia were short-lived and mainly confined to increased macrophage activity in bronchiole lavages of steers exposed to 45 ppm ammonia. The proportion of steers with lacrimation and nasal discharge was 10-20% after exposure to 15-30 ppm ammonia and 35-40% after exposure to 45 ppm ammonia. Irritation of the nasal or ocular mucosa was not recorded in sheep at any ammonia concentration. However, sheep exposed to 30 and 45 ppm ammonia lost 6-8% of live weight.

Zhang et al. [137] reported that sheep exposed to elevated ammonia in a simulated live export voyage had reduced feed intake, chewed less during eating and rumination, and had retarded rumination. They concluded these changes were most likely caused by irritation to the mucosa in the buccal cavity.

Phillips [99] recommends an ammonia exposure limit of 30 ppm for sheep and steers. Costa et al. [27] propose that a critical atmospheric concentration of ammonia for cattle, sheep and goats during live export should be set at 25 ppm – the same as the TWA threshold for humans.

3.3.3 Livestock housing

Gaseous ammonia is produced by urease enzymes in bacteria breaking down urea in urine and undigested protein in faeces. It is mainly a problem in housing systems where there is an accumulation of moist faecal matter, particularly in the pig and poultry industries [64].

There are few reports in the scientific literature on the ammonia concentration in sheep houses, with most studies involving cattle, pig and/or poultry housing. Phillips [99] monitored ammonia, carbon dioxide and hydrogen sulphide concentrations in naturally ventilated sheep sheds at an Australian pre-export assembly depot and found the concentrations of all three gases were below the recommended safety thresholds for humans and livestock. Kilic et al. [65] measured the ammonia concentration in a closed, mechanically ventilated sheep barn in Turkey and reported a mean ammonia concentration of 0.77 ppm in the intake air and 15 ppm in the exhaust air.

Groot Koerkamp et al. [47] surveyed the ammonia concentration in cattle, pig and poultry houses in England, The Netherlands, Denmark and Germany. The mean concentration of ammonia was less than 8 ppm in cattle barns, 5-18 ppm in pig sheds and 5-30 ppm in poultry sheds. In a number of pig and poultry houses ammonia exceeded the threshold of 25 ppm and was considered likely to adversely affect the health of both stockpersons and animals.

Seedorf and Hartung [115] recorded the ammonia concentration in livestock buildings in Germany and reported a mean ammonia concentration of less than 8 ppm in cattle barns, 9-16 ppm in pig sheds and 21 ppm in broiler poultry sheds.

Key factors affecting ammonia emissions are the temperature, nitrogen and moisture content of the manure, type of flooring, manure storage method and frequency of manure removal [82]. Ammonia emissions may be reduced with adaption of the housing design, especially the mode of manure collection and storage. Ammonia emissions can also be reduced by dietary manipulation and treatment of the bedding or manure [52] [69] [77] [78]:

- Lowering the crude protein content in the diet to decrease the urea-N substrate for ammonia production.
- Including salts in the ration to acidify the urine.
- Adding an agent such as gypsum to the bedding, to lower its pH.
- Acidifying the bedding and manure by spraying it with citric or acetic acid.

The dietary manipulation and bedding treatment strategies listed above often involve unacceptable productivity losses or are not practical or cost-effective for commercial livestock producers – unless there are regulatory or social licence constraints such as odour control [59].

The standard method of dissipating ammonia from an animal house is with ventilation and air exchange. In order to comply with regulatory requirements to reduce environmental emissions in Europe, and with urbanisation and odour abatement increasingly important, Melse [81] anticipates growing interest in end-of-pipe air treatments by the intensive livestock industries.

Air scrubbing to remove ammonia and odours from animal house exhaust air is proven technology used by some commercial pig and poultry operations in Europe [82]. Biotrickling filters have also been trialled experimentally [45] [135]. However, if compliance with regulatory requirements for ammonia emissions and odour are not an issue, the most practical and cost effective way to dissipate the ammonia from an animal house is by ventilation with increased air exchange.

3.3.4 Shipboard environment

The concentration of ammonia in the animal house has been an issue of concern on some livestock export voyages, and has been the focus of a number of livestock export industry research projects [27] [76] [99].

Phillips [99] monitored ammonia concentrations in the animal house air on two voyages with sheep exported from Australia to the Middle East in May/June and July 2005. Measurements were taken daily, at 20 sites over 12 days. At four sites the mean ammonia concentration for the voyage was more than 25 ppm. Ammonia was found at higher concentrations and was more widespread and persistent on closed decks than on open decks. Two of the four closed-deck monitoring sites had a mean ammonia concentration for the voyage above 35 ppm, which is the Short-term exposure limit (STEL) for humans set by Safe Work Australia [109], and on three days an ammonia concentration above 50 ppm was recorded.

Ammonia production occurs with microbial activity in a moist dung pad. With cattle, the source of ammonia emissions on a livestock vessel can be removed by washing the pens, provided the ship's trim allows washing and the vessel is at sea in an area where effluent can be legally discharged overboard.

On sheep vessels, the manure pad builds up during the voyage and is washed out after the sheep have been discharged. With cool and/or low humidity weather, the dung pad remains relatively dry. A dry dung pad provides good sheep comfort and low ammonia emissions. With hot, humid weather, the sheep dung pad can become a slurry. This is a result of increased water consumption and urine production by the sheep and reduced water evaporation from the dung pad. A warm, wet dung pad provides conditions favourable to microbial activity and production of ammonia. Air flow over the pen floor is a critical factor affecting dung pad moisture content [77].

With current ship designs, washing and/or physical removal of the dung from pens containing sheep is not practical. McCarthy and Banhazi [77] suggested a system of raised slatted flooring that would allow dung to fall through and be removed without needing to wash a pen containing livestock. This system might aid ammonia control from sheep pens, but would require a major re-engineering of the decks on vessels in the current livestock fleet. Another constraint is that the ship would not be able to dispose of the effluent in restricted waters.

In a land based animal house, ammonia emissions can be reduced by spraying or dusting the dung pad with acids, gypsum, lime and/or urease inhibitors. However, frequent application is required and the effects are modest and short-lived [52] [59] [78] [103]. Practical constraints also limit application of dung pad treatment technologies in a shipboard setting.

Ammonia emission can also be reduced by keeping dietary protein levels to a minimum and/or utilizing a more digestible form of roughage. However, the shipping pellets generally used in the live sheep export trade typically have a low crude protein content, which provides limited scope for further dietary manipulation.

At present, dissipation of ammonia from the animal house on a livestock vessel is entirely by ventilation, with reliance on a high air exchange rate. McCarthy and Banhazi [77] list suboptimal ventilation as a risk factor for elevated ammonia in an animal house. In a shipboard study, Phillips [99] reported a negative correlation between ammonia concentration and air movement, with the highest ammonia recordings behind the bulkhead at the front of the vessel and near the engine room. If the air exchange rate in the animal house on a livestock vessel is greatly reduced, an increased concentration of ammonia can be expected. This would have both animal welfare and workplace health and safety consequences. Keeping the concentration of ammonia in the animal house below an acceptable threshold will be a significant challenge for desiccant dehumidification or any other environmental control system that involves significantly reduced air exchange rates.

The air scrubbing technology being used in the pig and poultry industries in Europe is not relevant in a shipboard context, as air scrubbing is an end-of-pipe clean up procedure that removes ammonia and other noxious odours before exhaust air is released into the environment. Air scrubbing does not change the rate of ammonia production or dispersion from an animal house.

3.4 Other noxious gases and odours

3.4.1 Livestock housing

Methane (CH_4) is produced during ruminant digestion and with fermentation in the dung pad. It has a very low toxicity and in livestock housing does not pose a direct threat to human or animal health or welfare. However, there is increasing interest in methane emissions from livestock as a source of greenhouse gases, with a focus on annual methane emissions rather than the concentration of methane in animal facilities [50] [80] [113].

Carbon dioxide (CO_2) in a livestock house is mainly produced from animal respiration. The CO_2 concentration in animal house air has been studied intensively, as CO_2 is used to estimate ventilation flows [94]. Elevated CO_2 levels are an indication of low air exchange rates [48]. The concentration of CO_2 in outside air is typically about 380 ppm. Animal house CO_2 concentrations reported in the literature are typically less than 1,500 ppm. Safe Work Australia has set a short term exposure limit (STEL) for CO_2 of 30,000 ppm [109]. Carbon dioxide is relatively benign and in animal housing does not pose a direct threat to human or animal health or welfare.

Hydrogen sulphide (H_2S or 'rotten egg gas') is a highly toxic gas. It is mainly produced with fermentation in a moist dung pad. Humans exposed to 10-20 ppm H_2S may experience eye and upper respiratory tract irritation, and above 50 ppm H_2S may cause vomiting, nausea and diarrhoea. More than 20 ppm H_2S causes reduced feed intake in livestock [77]. Animal house H_2S concentrations reported in the literature are typically less than 2 ppm. Safe Work Australia has set a short term exposure limit for H_2S of 15 ppm [109].

Donham [34] cautions that ammonia, carbon dioxide, hydrogen sulphide and methane may accumulate in poorly ventilated areas and confined spaces, creating a human health hazard directly or by displacing oxygen.

Much of the public concern about noxious gases emitted from animal facilities relates to odour rather than any toxic effects of the emissions [34] [69] [81] [82] [102]. There are many odorous gases with a very low human olfactory detection threshold. They include ammonia, hydrogen sulphide and volatile organic compounds, especially those that have low carbon numbers and contain sulphur.

Liu et al. [69] provide a detailed review of the literature on animal house odour abatement, with an assessment of the practicality, effectiveness and cost of the various strategies available. There are three main approaches to odour mitigation:

- *Dietary manipulation*. Reducing the crude protein content of the diet reduces nitrogen excretion in the faeces and urine, which in turn reduces volatile gas production in the manure. A ration formulation that includes acidifying salts to lower urinary pH also reduces dung pad emissions.
- *Manure treatment*. The range of strategies includes physical separation of solid and liquid fractions from freshly excreted manure, chemical additives to acidify the manure, the use of slurry pit covers and anaerobic digestion with biogas production.
- *Capture / treatment of emitted gases*. Biofiltration and air scrubbing are used in the pig and poultry industries to remove odorous gases from animal house exhaust air. With biofiltration, contaminated air is passed through a filter which absorbs odorants and allows the growth of microbial organisms that utilize them. Air scrubbing is a similar technique, with odorous gases absorbed on a filter and washed off with acidified water.

3.4.2 Shipboard environment

The carbon dioxide (CO_2) concentration in the air on livestock vessels has been monitored extensively during ventilation research studies [72] [77]. CO_2 levels are generally low – less than 600 ppm. McCarthy and Banhazi [77] note that higher concentrations of CO_2 occur in less well ventilated areas, but are still well below levels that would affect human or animal comfort or cause ill-health.

Hydrogen sulphide has a pungent smell with a human smell detection threshold of less than 1 ppm. An elevated concentration of H_2S would readily be detected by seafarers. The absence of reports about hydrogen sulphide odours on livestock vessels suggests that it is not an issue of major concern.

Phillips [99] monitored CO_2 and H_2S concentrations in the animal house air on two voyages with sheep exported from Australia to the Middle East. Measurements were taken daily, at twenty monitoring sites. The atmospheric concentrations recorded (CO_2 < 1,500 ppm and H_2S < 1.7 ppm) were well below Safe Work Australia limits for human exposure [109] and were considered unlikely to pose a risk for livestock.

McCarthy and Banhazi [77] caution that seafarers have described symptoms of fatigue and shortness of breath after working in some of the more confined areas on a livestock vessel. This might be associated with pockets of poor ventilation, where oxygen is depleted and there is an accumulation of ammonia, carbon dioxide, methane and/or hydrogen sulphide.

This review of the literature suggests that if the ventilation system in the animal house on a livestock vessel can adequately disperse ammonia, then carbon dioxide, methane and hydrogen sulphide emissions are unlikely to be a problem.

3.5 Noise

3.5.1 Workplace health and safety

Irreversible hearing loss from exposure to work related noise is a significant health issue for Australians working in the agriculture, manufacturing and construction industries [33] [110].

Safe Work Australia is responsible for setting workplace noise exposure standards in Australia [110]. A key standard is an LA_{eq},8h of 85 decibels (dB). This is a time-weighted average maximum exposure limit for humans of 85 dB over an eight-hour working day. For work that demands attentiveness, or if it is important to carry on conversation, noise levels below 70 dB are recommended. Personal hearing protectors such as ear-muffs or ear-plugs may be used, but Safe Work Australia cautions that over-reliance on personal hearing protection increases the risk of noise-induced hearing loss, so control should focus on reducing the noise itself.
The International Maritime Organisation (IMO) has developed a *Code on noise levels on board ships* [56]. The IMO Code is intended to provide for safe working conditions on commercial ships, by protecting seafarers from noise levels which may cause induced hearing loss. The IMO Code is a mandatory instrument under the International Convention for the Safety of Life at Sea (SOLAS), to which Australia is a signatory.

The IMO Code sets a noise limit of 85 dB for 'non-specified work spaces', which would include the animal house on a livestock ship. The Code also states that personnel entering a work space with noise levels greater than 85 dB should be required to wear hearing protection whilst in that area.

3.5.2 Effects on animal health and welfare

The noise produced in an intensive animal house from the ventilation system, feed delivery and manure removal systems, and the animals themselves, is a potential stressor. However, there is little evidence in the literature to suggest that, under commercial conditions, animal house noise has an adverse effect on livestock health or welfare.

Assessing the impact of noise on livestock is more complex than just measuring the intensity or loudness of the sound (measured in decibels). The frequency of the sound (measured in Hertz) is also important, as other species have different spectrums of audible sounds, and may have maximum sensitivity at a frequency not readily audible to humans. The duration and pattern of the sound also affects the level of stress, if any, induced by the sound.

Brouček [17] provides a comprehensive review of the effects of noise on the performance, stress and behaviour of animals. Brouček concluded that livestock adapt well to repeated exposure to noise.

Quaranta et al. [101] exposed a small cohort of Merino lambs, in a controlled environment, to a recording which simulated road noise for eight hours daily, at 42-44 dB (controls) and test groups with 75 dB, 85 dB and 95 dB. For the rest of the day, the ambient noise in the animal house was 35-40 dB. The growth rate in the lambs in the test groups was slower than in the controls, but there were no differences between the groups in terms of cell mediated immunity or blood metabolites. Quaranta et al. concluded that noise in the 75-95 dB range did not severely impair animal wellbeing.

This review of the literature suggests that sheep health and welfare will not be adversely affected if the noise in an animal house meets human comfort requirements (< 85 dB).

3.5.3 Shipboard environment

The animal house on a livestock ship can be a very noisy place. The MAMIC ventilation investigation report [72] states *'While no noise measurements were taken, the levels were high in empty, reverberant ships and caused discomfort to 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.'*

Ventilation fans are the major source of noise in a livestock ship's animal house. MAMIC [71] provides a raft of recommendations on ways to reduce noise from the ventilation fans, with addition of attenuators and fine-tuning of the fan and ducting design and operation.

Noise of less than 85 dB is achievable on medium-sized cattle ships. Livestock Express has adopted a noise limit of 80 dB in the cargo holds of its livestock vessels. This noise level is only reached within two metres of the exhaust grills. Further away from the exhaust grills noise in the cargo holds typically drops to 76-78 dB [70]. This literature review did not find any quantitative animal house noise data for the larger vessels that export Australian sheep to the Middle East.

If a dehumidification system in the animal house on a livestock vessel significantly reduces the rate of air exchange required, there is likely to be a concurrent reduction in noise emissions. However, noise generated by the dehumidification system must also be taken into account. A reduction in noise intensity would enhance the comfort of seafarers working in the animal house, but have little effect on the animals on board.

3.6 Particulate matter (dust)

3.6.1 Workplace health and safety

Airborne particulate matter is classified as 'total dust', 'inhalable dust' and 'respirable dust', based on particle size. The classifications and recommended workplace limits are shown in Table 4.

Table 4. Classification of dust and recommended workplace limits

	Total dust	**Inhalable dust**	**Respirable dust**
Particle size	All particles suspended in the air	< 100 microns	< 4 microns
Penetration of the respiratory system	Contacts the nasal and oral mucosa	Inhaled through the nose and mouth	Penetrates to the bronchioles and alveoli
Potential human health issue	Allergies, sinusitis, irritation to the eyes and nose	Allergies, bronchitis, irritation to the eyes and nose	Impairment of the cardiovascular and respiratory systems
Recommended limit (Safe Work Aust) *		< 10 mg/m^3	
Recommended limit (AIOH) *		< 5 mg/m^3	< 1 mg/m^3

* Recommended limits expressed as an 8-hour time weighted average

The dusts of importance in agriculture are mostly insoluble or poorly water soluble dusts of inherently low toxicity. However, with exposure to excessive respirable dust, a person's lung clearance mechanisms can be overloaded. There is a well-established link between exposure to dust and short-term, reversible loss of respiratory function. Dust also exacerbates the effects of occupational exposure to ammonia. The combination of exposure to ammonia and dust is recognized as an occupational hazard for workers in the pig and poultry industries [6] [7] [35] [57] [107].

The Safe Work Australia airborne dust limit is not a mandatory standard [108] [109]. There is recognition that dust control is difficult in many working environments. The recommended limit simply provides a trigger for implementing 'reasonably practical' exposure controls.

The Australian Institute of Occupational Hygienists (AIOH) recommended limits for airborne dust are not mandatory standards either [7]. Rather, they provide guidance for industry and health professionals, based on a comprehensive review of the international literature.

The dust in an animal house includes airborne microorganisms and endotoxins [116] [77]. Q fever is a serious infectious disease of humans, with transmission from animals to humans via aerosols and contaminated dust. It is an occupational hazard for livestock industry workers, but Q fever disease risks can be effectively managed with vaccination [36].

3.6.2 Effect on animal health and welfare

The scientific literature includes reports of physiological changes in sheep and goats after controlled experimental exposure to dust [22] [100]. However, we did not find any compelling evidence that dust caused respiratory disease in small ruminants.

After reviewing the literature, Jones et al. [61] found no evidence to either support or contradict the theory that dust predisposes feedlot cattle to respiratory virus infections.

Ocular irritation from dust predisposes sheep and cattle to pinkeye infection [62] [67]. Pinkeye is a cause of animal welfare concern for sheep and cattle on some long-haul voyages, but the importance of shipboard dust as a risk factor for the disease at sea is unknown.

3.6.3 Livestock housing

Management of airborne particles in the animal house is a significant issue for the intensive pig and poultry industries [54] [122]. Much of the concern relates to the wellbeing of farm workers, environmental stewardship and dust-borne odours rather than animal health and welfare. Cambra-López et al. [18] provide a comprehensive review of particulate matter characteristics, concentrations and mitigation strategies for the pig and poultry industries.

Hoff [54] states that with intensively housed pigs, most of the airborne particulate matter (98% of inhalable dust and 94% of respirable dust) comes from the bedding and manure. By contrast, a large proportion of the dust in poultry sheds was reported to be feather material.

Dust mitigation strategies for intensively housed pigs and poultry focus on reducing sources of dust generation rather than removing airborne dust or dispersion by increasing air exchange [122]. Strategies to reduce sources of dust mainly involve feed pelleting and addition of oils to reduce respirable dusts of feed origin; and bedding management [6].

Carpenter and Fryer [21] found that air quality in a piggery can be enhanced by filtering and recirculating air to remove airborne dust. However, this is impractical with large livestock buildings which require a large volume of air to be filtered. Dawson [30] demonstrated that airborne particles in an animal house could be reduced with electrostatic precipitation. However, this technology also has practical limitations in a large animal house.

Pedersen et al. [95] report an investigation into particle movements in a mechanically ventilated piggery, using a computer simulation model with experimental verification. The location of the dust source and air turbulence were found to have a greater influence on particle concentration than the air exchange rate. Liao and Feddes [68] also developed a computer simulation model to predict airborne particle movement in livestock buildings. The relationships were found to be complex, with particle concentration, size, mass and buoyancy, type and location of the dust source, airflow characteristics, turbulence and animal activity all affecting particle movement within the animal house.

Wallinder et al. [130] found no difference in total and respirable dust concentrations after installing mechanical ventilation with increased air flow in a horse stables.

3.6.4 Livestock feedlots

Dust is a significant management issue for outdoor cattle feedlots [61] and confinement feeding systems for sheep [14]. The main focus is dust prevention and suppression, especially involving road vehicle activity and animal handling procedures, rather than ventilation to disperse dust.

3.6.5 Shipboard environment

Dust within the animal house is an issue of concern on some live export voyages. However, there is little information available about the concentration of airborne particles on livestock vessels. McCarthy and Banhazi [77] state that dust on livestock vessels may be underrated as an air pollutant and recommend further monitoring on sufficient voyages to determine typical dust levels under a range of scenarios.

There are two principal sources of dust on a livestock vessel – dust from a dry sheep dung pad and fodder dust ‘fines’.

Excessive dust from a sheep dung pad is only likely to be of concern if the humidity is low and the dung pad is dry. Fodder ‘fines’ occur when pellets fragment whilst being trucked, augured, blown on-board, and mechanically distributed from a feed silo on the ship to feed troughs in the animal house. Pellet durability is determined by the pellet components, screen sizes used to manufacture the pellets and the manner in which the pellets are handled [93] [134].

It is not clear what effect a dehumidification system with reduced air flow rate would have on the concentration of airborne particulate matter in a ship’s animal house.

4. Acclimatization to heat stress

4.1 Mechanisms of acclimatization

Sheep respond to heat stress with a combination of behavioural and physiological responses. Behavioural responses to minimize thermal stress include things such as reduced feeding, increased water consumption, greater frequency of drinking and actively seeking respite in shade, away from radiant heat, or in an area with better ventilation. Physiological responses include increased respiratory rate, peripheral vasodilation, increased sweating and a reduced metabolic rate [13] [44] [73]. These are short-term responses, mediated by the animal’s sympathetic nervous system.

Stockman et al. [119] [120] reported significant physiological changes in Merino wethers exposed to simulated live export heat stress conditions in a controlled environment animal house, with core body temperature and respiratory rates increased during periods of heat stress, open-mouth panting, decreased plasma partial pressure carbon dioxide and bicarbonate concentration and increased plasma pH. However, the sheep quickly recovered when conditions returned to thermo-neutral.

‘Acclimatization’ occurs with physiological changes that are mediated by the endocrine system and progressively come into effect over a period of days. Such changes include altered carbohydrate, lipid and protein metabolism [24] [25]. Acclimatization effects slowly decay when the initiating stressor ends.

Genetic traits which favour survival in a hot environment, such as a sleek coat with short fine hair, a higher density of sweat glands, less subcutaneous fat and smaller body size are the prime reason for breed differences in susceptibility to heat stress [13] [44]. They are long-term, permanent adaptions to the environment, not short-term acclimatization responses.

Acclimatization or lack of acclimatization to heat stress was recognized as a risk factor in the HotStuff risk assessment model developed for livestock exports to the Middle East [74]. The HotStuff model divides Australia into six acclimatization zones, based on historical wet bulb temperature data, with a different risk weighting for each zone. Animals are considered to be acclimatized to the zone from their property of origin, unless they have been at an assembly depot in another zone for more than four days. Animals at an assembly depot for 15 days or more are assumed to be acclimatized to the assembly depot zone. Animals at an assembly depot for 5-14 days are taken to be acclimatized to the average of the property of origin and assembly depot zones. In the absence of hard data for sheep, the HotStuff model uses the same acclimatization zone risk weightings for sheep as for cattle.

This literature review did not identify any original research to determine either the rate of sheep acclimatization after exposure to thermal stress, the rate of de-acclimation after cessation of thermal stress, or the effects of moving sheep from a controlled to an uncontrolled environment. However, there is some information for cattle and a large body of original research on human acclimatization to heat stress, derived from sports medicine, military and occupational health and safety studies [85] [97].

In a series of trials to investigate ventilation efficacy on livestock vessels, acclimatization of *Bos indicus* cattle was considered to account for variations in heat tolerance equivalent to a wet bulb temperature change of 2-3°C [72].

In humans, repeated exposure to thermal stress produces a range of acclimatization changes, including a lower core temperature during exercise, sweating at a lower body temperature, with less electrolyte loss, a lower heart rate with increased stroke volume, greater retention of muscle glycogen and lower muscle and plasma lactate concentrations during exercise [87].

The rate and extent of acclimatization to heat stress depends on the severity and duration of thermal stress. However, it is a relatively rapid process that begins on the first day of exposure, with about 75% of adaption in the first seven days [28] [92].

4.2 Relevance to the live sheep export trade

Great care must be exercised when extrapolating physiological findings from one species to another. However, in the absence of hard data for sheep, the findings from cattle and human studies may be cautiously interpreted in a live sheep export context.

It is reasonable to assume that, if sheep exported to the Middle East during the northern hemisphere summer are held on the vessel in anything other than a fully air conditioned animal house, they will arrive with at least modest if not strong acclimatization to heat stress.

After discharge in the Middle East, thermal stress will be largely determined by the weather and by the design and management of the destination feedlot – ambient temperature and humidity, availability of shade, exposure to radiant heat, stocking density, air flow across each pen, availability of cool, clean water, stock handling activities etc. The ventilation system on the ship is unlikely to have a detrimental effect on the sheep after discharge.

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