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ORIGINAL PAPER

Potential impact of ash eruptions on dairy farms from a study of the effects on a farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation

Thomas M. Wilson · James W. Cole

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Abstract This paper investigates the impact ash fall would have on dairy farming, based on a study of 'Tulachard', a dairy farming operation at Rerewhakaaitu, North Island, New Zealand. It includes analysis of the potential effects on the dairy shed and milking machine, electrical supply and distribution, water supply and distribution, tractors and other farm vehicles, farm buildings (haysheds, pump sheds, implement sheds, etc.), milk-tanker access to the farm and critical needs of dairy cows and farm to keep milking. One of the most vulnerable areas identified in the study was the cooling of milk at the milking shed, pending dairy tanker pick-up. The cooling system's condenser is exposed to the atmosphere and falling ash would make it highly vulnerable. Laboratory testing with wet and dry ash was conducted to determine its resilience to ash ingestion. It was found to perform satisfactorily during dry testing, but during wet testing significant clogging/blocking of the condenser's radiator occurred, dramatically reducing airflow through the condenser. Specific mitigation recommendations have been developed that include cleaning with compressed air and adapting farm management techniques to lessen usage of the condenser during an ash-fall event. Specific recommendations for management of dairy farm operation are given to mitigate the effects of an ash-fall event.

Keywords Ash · Dairy farming · Condensers · Testing · Mitigation

1 Introduction

The New Zealand dairy industry is one of the most productive and efficient in the world. Lush pastures, temperate climate and well-established industry infrastructure create a world-class dairy industry (http://www.fonterra.com), and in 2004 dairy products made up

T. M. Wilson · J. W. Cole (✉)
Natural Hazards Research Centre, University of Canterbury,
Private Bag 4800, Christchurch, New Zealand
e-mail: jim.cole@canterbury.ac.nz

17% of New Zealand total exports (~$5.0 billion; http://www.mfat.govt.nz). Fifty percent of New Zealand's dairy farming operation is located within a 150 km radius, but particularly to the north-west of, the volcanically active Taupo volcanic zone (Fig. 1), suggesting the industry has significant exposure to volcanic risk in this region. Dairy farming also occurs near volcanoes in many other parts of the world (e.g. United States, Chile, Ecuador), and would experience similar risks. This study investigates the impact ash fall from small to moderate sized explosive eruptions would have on dairy farming operations in the central North Island of New Zealand, in particular to assess the susceptibility of a typical dairy farm's infrastructure, machinery and operational processes to the resultant ash fall. The range of issues outlined, and recommendations for mitigation, are however applicable to all comparable dairy farms around the world. In event of a large eruption, emphasis would inevitably be on recovery and land rehabilitation, which is beyond the scope of this paper.

1.1 Taupo volcanic zone

The Taupo volcanic zone (TVZ) extends from White Island to Ruapehu across the central North Island of New Zealand (Fig. 1), and is one of the most active rhyolitic centres in the world (Wilson et al. 1995). The broad range of volcanism in the Zone means that the magnitude of possible eruptions range from minor andesitic events (such as the 1995–1996 Ruapehu eruptions, which had a notable effect on agriculture in the region), to a plinian rhyolitic event that could potentially eliminate human settlement in the central North

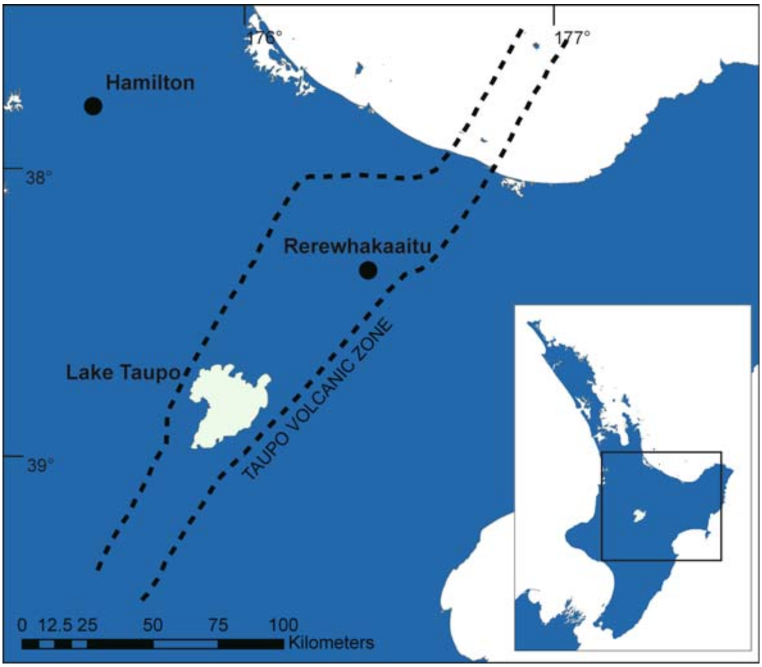

Fig. 1 Location of Rerewhakaaitu, eastern Taupo volcanic zone

Island for a time. Ash[1] can be deposited hundreds to thousands of kilometres from its source, making it the product that may affect the largest area and the most people during an eruption.

Intensive farming has only taken place in TVZ for the last 100 years (Keam 1988), so there is limited historic data on the effects of ash fall on intensively farmed land for agricultural production. Where volcanic eruptions have affected agricultural land in recent history, the depth of ash has usually been <50 mm and produced only a moderate impact (e.g. Chaplin and Braatne 1986; Cook et al. 1981). Suggested impacts of larger eruptions are conjecture and extrapolations of impacts from eruptions such as those at Mt. St. Helens, Mt Ruapehu and Hekla (e.g. Johnston et al. 2000).

A dairy farm at Rerewhakaaitu, SE of Rotorua (Fig. 1) was used as the basis of the study.

1.2 Study farm

The study farm, known as 'Tulachard', is located on Brett Road, Rerewhakaaitu, bordering the western shore of Lake Rerewhakaaitu, and is owned and operated by Mac and Lynda Pacey. The farm covers 116.7 hectares (ha) and has 350 cows in two herds, supplemented by a 24 ha 'run-off' block rented for the purpose of supplementary feed production and extra grazing area. It is considered a typical, modern dairy farm for a temperate region. Modern dairy farms share common requirements throughout the world, requiring abundant and secure water supplies, electricity to run the milking machine and sufficient area for farming operations to occur. This allows comparison between material presented here and international examples.

The chief economic activity of the farm is to sell milk to Fonterra, the largest dairy cooperative in New Zealand. This only occurs if dairy cows can be milked, the milk stored for up to 24 h, and the milk tanker able to access the farm to pick up the milk. Scenarios that would stop milk being delivered to Fonterra from ash fall hazards would be inability to milk (e.g. power failure, roof collapse, inability to clean the milking shed, too much pressure on the dairy cows), if the milk cooling system were to shut down (i.e. condenser damaged) or if the roads and/or farm tracks were blocked inhibiting the milk tanker to get access onto the farm.

Following significant ash fall, pasture recovery is perhaps the single most important long term rehabilitation step for a farm to take. However, if the farm can continue economic activity throughout any eruption, the eruption's impact to the farm as an economic entity will be reduced.

It is important to note that the use of only one farm in this study may result in some bias and limitations in the hazard analysis as each farm will present its own site-specific challenges and complications if affected by ash fall.

[1] Strictly speaking the material deposited is 'tephra', as it is likely to be of a greater size range than 'ash', but for the purposes of this paper the term 'ash' is used in a general sense for all unconsolidated pyroclastic debris.

2 Potential volcanic hazards to the farm

The farm is located near the centre of the TVZ making ash fall a significant risk to operations from any eruption in the TVZ. How badly the farm will be affected will depend largely on which volcano is erupting, wind direction, eruption type, magnitude of eruption, the local topography in the vent area and duration of the eruption (Blong 1984; Nairn 1991, 2002).

It is globally recognised that it is extremely hard to predict exactly where and when a volcano is next going to erupt with sufficient warning to completely prepare for the event (Blong 1984; http://www.maf.govt.nz). The only really safe way to protect people and their livelihoods from the hazards of volcanoes is to remove the people themselves. But the reality is that people have chosen to farm in the shadow of active volcanoes and thus accept the risk this presents (Paton 2000). This is largely because volcanic soils are good for pasture growth.

2.1 Okataina

The main risk to the farm is from an eruption centred on the Okataina Caldera Complex (OCC; Cole et al. 2005; Spinks et al. 2005), located approximately 5 km to the north. OCC is the most recently active of the young rhyolitic eruptive centres in the TVZ and one of the most active, having erupted ~ 80 km^3 of rhyolite magma and ~ 1 km^3 of basaltic magma in 11 distinctive eruptive episodes from over 40 vents in the last 22 ka (Nairn 2002). The farm has been heavily affected by Holocene eruptive episodes from the OCC, which represents the greatest volcanic hazard to farming operations due to its proximity and highly active nature (Table 1). The average return interval between major eruptive episodes during the past 22,000 years at OCC has been 2,090 ± 770 years (Nairn 2002).

Table 1 Eruptive episodes of the Okataina Caldera Complex (OCC) of the last 22,000 years[a]

Eruptive episode[b]	Age (ka)	Lava volume (km^3)	Pyroclastics volume (km^3)	Eruptive centre
Tarawera Basalt	1886 AD	–	2	Tarawera
Kaharoa	0.7	2.5	5	Tarawera
Rotokawau Basalt	3.4	–	0.7	Haroharo
Whakatane	5	9	10	Haroharo
Mamaku	7.5	15	6	Haroharo
Rotoma	9	2	13	Haroharo
Waihau	11	4	15	Tarawera
Rotorua	13.5	1	7	Haroharo
Rerewhakaaitu	15	2	6	Tarawera
Okareka	18	5	6	Tarawera
Te Rere	21	10	5	Haroharo
	Total	40.5	75.7	

[a] Taken from Nairn (2002)

[b] All eruptions are rhyolitic unless otherwise stated

The probability of a further eruption from Okataina, using an equation proposed by Dibble (1965) is 4.7% in 100 years (Nairn 2002). This however assumes the post-22,000 sequence is a random sequence, which is considered unlikely (Table 1; Nairn 2002).

2.2 Taupo

The rhyolitic Taupo volcano (TV) is the most frequently active and productive rhyolite volcano in the world (Walker 1980; Wilson et al. 1995), with a major event at 1.8 ka (Wilson et al. 2004). As such it is reasonable to predict that TV will erupt again in the future and will be a significant threat to the farm in terms of distal ash fall hazards. This would cover the area with fine to coarse ash and fine lapilli, likely to be the grainsize variation in any air fall deposits. The farm received ~40 cm of ash from the 1.8 ka 'Taupo Eruption' (Cole 1970), an eruption estimated to have lasted from days to weeks (Wilson et al. 2004).

2.3 Tongariro

Volcanoes within the Tongariro Volcanic Centre have erupted frequently within historic times implying that this will also continue in the near future and the farm is within the likely ash-fall hazard zone with south-south-westerly wind conditions. Many dairy farms in the Bay of Plenty experienced ash fall with the 1995/1996 Ruapehu eruptions. Whilst the farm did not experience any ash fall during the event, only a slight variation in wind direction would have covered the farm (Cronin et al. 1997). As an andesitic centre, eruptive activity would be on a much smaller scale; however the higher frequency with which it erupts suggests ash fall from this centre is perhaps more likely to affect the farm than a more infrequent rhyolitic eruption.

3 Hazard assessment of the farm

3.1 Farm seasonality

The farm is a typical New Zealand dairy farm with different farm operations carried out at different times of the year, mainly as a result of the seasonality of New Zealand's climate. This would however be applicable to any farm in a temperate area. A general guide to the annual farm operation is illustrated by Fig. 2. This shows that an eruption in early spring (i.e. September in the southern hemisphere) would have the greatest impact on the farm. Milk yields would be severely depressed, especially with cows under considerable stress during calving and beginning lactation. This would carry over for the whole lactation, and lack of (or reduced) spring growth from ash cover on pasture will cause major feed shortages (Neild et al. 1998). October to November would also be a period of vulnerability with supplementary feed reserves at their lowest and peak milk production. The peak production period creates high energy demands on the cows, requiring consumption of large volumes of feed. It is the time the farm normally makes a significant percentage of its economic income. Some of this vulnerability would be lessened as some pasture is not used for herd consumption at this time, but saved for grass silage production (4–8 ha at the farm and 15 ha at the 'run off'). The pasture in these paddocks will be denser and taller than

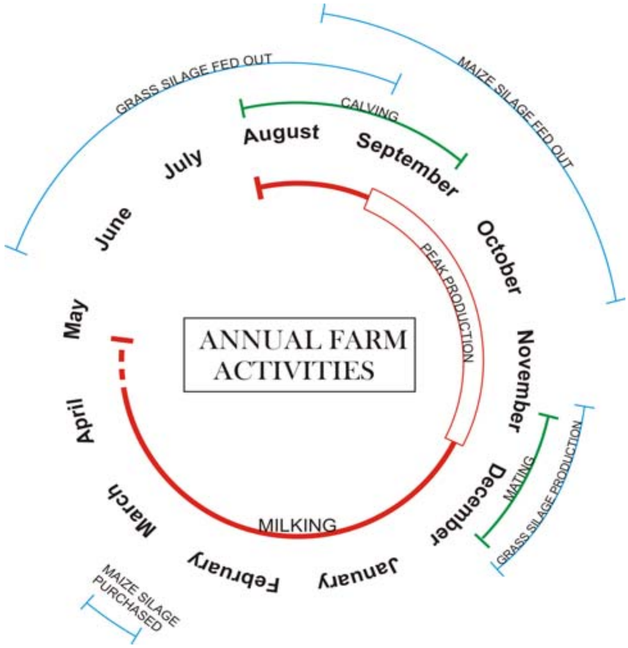

Fig. 2 The annual farm activities at the farm shows the key vulnerable periods during the year of farming operations. The farm's most important activities are closest to the centre, with activities of decreasing importance progressively further out from the centre

other paddocks on the farm and better able to survive light to moderate ash falls (<50 mm). Much of this would all be located at the 'runoff' however and the cows would need to be walked the $\sim$10 km, creating animal health issues in the event of an eruption (i.e. hoof abrasion, eye and respiratory irritation; Neild et al. 1998). The cows could be self-fed from the maize bunkers (Fig. 3), although maize silage must be supplemented with other feed due to nutritional requirements. Whilst this would result in a lot of waste it may be acceptable under survival conditions.

It would be unlikely that farmers would be able to buy any supplementary feed at this time as any regional reserves would have been mostly used up, although 'meal' may be available depending on how much is stockpiled by farm supply stores.

It is important to note here that Northern Hemisphere farms usually winter their cows inside barns, whilst Southern Hemisphere farms keep their dairy herd on pasture all year round.

3.2 Milking shed

The milking shed is the hub of the farm (Fig. 3). Two herds of cows are milked twice daily for most of the year, with the milk picked up daily by tanker for sale to Fonterra. If the milking shed was to cease operation the farm's economic viability would be severely threatened, making it one of the most important and vulnerable areas of the dairy farm. Four main areas of vulnerability were identified that would affect the milking shed's ability to operate:

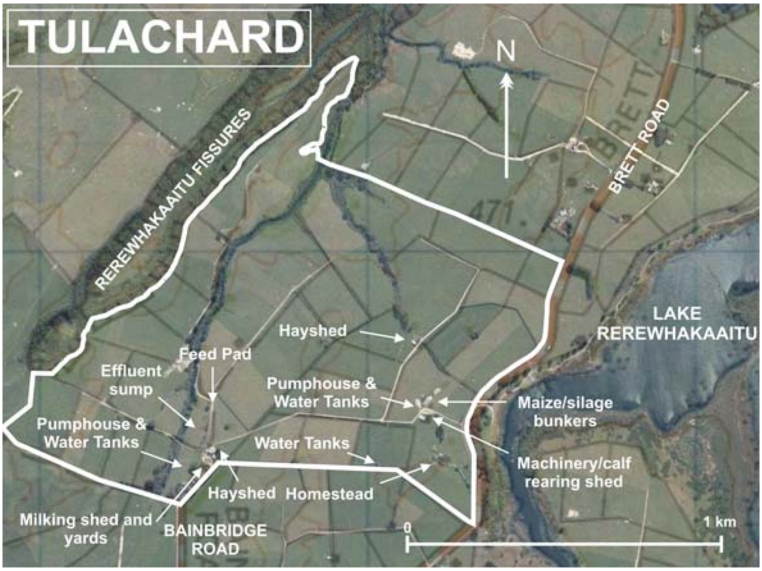

Fig. 3 This aerial photograph shows the boundary and infrastructure layout of the farm

(1) Loss of electrical power
(2) Ash damage of the milk cooling system.
(3) Roof collapse
(4) Inability to remove/clean ash and animal excrement from milking shed (loss of water supply)

The effect of ash fall on buildings depends on thickness, mass and its chemical reactivity, the building's roof shape, construction and orientation and the spacing of other buildings near by (Johnston et al. 2000). Light to moderate ash falls will cause less damage to buildings than those greater than 100 mm thick (Blong 1984).

3.2.1 Operation

The milking shed is a 24-station herringbone system, the operation of which depends entirely on electrical power, with water used at the end of milking to wash down the equipment and holding pad. A typical milking usually takes 3.5 h. The cows are brought in from the paddocks in which they have been grazing and contained on the holding pad where 280 can be accommodated. Cows are milked 24 at a time. Cups are put on the cow's teats and pulsators driven by filtered compressed air stimulate the teat to milk it. The milk is pumped from the cups to a receiving can along individual lines, and is filtered to catch impurities in the milk. The milk then passes through a heat exchanger (cooling provided by a condenser) which chills the milk and into the storage vat.

3.2.2 Ash hazards to the milking shed

The milking shed is completely open to the north and ash would easily enter the building from any eruption sourced in the OCC. This would cause problems to humans, cows and equipment, if milking continued during that eruption. Ash in the milking shed would decrease the quality of the working environment and cause health hazards to humans and animals alike. It would be a major irritation for the cows, potentially causing the on-set of mastitis (a condition of inflammation of the teat which can lead to an infected udder, spoil milk production and even lead to death), and making them harder to deal with due to their distressed and irritated state; it would also get onto the teats of the cows, and dirty the milking cups between milking. Mitigation of this would be to simply wash the ash off teats before milking. If ash was not cleaned from the cups or cow's teats it may enter the pump and milk storage equipment of the milking shed. The ash could damage the pumps due to its highly abrasive nature, block the milk filter or get into the milk storage vat. Any ash in the milk to be sold will lower the quality, reducing the price paid for it. Depending on the severity of the ash contamination in the milk it may be refused by Fonterra. If the air filters on the pulsators were blocked by ash in the milking shed, the cups would be ineffective until the filters were cleaned. The abrasiveness of ash may damage the pulsators stopping milking. It may also allow ash to mix with harvested milk.

Once ash is in the milking shed it is hard to remove. The conventional method used to clean the shed is high pressure water sprayed to remove animal waste and dirt. This would be less effective against the ash, simply turning it into a sticky paste and water may need to be preserved if electrical power supplies were down. It would be a better practice to lightly wet the ash and then shovel the ash out. This would increase the milking time and increase the physical and time demands on the farmer, both important considerations during the stressful period of managing an ash fall. Wet, sticky ash would also probably block milking shed drains, as discussed later in Sect. 3.2.6.

The milk pump and pump computer are all well cased and housed under the cover of the roof in the centre of the shed and should not be affected. The compressor, filter and milk storage vat are all housed in a walled wing of the milking shed and the milking system, with associated computer and electrical system, is well contained in the middle of the milking shed. The latter is well sealed, so it is unlikely ash would affect them. However if ash were to get into these critical electrical systems it could lead to short circuiting and fires. Gordon et al. (2005) demonstrated that computers are vulnerable to damage when the ash is wet.

3.2.3 Roof collapse

Roof collapse in a thick ash-fall event is of concern to all the farm buildings. Field observations and testing data from Spence et al. (2005) suggests collapse is 80% for ash loads of 2–7 kPa. A guide to tephra load is given in Table 2, where five samples of Kaharoa ash (most recent rhyolitic eruption in New Zealand, 1315 A.D.) with an average bulk

Table 2 Maximum possible ash loading from 'Kaharoa' ash fall

Max. possible ash thickness (mm)	Loading dry ash, no wind drifts (kPa)	Max. loading dry ash with wind drifts (kPa)	Loading wet ash, no wind drifts (kPa)	Max. loading wet ash with wind drifts (kPa)
300	4.4	8.8	5.9	11.8
150	2.2	4.4	2.9	5.9
75	1.1	2.2	1.5	2.9
50	0.7	1.5	1.0	1.9
25	0.4	0.7	0.5	1.0

density of 1,500 kg m^{-3} and an approximate wet density of 2,000 kg m^{-3} expected maximum values for roof loading (in kPa) from future ash falls are presented. Note that wind-drift represents ash that has been blow by the wind and concentrates on particular parts of the roof, forming drifts (an assumption has been made here it that represents twice the thickness of undisturbed ash fall, after Johnston 1997).

The table demonstrates that ash thicknesses >150–300 mm (depending on moisture content) are sufficient to cause roof collapse, a thickness exceeded by most of the Holocene eruptive deposits mapped on the farm. The parameters that determine whether collapse will occur are: thickness of ash, density of ash (including whether it is wet or dry), building's orientation, wind direction/speed and building's construction. This includes the pitch of the roof, cladding materials, structural support of roof and walls, and the span of the roof. Long span buildings (>5 m) will suffer more damage than short span domestic scale construction (Spence et al. 2005); which will have implications for the milking shed and other farm sheds. Collapse may not be constrained to the roof buckling or rupturing; it may be the supporting walls that fail too.

Wind will also influence accumulation of ash on the roof, causing drifts to form and uneven loading, causing loads up to two times greater than that of the ground load (Blong 1981). Pre-existing drifts that are subsequently wet by rainfall may cause collapse in buildings that have otherwise survived dry ash loading. It is thus desirable to regularly clear ash from all roofs across the farm, especially if there is risk of rain. This would be impractical on the farm as seven roofs would need to be cleaned, so only key buildings could be done. These in order of priority would be the homestead, milking shed, water-pump sheds, and haysheds and implement shed (Fig. 3). Injuries are commonly reported when cleaning ash off roofs, such as falls from ladders and roofs (Spence et al. 2005), so extreme care would need to be taken by whoever cleans the roof. This risk of injury is increased when cleaning is undertaken during an ash fall given the reduced visibility.

The milking shed will be particularly susceptible to collapse in a moderate to heavy ash fall due to the shallow nature of its roof pitch at $\sim 10^{\circ}$. However, the galvanised iron used in the construction of the roof at the farm has a low friction coefficient and should be relatively effective at shedding dry ash (Blong 1981). The pump, filter and vat wing of the shed may result in some drifting of ash, causing addition loading and difficulty in cleaning.

3.2.4 Spouting and guttering collapse

Spouting and guttering are a common point of failure during even light ash falls. Ash is washed into roof guttering, blocking it and causing collapse. Several houses experienced guttering failure during the 1995–1996 Ruapehu eruptions (Johnston et al. 2000). Removal of guttering on the homestead would be advisable once ash began falling. This not only minimises damage to guttering itself, but also allows ash to more easily slide off pitched roofs as it stops build up on the edge of the roof (Spence et al. 2005).

3.2.5 Condenser

Maintaining high milk quality is paramount for modern milk producers, with Fonterra requiring high quality standards to be met for milk to be accepted. It is therefore essential that dairy farms are able to continue to chill milk on-farm. The practice of cooling milk 'on-farm' has been standard practice for most New Zealand dairy farms for the last

30 years, and now in most modern dairy farms in the developed countries, such as the United States and in the European Union (EU; http://www.fonterra.com). Condensers allow the time between on-farm milking, and transport to the dairy processing plant to be significantly greater than in the past. Temperature is the greatest single factor affecting bacteria growth and reproduction, and food deterioration (http://www.delaval.com). By lowering the temperature of stored milk, chemical processes and microbiological growth slows, maintaining the quality and extends the time it can be stored until milk tanker pickup.

Keeping milk refrigerated is the operation of the milking shed's refrigeration system. A key aspect of this is the condenser, which acts as a heat exchanger taking heat away from the milk and into the atmosphere outside the milking shed by sucking air through radiators, allowing the air to take away heat (note a detailed description of the cooling systems has not been attempted here; rather it has been limited to the function of the condenser). Condenser units on dairy farms are mounted outside to get the best temperature contrast in the air sucked through it and so are particularly vulnerable to sucking in falling ash. As one of the most vulnerable pieces of equipment at the farm milking shed the condenser was tested to find out the effects of ash on its performance (results given in Sect. 4).

Current recommended mitigation techniques are derived from guidelines for air conditioning condensers. The same techniques can be assumed to apply here. Damage can be prevented by turning off air-conditioning systems before an ash fall begins or immediately at first signs of ash fall. However this is not economically acceptable for dairy farming situations (FEMA 1984).

A typical dairy farm cooling condenser has exactly the same function as an air-conditioning condenser, which is recognised as vulnerable to ash fall. (Gordon et al. 2005). The abrasive and mildly corrosive nature of ash can damage air conditioning units and has occurred in a number of instances with modern eruptions (e.g. Mt. St. Helens 1981; Mt. Pinatubo 1991). Units are vulnerable to fine ash clogging and abrading the condenser's radiator, and (if left long enough) dissolving unprotected surfaces within the unit. Each impact causes a reduction in the efficiency of heat exchange and could cause potential failure.

The farm's condenser is located on the western side of the milking shed facing south, away from the direct danger of the OCC, but susceptible to eruptions from the south (e.g. Taupo and Tongariro). As part of the general milk cooling system, the condenser is supplied and serviced on a 12 monthly basis. It is approximately 10 years old and has a large amount of redundant capacity. The previous condenser is still installed and while no longer used would act as a back up.

The condenser is necessary for refrigeration of the milk to keep it hygienic in order to be saleable for more than a day. If the condenser fails, milking would continue but the milk would need to be discarded. This would keep the cows lactating, avoiding health issues and allowing the potential for full scale milking operations to continue once the condenser was repaired. The time milking takes place can be adapted so milk does not have to be warm in the tank for more than several hours before the milk tanker arrived for milk pick up (assuming the milk tanker can still operate).

Ash-fall hazards for air conditioning units are usually avoided by completely shutting the systems down, however this mitigation measure is impractical on an ordinary dairy farm (without causing major disruption) as the farm must continue to sell milk to remain economically viable.

3.2.6 *Effluent sump*

The effluent sump is located beside the milking shed to allow animal effluent washed from the milking shed to settle out of the washing water. The remaining water is then sprayed onto paddocks. In normal operation the sump occasionally blocks with silt. Ash suspended in water from washing down the milk shed and concrete holding pad would almost certainly have a similar effect, blocking drains, and damaging the sump pump. The grills covering the drains at the milking shed would stop big clasts and some consolidated wet ash from entering the pipes, but may block as a result causing flooding, so would need to be regularly cleaned during wash down. If the pipes were to block with ash, removing ash from them would be a difficult, time consuming and costly effort. Ash fall on the surface of the sump pond would increase the concentration of suspended ash, increasing the possibility of blocking the outlet of the sump. Any suspended ash within the sump pond would probably cause the pump to fail. Ash entering the sump is likely to increase the acidity and turbidity of the water, but would probably not restrict the usual practice of spraying the water on to paddocks, assuming there were no blockages in the pipes, and pump was still operational; conditions considered unlikely by Neild et al. (1998). This would be similar to problems that waste water systems and sewage treatment plants face during ash falls, but on a smaller scale.

Failure of the effluent sump drains would result in cleaning water and animal effluent generated at the milking shed following the surface drainage routes into the gully to the west. Localised flooding may occur around the milking shed, including the holding pen, track, lower elevation paddocks and possibly the feed pad, creating a major inconvenience with wet ash forming a sticky mud-paste. If this were to occur in winter with the water-table near the surface, effects would be intensified making conditions difficult for human and animal movement.

To avoid blockages the best practice would be to remove as much of the suspended ash and effluent sludge with the tractor's frontal attachments (bucket and blade) and/or shovels, and then wash away the remaining deposits which are hopefully small enough in size and volume not to cause blockages.

3.3 Electrical supply

Power is critical to the normal operation of the dairy farm. It supplies the milking shed, the homestead, water pumps and electric fences. The loss of power to the milking shed would mean that the electrically powered milking pumps, water pumps, pump computer and cooling system would not operate, resulting in the complete inability to milk. Once electrical power was lost any stored milk from a previous milking would no longer be chilled, potentially needing to be dumped depending on when the milk tanker next arrived. There would also be a loss of artesian water pumps, and hence the ability to refill the water storage tanks located around the farm. If the fences are not electrified the cows are likely to push through if hungry, as is likely to be the case with pastures coated in ash.

3.3.1 *Electrical power supply to the farm*

The farm's electrical power is supplied on domestic supply lines, with smaller insulators more likely to experience insulator flashover. Two sets of lines supply the farm, supplying separate areas of the farm with no connection between the two (the homestead and eastern pump are powered by a different set of lines to that of the western pump, milking shed and worker's house). The double connection creates some resilience if in an eruption one line was to go down, although there is no connection between.

Both sets of power lines are very old. It has been recommended by the power supply company to replace them, but the cost is prohibitive. Due to their degraded condition there is an increased risk they may break due to the extra weight of ash on the lines and poles. This would be even more applicable to the mud erupted in phreatomagmatic eruptions, with its stickier, moister nature making it more likely to adhere to transmission lines.

In the event of power loss it is possible the milking machine could be run on 12 V batteries. The batteries could be sourced from and recharged in a vehicle (such as a tractor or pick-up truck), as long as the engine can still operate. This would at least keep the cows lactating, and thus be an asset to the farm when power is restored, even if the milk has to be dumped with no way to filter, cool or store it without mains power. It would also be beneficial to the health of the cow, avoiding mastitis. The loss of power to the homestead would be of concern with dependence on electric heating and cooking. However, contingency measures have been undertaken in previous power outages with no significant disruption and the house is ''well insulated'' (M. Pacey, pers comm. 2004).

3.3.2 Effect of ash on electrical distribution systems

The most common problems caused by ash are supply outages from insulator flashover, line breakage (weight of ash and ash laden trees falling onto the lines) and controlled outages during ash cleaning (Heiken et al. 1995; Johnston 1997). Heavy rainfall eliminates the ash build-up problems by washing the ash away, but creates other problems; the risk of flashover is greatest if light rain occurs during an ash fall (Heiken et al. 1995).

Substation insulators are more vulnerable to flashovers than line insulators, because of their shape and orientation, so it is likely the regional electrical distribution network will fail at critical nodes creating widespread outages during moderate to severe ash falls. This will cause large disruption to the dairy industry's ability to operate, even if farms are not affected by ash. Electrical distribution companies must communicate when power will be restored, or when controlled outages will be necessary for cleaning, critical for dairy farmers to plan when they can begin milking again or whether it is better to dry off the cows (i.e. stop milking and the cows stop lactating).

Electrical storms are commonly associated with ash falls due to the static build up from ash particles interacting. This creates lightening strike hazards for electrical supply networks. This was observed in the Tarawera area during the 1886 eruption, with telegraph poles and lines struck, cutting communications (Smith 1886). Such strikes also occurred during the 1980 Mt. St. Helens eruption and during the May 1924 Kilauea eruption, when 21 consecutive poles were hit (Blong 1984).

3.4 Water supply

Water is critical to any dairy farm. It is required for consumption by stock (drinking water) and is used in large amounts for washing down the milking shed and associated structures to keep them in an hygienic and acceptable working environment. Where there is a significant ash fall, uncontaminated surface water would be in short supply, with natural surface water supplies and dams contaminated, and pump functions severely reduced by the abrasive nature of the ash (Neild et al. 1998). The farm however has two artesian pumps servicing the farm's water supply needs, including the homestead. They consist of a submersible pump in a bore supplying four 22,500 l tanks and simply keep the tanks full. Currently the eastern pump supplies all troughs on the farm and the homestead, whilst the western pump supplies water to the milking shed, but the two can be merged into one system if need be. The key vulnerability of this system is the reliance on electrical power to access fresh water. If electrical power was cut to the farm, there is the potential to set up gravity fed troughs from the tanks, which stock could access water from. This could give several days worth of water to the herds, depending on climatic conditions. The amount of water that would be consumed by the cowherds is largely controlled by weather conditions. Dry and hot conditions would mean the cows are each drinking 40–50 l of water daily equating to 17,500 l for the herd. Cold and wet conditions would mean a minimal amount of water is consumed with the cows deriving hydration through pasture consumption. The lack of water for washing down the milking shed has been noted above as a key issue for the successful operation of the milking shed.

Ash fall would contaminate the uncovered 350 l stock-water troughs in each paddock, causing problems as cows drank suspended ash and any aerosols dissolved within the trough water, potentially leading to poisoning. The remedy for this would be to clean the ash out of the trough and replace the water regularly (adjusting the buoy-cock so the troughs are refilled to a lower level would mean less water needs to be replaced, but may alternatively concentrate harmful aerosols if left too long); again this would be time consuming, especially in remote paddocks. A management option would be to cover and disconnect troughs from the farm water supply in paddocks not containing stock. This would be an important but difficult task as it involves getting out to the paddocks and then working with wet ash. Lake Rerewhakaaitu could be used as an emergency water option; however it would be filled with suspended ash from direct fall and drainage systems.

3.5 Ash on concrete surfaces

Fine grained, moist ash will be a problem if it coats key areas such as the feed pad and milking shed holding pen (Fig. 3). Every effort should be made to remove dry ash from critical areas before there is any chance that it is moistened.

The bucket attachments for the tractor would be extremely effective at removing ash from the flat concrete pads. It would also be able to clear farm tracks of ash and create new temporary tracks through paddocks if need be. Creating temporary tracks through paddocks is common practice during winter when mud becomes an impediment to moving stock. If the ash is dry it can be given a light covering of water to dampen it before mechanical movement with the tractor, making it slightly more cohesive (Blong 1984) which would settle the dust (creating less of a hazard for the tractor and its driver) and make the ash easier to pick up or grade. If the ash was wet this would make it more difficult to move, but these implements should still remove enough of the ash to achieve a relatively clean concrete surface.

3.5.1 Dairy shed

Hygienic and clean conditions in the milking shed are required by processing companies to ensure milk is of a high standard (http://www.fonterra.com). It is therefore a requirement to always keep the shed clean. Any ash would therefore need to be removed before milking. In a crisis situation where cows are being milked simply to keep them lactating and in a healthy state, with milk not necessarily stored for collection, it would still be preferable to have the shed clean. Cows react better to a clean environment, and the milking shed operators find it less stressful to do their job in a clean milking shed.

3.5.2 Feed pad

The feed pad (Fig. 3) was built in 2001 with the intention of creating a mud-free feeding surface for the winter. The close proximity to the milking shed allows all key operations to be constrained to a small area of the farm, reducing the time the tractor would have to travel in the ash fall conditions, and travel time for humans and animals to the milking shed. With pasture covered by ash, stock survival in the short term would be dependent on the ability to feed up to 100% of their diet in supplementary feed; until they could be evacuated out of the area, slaughtered or pasture re-established. Following ash falls from Ruapehu in 1995, farmers on the Rangaikei Plains noted grazing animals were readily put off their feed by light (<3 mm) ash deposits. Hence, even with very light deposits of ash, supplementary feed would be required (Neild et al. 1998). The ability to provide supplementary feed to stock is thus critical to keep cows alive and lactating if milking continued. Animal excrement is able to be pushed off the pad by frontal attachments to the tractor. During ash fall the pad's flat surface could be graded clear of ash by the tractor (assuming it could operate) with a frontal attachment and the feed troughs cleared by shovel, so supplementary feed could be distributed on a relatively clean surface, reducing the impact on animals (ash/aerosol ingestion with their feed, abrasion to their feet/hooves). This feature makes the feed pad an excellent medium upon which to distribute supplementary feed and is likely to be a significant part of the farm's response to an ash fall.

It is important to note that the physical removal of the ash from buildings, yards, tracks, etc. will be difficult due to the large quantity of ash. The gullies have been identified as an option to dump the ash in. However, this may cause drainage problems with damming of water ways a potential resulting hazard. An alternative option is to dump ash in a paddock, creating a stockpile. Any dumping sites would need to be stabilised (top soil added and seeded with grass) to prevent reworking (Tilling et al. 1990).

3.6 Mobility

3.6.1 Vehicles

Fine ash clogs air filters, blocks radiators, causes mechanical wear or abrasion on moving parts, and may cause brakes to fail (Blong 1984; Johnston et al. 2000). These problems can lead to engines overheating, a reduction in engine life, and potentially cause engine failure. These impacts would be disastrous as the tractor is likely to be the only vehicle on the farm that could operate due to its 4-wheel drive capability. Supplementary feed (grass and maize silage) is also fed out by the tractor and towed silage wagon.

The tractor is serviced regularly to the manufacturer's recommendations by a trained mechanic, and can be expected to be in good condition at any time of the year. However an increased maintenance schedule should be carried out on the tractor, and all other machinery expected to operate during and after ash fall. During ash fall the tractor should not be used unless it was critical. If operation did take place, its radiator and air filters should be cleaned with compressed air every 30–60 min depending on the severity of the ash fall, however the radiator and air filter should be monitored regularly during use (http://

www.ak-prepared.com/plans/mitigation/volcano.htm). Even when ash fall has stopped, care for the engine should be paramount when operating on unconsolidated ash deposits, as these can be stirred up by vehicles, wheels and mechanical removal (Tilling et al. 1990). It is critical the tractor is well maintained during such a crisis period as access to spare parts and mechanics would be minimal due to high demand and probable lifelines damage. Tractor failure would immediately require decisions whether to reduce milking numbers, continue milking at all, and/or destroy stock.

3.6.2 Tanker access to the farm

Transportation networks are inherently vulnerable to ash fall. Wet and dry ash deposits make traction difficult and haphazard. Visibility is reduced by ash fall and passing vehicles raise the ash making visibility an issue after ash stops falling. Such hazards are likely to affect the ability of milk tankers to access the farm. The farm's rural location will mean road cleaners are unlikely to open roads for many days (concentrating instead on urban areas), especially during prolonged or multiple ash falls (P. Journeaux, pers comm. 2005). Farmers may need to take on this responsibility themselves, accepting the risk of damaging machinery against the economic benefit of still selling milk. It is important to note the removal of ash from roads is a deceptively time consuming and costly exercise (e.g. Mt. St. Helens 1980), which may negate farmer's efforts to maintain tanker access (Blong 1984).

3.6.3 Stock movement

The passage of cows along dry tracks would stir up clouds of fine ash, even after the ash had stopped falling. This would make herd movement around the farm, such as to and from milking, difficult and stressful for the animal in terms of respiring, hoof abrasion and eye irritation.

The leaders amongst the cowherd would be important in managing the rest if they were to be walked off the farm, so their health should be closely monitored.

3.7 Stock

A moderate to severe ash fall (>50 mm) will place considerable pressure on the farm requiring limited or total de-stocking depending on the severity of the impact (evacuation or destruction of stock). If rehabilitation strategies were successful, subsequent restocking may not be physically possible where the eruption devastated a large part of the country (Neild et al. 1998).

3.7.1 Evacuation of stock

Calves would be the first stock evacuated; their small size means large numbers are easily transported. This would take pressure off farm resources, allowing concentration on keeping the milking herd alive and hopefully milking. Typically 70–120 calves are carried annually. The shelter provided by the sheds used for calf rearing may be better utilised by the milking herd; along with the calf's water and meal demands.

If the situation arose where the two main milking herds could be evacuated in the face of a looming eruption, the Paceys estimate it would take 20 min for the first herd to be brought into the cattle yards. Another person would then bring in the other whilst the first is being loaded on the trucks. The truck and trailer stock transport units do not have to un-hook in the yards, allowing them to back straight onto the loading ramp.

It is perhaps more likely that only a percentage of the dairy herd was evacuated due to the huge logistical demands a stock evacuation would create in an area. In addition to this, there needs to be somewhere for the stock to be taken to. If a situation like this arose then the best genetic stock would be selected for evacuation. A mass evacuation of entire districts would involve the movement of potentially tens of thousands of dairy cows, logistically impossible unless several months warning was given of a pending eruption. Even if such warning time was given (such certainty is unlikely with current warning techniques) it is unlikely farmers would believe it and only act when it was too late.

3.7.2 Destruction of stock

The destruction (slaughtering) of cows with lesser value may allow continued operation of the farm. This is not an option to be taken immediately; rather it should be a ‘last resort’ as the loss of valuable stock means immediate financial loss, loss of potential earnings and loss of genetic value that would take many years to rebuild (Neild et al. 1998). However, the benefits would quickly reduce any pressure on reserve water supplies and supplementary feed stocks. The cows likely to be destroyed first are:

- ‘non-cyclers’ (not pregnant and thus not lactating)
- bulls (but not during mating period)
- empties (not lactating)
- low milk producers
- old cows
- cows with bad temperament (many cows may react badly to the ash fall).

3.7.3 Behaviour of cows under stress

Stressed cows will react badly during movement and milking, hampering efforts. Rough handling from stressed humans will accentuate this. The hunger of the cows would be a key factor in many of the key decisions as to how to adapt the farm to the ash fall event. This would be especially important in terms of the cow’s energy levels and whether milking should continue. The stress level of the cows should be closely monitored by the farmer to determine whether milking would continue and at what level (i.e. twice-a-day milking). Once-a-day milking would be introduced at the first sign of stress to the cows and or feed concerns.

3.8 Supplementary feed

Supplementary feed (such as silage, baleage, maize or hay) would be critical to continue feeding cows when grass is covered by ash. Such stocks represent an excellent ‘reserve option’ that would take the stress off a farm’s pastures. A farm’s ability to manage through a volcanic eruption crisis is likely to be influenced by the quality and quantity of supplementary feed available. It is important to note that farmers do not usually keep extra or reserve feed in case of an emergency of any kind; it is all intended to be used during the following year for maximum efficiency. Once supplementary feed ran out the ability to 'buy in' more supplementary feed would be dependant on the season. This may however only be practical during a small eruption, as demand and transport availability would be at a premium during a moderate to large event.

The quantity of supplementary feed usually stored and consumed at 'Tulachard' consists of:

- Round wrapped bales—160 at runoff; 110 on the farm
- chopped silage—30–40 tonnes at runoff
- dry matter maize—100 tonnes on the farm

The majority of supplementary feed is stored at the runoff, a 24 ha leased block used for growing most of the supplementary feed and winter pasture for grazing. It would be an excellent 'reserve option' that would take the stress off the farm's pastures. Whilst both dairy herds are familiar with the road walk to the 'runoff', they may react differently under the stressful conditions of ash fall.

Once supplementary feed ran out, trips would need to be made back and forth from the runoff with the tractor and silage wagon to bring back feed. If sufficient warning was given about an impending eruption, supplementary feed could be transported to the farm in preparation for the milking herd remaining on the farm. All other non-milking cows could be moved to the run-off to 'fend for themselves'.

Government aid for such an event could include the mass transport of hay and straw from non-affected areas. In the case of the central North Island of New Zealand, feed supplies from the South Island (e.g. Marlbourgh, Canterbury) may become a valid option (P. Journeaux, pers comm., 2005).

3.9 People, the greatest assets

One of the most important variables as to whether the farm will recover from an ash fall event is how well the farmer(s) manages the farm. Key decisions will have to be made at the beginning of an ash fall to cope successfully, the hardest ultimately being what to do when advised to evacuate if an eruption began to endanger the farmer's lives.

Dairy farming involves working outside and in exposed conditions which will bring dairy farmers and their workers into prolonged contact with ash which may result in health problems. The ability of people to operate in the ash will again depend on ash fall rate, a deposit's thickness and moisture content. Respiratory problems likely to arise during an ash fall event includes nasal irritation and discharge, throat irritation, flare-up of pre-existing chest complaints, airway irritation for people with asthma or bronchitis, and discomfort breathing. Irritation of the eyes may occur, making them feel gritty, painful, itchy or bloodshot, with sticky discharge or tearing. Corneal abrasions or scratches and acute conjunctivitis may occur in extreme cases. Minor skin irritations may affect people exposed to the ash for an extended period of time, although this is less common (http://www.ivhhn.org/; http://volcanoes.usgs.gov).

Dairy farmers are required to be outdoors for most farm activities, so should take significant precautions when operating in an ash-rich environment. A key precaution should be the use of an appropriate dust mask or respirator. Appropriate masks should provide a good seal with the face, be capable of providing adequate protection, and be used appropriately. Potential disposable models include EN 149:2001 in the European Union or N95 in the United States (http://www.ivhhn.org). Wearing of full cover overalls, hat (balaclava would be preferable), gloves and sturdy gumboots to avoid contact with the ash on the skin is also useful. Some of these items are clothing commonly worn by most dairy farmers and represent little change to normal operation; however the dust mask may cause some impairment and discomfort. An enclosed-cab tractor would be of great value, but tractor use should be restricted, as mentioned above. If water supplies are secure, damping down of the milking shed area with water or washing ash away will greatly suppress ash re-suspension and reduce health risks to both humans and animals.

4 Condenser testing

Laboratory testing of a condenser was undertaken to establish how badly ash would affect this important component of a modern dairy farm, and to investigate measures that might be applied to ensure the condenser continues to operate during an ash eruption.

4.1 Test set-up

A sealed Perspex testing box (volume = 0.96 m^3—1.2 x 1.0 x 0.8 m^3) was made to house the test condenser so that ash could be added in a controlled environment. The condenser fitted inside with plenty of space for circulation of ash. Small ‘ash catchers’ were placed at locations in and around the condenser to monitor circulation, and two computer cooling fans mixed the ash and to keep it airborne for longer. These fans were run for the entire length of the test runs. Two tests were carried out; a dry test and a wet test. Temperature and wind flow was monitored during all tests with a Kestrel 3000 Environmental Meter (http://www.nkhome.com). Airflow velocity readings (maximum and average flow) and the ambient temperature were taken within the test box every 30 min.

Ash was introduced at the rate of 1,000 g of dry ash per 30 min through a hole in the top of the test box. This rate is higher than concentrations measured from historic eruptions (e.g. Mt. St. Helens 1980; av. 174 488 μg/m^3, and max 219 536 μg/m3; Heiken et al. 1995), but preliminary testing showed effects on the condenser were similar to lower levels. Ash was added for a total of 7 h in each test (Fig. 4).

Three types of ash were initially collected; Kaharoa ash, Taupo ash (both rhyolitic) and Tarawera ash (basaltic), but it soon became apparent that ash chemistry was not a significant factor in the experiment, so a blend of ash types was used in both dry and wet tests. For the dry tests, the ash blend was mixed randomly and baked at 105°C in an oven for 48 h to remove moisture. It was then divided into 500 g bags (grainsize distribution is shown in Fig. 5), and introduced in 500 g increments by slowly trickling it in front of the continually running condenser, which then sucked in a portion of the ash whilst the rest fell to the base of the box. Airflow through the condenser was monitored throughout. At the end of each test, the condenser was removed, and air cleaned with an air-compressor and examined for signs of wear.

For the wet test a mist of water was sprayed into the test box at the rate of 250 ml/ 30 min to simulate a moisture-rich environment.

4.2 Results

4.2.1 Dry ash test

Six minutes after the first ash introduction there was a thin ash coating blanketing the entire condenser, and a significant amount on the floor. The air mobilised fines were either deposited inside the condenser’s vanes, onto the condenser’s base inside the fan cavity or

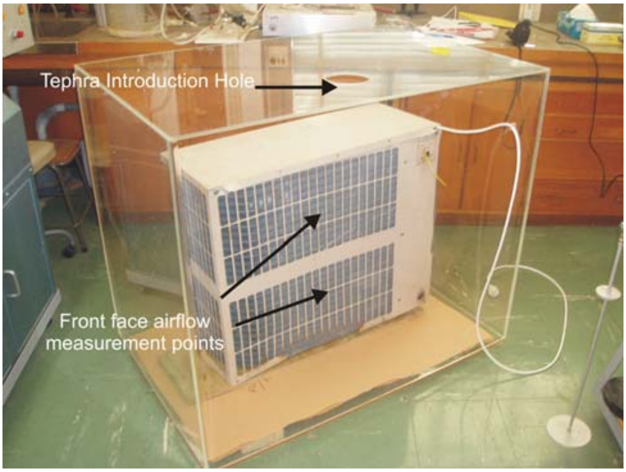

Fig. 4 Condenser located inside in the test box

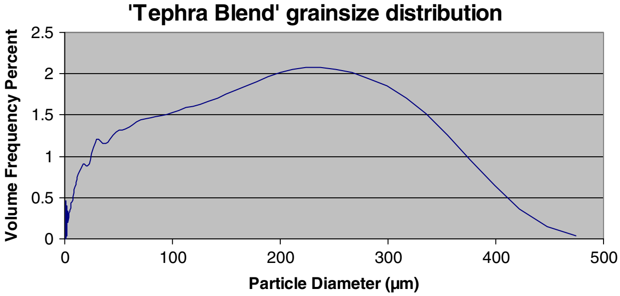

Fig. 5 One hour into the wet test. Note the greater accumulation of ash on the walls of the test box and the circulation pattern of the airflow

was blown through the condenser. Ash blown through the condenser generally rebounded off the wall of the box and re-circulated around to the front where it was kept suspended by the supplementary computer fans, with a portion deposited onto the base of the box.

Twenty minutes after the test began, coarse ash and lapilli were trapped between the protective grill and the radiator. After 1 h, ash deposition occurred on damaged vanes and after 2 h side facing vanes began to be covered, ash built up where cooling pipes joined the vanes inside the radiator, and fine lapilli caught between radiator vanes. After 3.5 h deposition on radiator vanes was noticeable across the entire radiator, with an estimated 10–15% blocked. After 5.75 h motor noise increased, but eventually faded over 10 min, suggesting ash had got into the bearings of the motor and then slowly cleared. Finally after 6 h the vanes were significantly clogged at the top and at the base of the curved radiator. There was however no apparent abrasion of the radiator vanes. Only 1–3 mm of ~0.5 mm sized ash was deposited on top of the motor and a thin veneer of ultra-fine ash coating the surface of the motor, and it was still in working order. The fan spun freely, with no sign of wear or abrasion. There was no indication that ash had entered the bearings, with no rubbing or grinding when the fan was manually spun. Slight wear occurred to the tips of the condenser fan blades, but there was no abrasion on the blade's surfaces. The electronics and power section of the condenser was covered with a thin dusting of ash (<1 mm), but not enough to cause any issues with the electronics.

4.2.2 *Wet ash test*

Within 30 s of ash introduction, preferential build up occurred on the area of the radiator directly in front of the circulation fan, and the inside walls of the test box became covered with a fine build up of ash, but no abrasion. Ash immediately began to be deposited in blister-like clumps. After 70 min the front face of the condenser was becoming significantly clogged up and after 100 min an estimated 70% of the front face of the condenser was covered in ash (in contrast to the estimated 10–15% blocked 3.5 h into the dry test). After 2 h the sides had became clogged, as airflow was blocked in the centre and had to flow through the extremities. The fan motor also began to make a rubbing, grinding noise for $\sim$30 s, similar to that made in the dry test after 5.75 h. The suction noise from the front of the test box had distinctly changed from a light hum to more of a whistle, suggesting a changed airflow regime. After 4 h the front screen of the condenser was difficult to see because of particle deposition, and after 5 h the entire front face was significantly blocked. The least affected areas had significantly more ash deposition than the most heavily clogged areas in the dry test. Even the curved section of the radiator at the left side was blocked in many places. The blister-like clumps on the front face continued to grow, probably through electro-static attraction as airflow at the front had stopped, and some would fall off. This continued through to the end of the test, with a larger proportion of the introduced ash simply falling to the base of the test box due to the reduced wind-flow regime and thus energy to pull the ash into the condenser. At the end of the test an estimated 75–80% of the front intake face was blocked with deposited ash (Fig. 6).

The motor received a $\sim$1 mm coating of fine grained ash on top of it and was fully covered in a thin veneer of ultra fine ash, but still appeared to be in perfect working order. The fan still spun freely, with no sign of wear or abrasion. There was no indication of ash having penetrated the bearings with no rubbing or grinding occurring as the fan was manually spun. No wear occurred to the tips of the condenser's fan blades, as in the dry test.

4.3 Discussion of condenser results

The most important result of the wet test was a complete blocking of air flow from the front of the condenser. The 75–80% clogging of the front intake face would have extremely significant implications on the efficiency of heat exchange from the condenser. This could potentially cause overheating leading to damage and possible fire hazards.

The increased temperature of the air noted in both tests is negligible. However, the significantly increased surface temperature of the motor in the dry test is cause for concern. If the test had continued for a greater time the risk of the motor burning out would have greatly increased. This was less of a hazard for the wet test with the moisture possibly acting as a coolant. The ash deposited in the vanes of the radiator would have reduced the efficiency of the condenser's ability to exchange heat with the outside air.

There was no evidence of shorting or grounding of circuits. This may have been due to the electrical insulation provided by the Perspex testing box, although there was no evidence of arcing or damaged wires inside the electrical compartment of the condenser following either test.

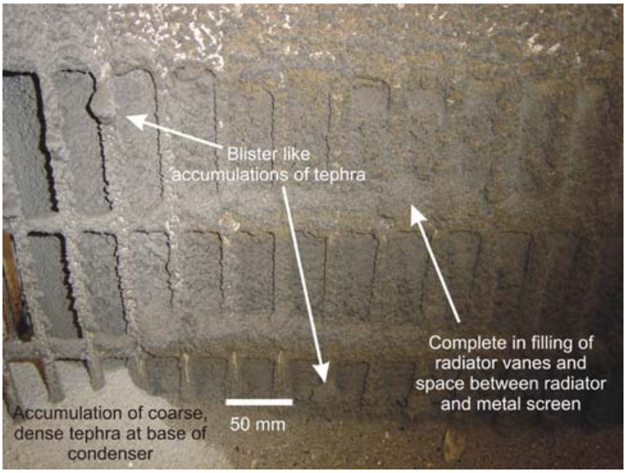

Fig. 6 Surface of the condenser's intake face following the wet test

There was some evidence of etching of painted and metal surfaces but the ash used was volatile-free. Fresh ash is however likely to be coated with acidic aerosols (e.g. H_2SO_4 and HF) could corrode the 'fresh' metal surfaces causing irreversible damage to the condenser, possibly resulting in the need for replacement far earlier than may have been the case.

4.4 Suggested mitigation measures—condenser

The most practical mitigation measure would be to regularly blow out the condenser with compressed air. Many modern dairy farms have an air compressor, commonly stored at the dairy shed. Taking into account the accelerated nature of these results, a regime where cleaning occurred every 2–3 h in dry ash fall conditions and every hour in wet ash fall conditions during condenser operation would be extremely beneficial to maintaining the condenser in a working condition, but would be very difficult to maintain during an ash fall.

An important consideration is that the uncontrolled use of compressed air can also cause problems when blowing-out ash affected machinery. Thirty psi or less has been found to be acceptable for blowing items clean; any more pressure and sandblasting may occur (http://www.ak-prepared.com). Care must also be used to avoid blowing ash onto other surfaces or machinery that should be kept clean. Ideally it is better to use a vacuum when possible, although this would not be practical on a dairy farm.

Key recommendations are:

1. House the condenser under a roof, perhaps with a hessian cloth enclosing it to provide a filtering affect so minimal ash and moisture are sucked in. This may need to be replaced during heavy ash falls.
2. Milk just before the tanker arrives so that minimal time is spent using the condenser.
3. Ensure the radiator vanes are not damaged. If they become damaged it may be necessary to bend the vanes back into line with a thin screwdriver before use; this will delay dry ash build up on the radiator.
4. Blow out the condenser regularly with compressed air.

5 Discussion

The farm is most vulnerable to electrical power loss. The best way to mitigate ash fall hazards to electrical power supply is to bury power-lines, and install insulators and power lines resistant to ash accumulation. This is however costly and difficult to justify for New Zealand's current energy sector. A controlled power outage to allow cleaning of the insulators is commonly used, but this is also costly, both in terms of cleaning and the loss of power to consumers (e.g. as used by Transpower during the 1995–1996 Ruapehu eruptions; http://www.transpower.co.nz). It is also unlikely power supply maintenance personnel would be available to rural customers immediately, with urban centres and higher voltage lines getting priority. The installation of a diesel powered electrical generator would be extremely useful and allow a degree of self-sufficiency. It would cost $10,000–12,000 for a generator and appropriate additional transformers that would supply a regular current to the milking shed and that wouldn't harm the sensitive pump computer (discussed further below).

A generator would be invaluable if district and or regional electrical networks were to go down. Even if just one central farm had a generator, that farm's milking shed could milk the local area's cows, with the dairy herds all dropping to once-a-day milking. This would continue production for all the farms and provide certain economies of scale. A bottle neck would be the storage capacity of the milking shed's vat, normally required to store only one farm's milk production. It is unlikely to cope with the volume of milk from 3–4 farms (even with a change to once-a-day milking). The milk tanker would have to make several pick ups of the milk daily from this node, given many farms would not be milking. Fonterra would want access to as much milk as possible so is likely to be flexible. Supplies of cleaning water may also be an issue, possibly leading to only cleaning cups with water, and excrement shovelled out by hand. Keeping diesel supplied to the generator may be an issue if this arrangement had to continue for an extended period, although neighbour's diesel tanks would be a ready source of fuel. Road clearing for milk-tanker access would be dramatically reduced under such a scheme. Such an arrangement could allow milking to continue for several days to even several weeks until power was restored. This could potentially be undertaken using a farm, such as the neighbouring 'Hills' modern (5 years old) rotary milking shed. This is a high capacity semi-automated modern milking shed with a back up diesel generator. The milking shed (equipment and infrastructure) and yards are in very good condition and would be able to cope with the increased load of additional herds being milked there. For the herd to reach the neighbouring farm it would simply be a case of lowering a southern boundary fence and a short trip across the road to the Hill milking shed. Such a venture would largely be reliant on the good will of the Hills. However, the fostering of community spirit and working together in a crisis event is well documented in rural communities (Gough 2000).

The milk shed is the economic hub of the farm and may need to be protected. A solution to ash contamination would be to enclose the milk shed. This could be achieved by simply hanging wet sacking or previously used silage pit covers (effectively large plastic sheets) from the shed's roof to block ash from entering the shed. Both resources could be found on the farm or easily sourced. This would need to be completed during final preparations before an ash fall, or as soon as ash had begun to fall.

This report has outlined a range of issues that high intensity, modern dairy farmers need to be aware of during a volcanic eruption, and strategies that may assist mitigating these issues. However, it must be noted that this paper concentrates on issues likely to occur from a relatively minor ash fall of short duration. In a moderate to heavy ash fall (i.e. >100–150 mm), and especially if the ash fell over several days or weeks, then the farm may rapidly become untenable to the point the farmer may need to evacuate the property. As mentioned above, electricity and water are critical farm components (both interlinked as most farms rely on electric pumps to supply and reticulate water) and in a moderate to heavy ash fall it is extremely probable that electricity supply would fail, and the water supply along with it. Given the unlikely probability of livestock being evacuated, many would die as a result of dehydration and feed loss. Such an evacuation of the farm (and presumably many others like it) would then give rise to a significant range of other issues outside the scope of this report.

6 Conclusions

This study has shown an ash eruption would have a major impact on modern dairy farm operations. The electrical power supply is perhaps the most critical and most vulnerable part of farm infrastructure that could be lost during an ash fall. The water supply, the use of the tractor, and the condenser are the most vulnerable. Injury to one of the labour units on a farm would be something that should be avoided at all reasonable cost, given the probable need to have all labour units fully utilised during an ash fall.

If there is more than 150 mm of ash fall it will be very difficult for a dairy farm to recover. Below this the farm will survive, but measures need to be taken for recovery. It is important to note that how a farm responds to ash fall is dependant on social, health (physical and mental), economic and political considerations in addition to the amount of ash it receives. The 150 mm threshold has important implications for farmers when deciding when they must evacuate, as it would be pointless to continue habituating a farm with no economic future. Ultimately it will be farmers themselves that determine when the most appropriate time is to leave the farm; hard as that may be (Rogers 1997). Emergency management agencies responding to a major volcanic eruption could also use the 150 mm isopach line as a guide to where recovery efforts are most appropriately allocated or directed. It is also essential to consider the duration of ash fall. In an event of short duration effects can be more readily appreciated, mitigated and allow the emphasis of response to more rapidly change to recovery and land rehabilitation after the event. Discussion of these issues is beyond the scope of this paper.

Even in a major volcanic eruption, there will be a number of farms on the fringe able to successfully recover from ash fall. The quality of the actions taken (related to information available to the farmer) will determine how successfully a farm will recover; and indeed whether they recover at all (Slovic 1986). Recommendations developed in this study will hopefully allow dairy farmers to become more resilient to ash fall, minimising the effect it has on their farms and lives.

Any farm affected by ash will be dependent on the financial resources of the farmer and the robustness of the farm business, as even a 50 mm fall of ash will have serious financial implications in the year of the ash fall and the following season due to lost production and the increased costs of rehabilitation. In severe ash falls, land use change may be the only option. Given New Zealand's exposure to volcanoes, and the importance of agriculture to the national economy, further research on simulating effects of different types of ash fall on dairy farms, in terms of infrastructure, operational process and rehabilitation of pastoral agricultural systems, is necessary. Such programmes should be investigated and developed in conjunction with key industry players, such as MAF, Fonterra and Federated Farmers.

7 Recommendations

The effect of ash fall will depend on the magnitude, style of eruption, location of active vent zone, vent positions within the active vent zone, local topographic controls and wind directions. It is extremely hard to predict any of these factors for the next eruption, given the variety of styles of eruptions that have affected the farm during the last 22,000 years. Warning time is variable. There may be 1 year to 3 months warning for a rhyolitic eruption, while there may be only 3–4 h for a basaltic eruption.

Key recommendations to minimise the hazard are as follows:

(1) Long term planning (*periods of quiescence*)
- Maintain power supply lines so they are in good order.
- Develop a water supply with large tank storage capacity.
- Develop a 'feed pad' that is easily cleared of ash for distributing supplementary feed.
- Ensure roof pitches are greater than 30° and strengthened (perhaps to snow codes) on any new buildings.
- Ensure the tractor is 4WD and has front bucket and blade attachments.

(2) Medium term planning (*12 to 3 months out from eruption*)
- Conduct a vulnerability analysis of equipment and facilities to determine which would be the most affected by ash fall, and which are adequately and inadequately protected (http://volcanoes.usgs.gov).
- Identify appropriate methods of protecting vulnerable equipment and facilities from ash.
- Off load non-essential stock (i.e. beef cows, sick animals in the herd, dry milkers, old cows).
- Increase reserves of supplementary feed (i.e. buy in or produce more; alternatively use less by off loading stock).
- Ensure tractor and milking machine have been serviced recently.
- Attempt to stockpile tractor engine and milking machine filters (air, oil, pulsators and milk), lubricating oil, brake and hydraulic fluids, and seals.
- Purchase an air compressor or ensure it is in good working order.
- Ensure diesel tank is maintained at a high level.
- Have ladders and brooms (roof cleaning).
- Ensure sump, drainpipes and drain grills are clear. Make sure sump pump is in good working condition.
- Be prepared for false alarms; predicting a volcanic eruption is difficult.

(3) Short term planning (*immediately before an eruption*)
- Cover all essential equipment (either within sheds or under a covering).
- Move essential stock (milking herd) close to the milking shed.
- Store transportable supplementary feed close to areas where it would be distributed (i.e. feed pad, paddocks close to the milking shed).
- Ensure enclosed water storage tanks are at their maximum (especially if surface water is the farm's water supply).
- Place ladders for access to key roofs in a secure way for easy safe cleaning. Plan to have a lot of time to clean roofs (prevent injury).
- *Do not put stock onto the road* in the hope of finding somewhere better as they will hinder emergency service's and evacuee's mobility. They have a greater chance of survival on their farm (Neild et al. 1998).

- Conduct any maintenance on tractor, milking machine and other key machinery (e.g. change filters). If there is time purchase new filters.

(4) During eruption

- Keep ash out of buildings, machinery, vehicles, downspouts, water supplies and wastewater systems (e.g. dairy shed drains) as much as possible. The best way to prevent damage is to reduce machinery usage as much as possible, shutting down, closing off or sealing equipment. However, critical farm functions such as milking should be preceded by removal of as much ash as possible before operating equipment.
- Minimize human exposure to airborne ash by using dust or filter masks and minimising travel.
- Remove ash from roofs to prevent collapse and on going remobilisation. Take your time whilst cleaning roofs and wear a mask whilst doing so. Try to undertake the activity when you are alert and physically fresh.
- Plan each day, in terms of what activities are critical, required and optional. These may change each day so be prepared to remain flexible. Develop a priority list of facilities that must be kept operative versus those that can be shut-down during and after ash falls.
- Stay aware of the condition of your cows; they are the most important part of your farm.
- Do not put stock onto the road in the hope of finding somewhere better as they will hinder emergency service's and evacuee's mobility. They have a greater chance of survival left on your farm.
- Prioritize and sequence areas for cleanup (top to bottom).

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