3. History of Stray voltage Studies and Evolution of Experimental Techniques

3.1. Methods Used In This Literature Review

This review of literature uses published studies that include data from controlled experiments and field studies. Controlled studies are designed to establish cause and affect relationships by careful administration of causal variables (voltage / current) and careful measurement of responses (behaviors, aversion, water or feed intake) while minimizing or controlling for external sources of variability and comparing responses to a control group. Field studies can be useful in establishing correlation but are generally not useful in establishing cause and effect relationships. If a cause and effect relationship exists they may be apparent in field studies if causal variables and responses are properly characterized and sufficient sample size has been obtained to account for the normal farm to farm and seasonal variation that occurs in the field.

Each study has been critically reviewed in regard to the number of subjects, experimental designs used, appropriate verification of electrical exposures and animal responses, statistical analysis methods and the degree of peer review. Studies of similar nature have been compared to assess repeatability of results. There have been a number of different ways that researchers have used to quantify voltage and current levels. The most common is to report the root-mean-square (rms) average of alternating voltage or current and will be used in this report unless otherwise noted.[6] Repeatability is a fundamental criterion for judging the weight of scientific evidence. Both applied voltage and the resulting current flowing through animals was reported where measured by and stated by the authors. Some studies did not report both of these measures, however, and the authors reported values are cited.

3.2. Early studies in New Zealand

The first reported studies of animal response to voltage exposure were published by researchers from New Zealand (Phillips, 1962; Woolford, 1972; Whittlestone, 1975). These studies were initiated by reports from dairy farms that people were experiencing mild shocks in milking parlors and speculation

---

[6] *Measurement Terminology: The most common way to refer to AC voltages and current is as a Root Mean Square (rms) average. The default statement of voltage and current in the literature is as the rms average of 60 Hz current (milli-Amperes or mA) and the rms average of 60 Hz voltage (volts or V). This is the meaning implied in this report unless otherwise noted. In some cases other measurements have been used, especially when dealing with transient voltage and current, short duration voltage or current pulses, or when current of voltage waveforms are not sinusoidal.*

Some studies have used the zero-to-peak (or just peak) current or voltage has been used as the defining exposure or dose level. The zero-to-peak voltage or current is the same as the rms average for square waveforms. The zero-to-peak current or voltage is 1.4 times the rms average (the rms average is 0.7 time the peak value) for sinusoidal waveforms. The peak voltage or current is 3 times the rms average for triangular waveforms.

In a few studies the peak-to-peak current or voltage has been used to describe the voltage exposure or current dose level. The peak-to-peak voltage or current is 2 times the rms average for an alternating square wave. The peak-to-peak current or voltage is 2.8 times the rms average for alternating sinusoidal waveforms. The peak voltage or current is 6 times the rms average for an alternating triangular waveform.

that cows might also be experiencing these same electrical shocks. An electrical survey of farms showed that contact voltages ranged from zero to as much as 20 V with most between 3 V and 10 V. The most important sources of voltage were: unbalanced loads (resulting in high neutral current) and the resistance of the neutral between the shed and transformer (secondary neutral voltage drop). A series of experiments were carried out to establish the lowest level of contact voltage, applied to the teat-to-rear hooves pathway, at which there was a response (Phillips, 1962). While certain cows were more susceptible than others it was concluded that 3 V would be a likely minimum level for response.

A subsequent study measured the current through animals (front to rear hooves and between a wetted flank and 4-hooves) in an attempt to reduce the variability of responses and found that changes in cow behavior were observed when currents reached 3 to 8 mA and these behaviors were judged to be uncomfortable for currents of 4.5 to 12 mA (Woolford, 1972).

A further study was done using a more objective method of measuring behavioral responses using an operant conditioning system in which cows turned on an electric current applied to the teats, the rump or the flank in order to receive crushed barley and turned off current by pressing a second manipulanda (Whittlestone, 1975). A step-wise increase in current in the range 0 to 10 mA showed that behaviors changed with currents of approximately 7 mA for one teat, 6 mA for the rump, and 4 mA for the chest area, and 6 mA for the udder.

This series of studies shows remarkable repeatability in the range of currents required to produce behavioral changes and aversion. Furthermore the relationship between voltage and current exposure indicate an effective animal + contact resistance in the range of 500 to 1000 Ohms. Similar experimental technique has been repeated by several research groups around the world over the past 45 years.

3.3. Early North American Studies

The first on-farm case studies in North America were reported in the early 1970's (Craine, 1970 in Washington State; Feistman, 1975 in Canada). These were assumed to be localized problems and did not receive wide attention. The first study published in North America of controlled animal exposure to voltage was by Craine (1975). Groups of 70 and 30 cows each were exposed to voltages ranging from 0 V (control treatment) to 8 V. Mild aversion was noted at 3 V while suppression of water intake was noted above 4 V. The 8 V treatment was discontinued after 1 day because many cows refused to drink. These response levels agree remarkably well with the New Zealand studies with corresponding real-world cow + contact resistances of about 1000 Ohms.

Field studies and observations began to appear with greater frequency in the US, Canadian and European literature in the 1980's (Gustafson, 1980; Sanders, 1981; Erikson, 1984; Kirk, 1984; Rodenburg, 1984; Thornton, 1884; Winter, 1984). This heightened awareness resulted in the initiation of research programs by groups at the US Department of Agriculture, Agriculture Canada, the University of Minnesota and Cornell University . These research programs were undertaken to better understand the relationship between voltage exposures and current dose for a variety of exposure pathways, the variety of behavioral responses, and physiological responses such as blood chemistry, stress hormones, occurrence of mastitis, milk production and milk composition. These studies were primarily done using steady 60 Hz AC voltages and currents.

3.4. United States Department of Agriculture Research

Lefcourt (1982a) used EKG patches applied to shaved areas on the front and rear legs to eliminate the problem of contact resistance on five cows exposed to an ascending current series of voltage from 0.25 V to 5 V. The cow body resistance varied from 250 to 405 Ohms using this pathway. Four cows showed a mild response to a current of about 3 mA while one cow showed a mild responded to a current of 0.7 mA, although this may have been due to a cut in the skin during shaving. In a second study Lefcourt (1982b) Subjected 6 cows to 5 mA of current for 20 minutes (continuous) and one for 5 of every 30 seconds (intermittent) both starting 10 minutes prior to milking and continuing through the milking session. Milk yield and milking time decreased in cows subjected to stimulation by intermittent current. Neither treatment appeared to have an effect on norepinephrine. The continuous 5 mA treatment had a variable effect on milk yield, milking time and hormonal responses, some cows seemed to adapt and some cows were reported to have enjoyed the stimulation.

Lefcourt (1985) later subjected seven cows to 3.6 mA and six cows to 6.0 mA intermittently at a.m. and p.m. milkings for 7 days. One cow had to be removed from the 6.0 mA group because of severe behavioral responses. In this study milk yield, milking time, and Wisconsin Mastitis Test scores were not affected, the maximum rate of milk flow increased slightly and the number of behavioral events increased with a greater increase in the 6.0 mA group. Heart rate was elevated (+3 beats/min) only in response to shock during preparation (initial shock). Time to peak oxytocin response was delayed in the 3.6 mA group, and peak prolactin and area under prolactin response curves increased similarly for both groups during shock. The author concluded that any negative effects of electrical shock on milk production or mammary health most likely are not related directly to shock (physiological responses to shock were minimal and milk yield was maintained). They noted, however, the severe behavioral responses to this level of shock would almost assuredly result in management problems.

In a final experiment, Lefcourt (1986,) exposed seven lactating cows to 60 Hz currents of 0, 2.5, 5.0, 7.5, 10, then 12.5 mA, biweekly for 10 seconds. As the current dose increased, cows became more agitated and two cows were not shocked at 12.5 mA due to severe behavioral responses. Heart rate immediately after shock increased at 10 mA and 12.5 mA treatments while prolactin, norepinephrine and glucocorticoids were unaffected. Epinephrine doubled in two exceptional cows at 10 mA. Dramatic behavioral responses displayed by cows at the higher current exposures were not correlated with significant or prolonged physiological responses and electrical exposure was not considered a reliable way to induce 'stress' in cows.

3.5. The University of Minnesota

A team of researchers at the University of Minnesota (Gustafson, 1983) measured the electrical resistance of milking machine components and found milk hose resistances ranging from about 30,000 Ohms to 80,000 Ohms depending on the milk flow rate. The minimum resistance from the claw through the cow to the floor was 3,000 Ohms. It was estimated that 25 V to 50 V across the milking machine/floor pathway would be required to obtain perception level currents through a cow.

Norell (1983) measured electrical resistance for eight pathways through dairy cows. Significant variation in resistance was found for different pathways as well as for different cows. The mean path resistances

ranged from 359 ohms for a mouth-all hooves pathway to 738 ohms for a front-rear hooves pathway. Three experiments assessing animal sensitivity to current based on behavioral indicators were performed. No suppression of a learned response to obtain food was found up to 6.0 mA front-rear hooves shock. However, muzzle-all-hooves shock as low as 1.0 mA suppressed plate pressing behavior. A learned escape response to a front-rear hooves shock above a normal activity level occurred between 2.0 and 3.0 mA. It should be noted that these exposure conditions were not typical of farm exposures.

Appleman and Gustafson published an article in 1985 in which they stated that, based on research done to that point, less than 10% of cows are thought to perceive contact voltages below 0.35 V, behavioral modification may occur above 0.7 V and endocrine response above 3 V or 8 mA (60 Hz rms). They estimated the resistance of different cow body pathways to range from 350 to 1700 ohms. A subsequent publication by these same authors (Cloud, 1987) contains revised recommendations based on additional research. They note that the milking machine is not a likely pathway for electrical currents to the cow because of its high resistance. The failure of controlled research to find a direct physiological effect in animals subjected to stray voltages, and the absence of documented case studies demonstrating a marked improvement in these traits upon correction of an existing problem lead them to the conclusion that there was no direct and causal relationship between voltage exposures and milking performance and animal health. They state that problems may occur when voltages accessing dairy cows through the mouth-all hooves pathway exceed 1 V and that below 0.7 V problems would be minimal. On the issue of cow+contact resistance they state that because the resistance of the front-rear hooves pathway is approximately twice that of the mouth-all hooves pathway, it requires a 2 V step potential shock to produce the same response as a 1 V mouth-all hooves shock and they recommend continued monitoring when measured voltages reach the 0.5 V level. These authors were also part of the consensus opinion later issued in the 1991 UDSA handbook recommending that voltage levels be kept below 2 to 4 V to avoid problems on farms.

3.6. Cornell University

A group of researchers at Cornell University reported on their first study in which cows exhibit behavioral response between 2 and 4 mA, while current applications up to 8 mA applied between the udder and four hooves did not affect milk production or milk composition and hormone responses were minimal (Gorewit, 1984).

In a 1985 study (Gorewit, 1985) eight pregnant Holstein-Friesian cows in weeks 16-20 of lactation were exposed to a current dose of 4 mA in the following manner. A 96-hour experimental period was divided into 4 sub-periods of 24 hours each during which cows on treatment were given shocks of 4 mA at 30 second intervals during 5 min in every 4 hours, via sub-dermal electrodes on the spine. The treatment and control cows were alternated in consecutive periods. Milk yield was slightly but not significantly decreased by the shock treatment (down 0.16 kg/milking), but milk composition, and feed and water intake were not affected. Milk somatic cell count (SCC) [7] tended to increase during treatment, but the

[7] *Somatic cell count (SCC) is one of indicators of the quality of milk. Somatic cells are leucocytes (white blood cells). The number of somatic cells increases in response to pathogenic bacteria.*

increase was not significant. Behavioral responses were greatest on first exposure, but cows became accustomed to shocks within 24 hours.

Three experiments were conducted using water bowl exposures. In one experiment a total of 30 cows were divided into five treatment groups of six cows each. Treatments of 0 V, 0.5 V, 1.0 V, 2 V, and 4 V were applied between metallic water bowls and a metal floor plate for a period of 21 days (Aneshansley et al. 1987; Gorewit et al 1987; Gorewit et a1. 1988; Gorewit et al. 1989). Two of the six cows in the 4 V treatment group did not drink for 36 hours and were removed from the experiment and replaced with other cows. All other cows drank normal amounts of water within two days of the initiation of the 21-day exposure periods and there was no significant difference in water and feed intake, milk yield and quality over the 21 days for any treatment group. Cows in the 1 V, 2 V and 4 V treatment group did show an increasing delay from the time the voltage treatment was applied to the time that they drank their first gallon of water. This delay was not observed at the 0.5 V treatment level. The delay increased with increasing voltage for the 1 V, 2 V and 4 V treatment groups.

A second test involved 80 cows, 40 of which were first calf heifers (Gorewit, 1989). These cows were divided into four groups of 20 cows each and exposed to 3 V, 4 V, 5 V and 6 V for 48 hours. Two heifers in the 5 V treatment group and two heifers in the 6 V treatment group did not drink for 36 hours. They were removed from the study and replaced with other heifers (bringing the total to 84 cows). There was a similar dose response curve for voltage treatment level and the delay to drink the first gallon of water as observed in the previous study, with no changes in the total daily water intake for any treatment level.

Aneshansley (1988) applied the following five temporal patterns of voltages between water bowls and rear hooves:

Exposure Level	Time Pattern
5 V	6 hours on – 6 hours off
5 V	4 hours on – 4 hour off
5 V	2 hours on – 2 hours off
8 V	one second every 20 seconds for 50% of the time;
8 V	for one second randomly with a probability of occurring 1 time in 40 seconds or 2.5% of the time

Behavioral patterns showed no consistent pattern. There was no significant change in amount of water consumed for any of the treatments.

Milking exposures were investigated by Aneshansley (1990; 1992) and showed that first calf heifers kicked their milking machine at levels ranging from 5 mA to 12.5 mA, and second through fifth lactation kicked their milking machine off at currents ranging from 8 mA to 18 mA.

Cornell University scientists conducted a full lactation study that examined the effects of voltage at various levels over full lactations, approximately 12 months (Gorewit, 1992a, 1992b). Four groups of 10 Holstein cows each were exposed to 0 V, 1 V, 2 V, or 4 V between waterers and a metal grid throughout

an entire lactation. Cows could not drink without placing their front hooves on the metal grid. Although there were some behavioral changes on the first day of exposure, feed and water intakes were not affected by and of the voltage treatments. Milk yield for the full 305 day lactation showed no significant differences between groups exposed or unexposed to and of the voltage treatment levels. Somatic cell counts, milk fat and protein and reproductive performance showed no significant differences between groups exposed or unexposed to voltage. The Cornell group also examined the impedance of cows over a wide range of frequencies and found a similar relationship to humans with decreasing impedance at higher frequencies (Aneshansley, 1990).

3.7. University of Missouri

Currence (1990) examined response threshold of 24 cows and humans to 1, 10 and 100 cycles of 60 Hz sinusoidal alternating current. Current was applied from one front to one rear hoof for cows and through adjacent fingers immersed approximately 4 cm in two small beakers containing dilute salt water for humans. Significantly higher currents were required for the 1 cycle current duration than for 10 and 100 cycle durations to elicit the same response in cows and humans. The average mild behavioral response threshold for all cows was 3.6 mA rms for multiple cycle events and ranged from 2.2 mA for the most sensitive cow to 5.4 mA for the least sensitive cow. The average response for all cows was 5.5 mA for the single cycle stimuli (or about 20% higher than the multiple cycle stimuli). The average current levels for humans to first perceive the 100 cycle current was 0.37 mA with discomfort noted at 0.45 mA. Cows showed behavioral responses at 3.6 mA whereas humans noted perception at 0.37 mA and discomfort at 0.45 mA for the same signal applied to adjacent fingers. It thus took about 10 times more current to produce a similar response in cows than in people. This relationship is as would be expected because of the larger body mass of cows (about 10 times humans) and correspondingly reduced current density (the same total current is spread out over a larger amount of enervated tissue).

3.8. New Liskeard Study

A series of long-term exposures studies was conducted at New Liskeard College of Agricultural Technology from 1986 to 1990 (Gumprich 1992a and b). Cows were included in the study from 2 weeks post partum for 112 days. A switch back experimental design was used to determine the effects of the three different levels of voltage applied to the cows. The responses measured were: daily milk production, milking time, milk composition, water consumption, feed consumption, breeding and behavior.

The cows were exposed to a uniform voltage between the cow platform, water bowls, and all metal stabling components. To simulate on-farm conditions, a continuous low-level voltage was interrupted by two three-hour periods of higher levels at 5 am and 5 pm, to simulate higher loads during milking that occur on many dairy farms. The first treatment applied to 30 cows (level 1) was 1.0 V with a background voltage of 0.3 V. The second treatment applied to 30 cows (level 2) was 2.5 V with a background level of 0.75 V. The third treatment applied to 30 cows (level 3) was 5.0 V with a background voltage of 0.75 V.

At treatment level 1 (0.3 V and 1 V), cows receiving the voltage treatment had significantly higher milk fat percentage than cows in the control group (31.2 versus 30.6 kg/cow per day). No other response

variables showed a significant response. At treatment level 2 (0.75 V and 2.5 V), milking time was longer (8.5 versus 8.3 min) for the treatment group while no other response variable showed a significant response. At treatment level 3 (0.75 V and 5 V) there was a residual effect on milk production two periods after the treatment period. In addition, less water was consumed by the treatment group (97.6 versus 100 liters/cow per day). It was concluded that exposures up to 5.0 V in well managed tie-stall dairy operations were unlikely to cause observable changes in cow milk production or behavior.

3.9. Field Studies and Case Studies

There have been reports of a number of field and case studies in the literature. Many of these suffer from:

- Self selection bias: Farms are often enrolled because they have health or production problems that they believe may be related to electrical exposures rather than a random selection of farms. Farms that are experiencing problems are more likely to be implementing a number of measures to improve their performance.
- Small sample size: Some studies have enrolled only a few case studies or a small selection of farms that have installed a particular mitigation device. Valid correlations rely on a sufficient random sample to balance the enormous variability across farms, across regions and across time.
- Inadequate characterization of voltage exposures: In some cases, exposures have not been documented at all or have been characterized by neutral-to-earth voltages which have been shown to be poorly related to animal exposure levels.
- Inadequate measurement of animal response: In some studies, animal responses have been self reported by operators without validation of performance numbers.
- Lack of controls or appropriate points of comparison: Seasonal and year-to-year variations in animal performance as well as enormous farm-to-farm variability require careful and appropriate comparisons in order to establish which changes in the farm environment are related to which responses in performance.

Some notable field studies are summarized below.

Kirk (1984) reported on a field study in which stray voltage investigations were performed on 59 Michigan dairy farms. Levels exceeding 1 V alternating current were reported to have been found on 32 farms, although the exposure locations location and measurement methods were not specified. Information regarding somatic cell counts, prevalence of clinical mastitis, and response to corrective actions was collected at the time of the farm visit and from questionnaires sent to the farmers following farm visits. Statistical analysis indicated no significant relationship between the magnitude of stray voltage and milk production, or somatic cell counts. When on-farm, off-farm, and combination sources were consolidated into a single category and compared with no source of stray voltage (presumably less than the 1 V level?), animal behavior was found to be related to source of exposure, whereas the prevalence of mastitis and milk production decreases were not. On most of the farms where exposure levels were less than 1 V, the signs interpreted by the dairyman as being due to stray voltage could be explained by other factors. On farms where the milking machine was functioning properly and milking

technique was adequate and included post milking teat dipping, mastitis was rarely noted to be a serious problem even though voltage exposures exceeded 1 V. The authors concluded that these data supported the conclusion that exposures less than 1 V would not produce herd behavior, production or health problems and that there were many other causes for these symptoms. This study suffers from lack of appropriate exposure verification and lack of appropriate response verification (self reported).

Rodenburg (1984) reported on a survey of service entrance neutral to remote earth voltage measurements on 140 Ontario dairy farms. During a 24 hour monitoring period 80% of farms had peak voltages between the in excess of 1 V, 55% of farms in excess of 2 V and 28% of farms in excess of 3 V. The highest voltages were usually recorded during peak electrical load periods between 6 and 9 a.m. and 5 and 8 p.m. Cow contact voltage exceeded 0.5 V on 50% of farms, 1 V on 21% of farms and 2 V on 11% of farms. On 40% of the farms, cow contact voltages were very low in spite of the presence of voltage on the neutral because of poor electrical bonding of stabling. There was no report of the relationship between exposure levels and herd responses in this study but this study gives useful information on the occurrence of neutral to earth voltage on Ontario farms in the early 1980's.

Thornton (1984) reported on a survey of Alberta dairy farms with parlor milking systems and found that 11% had voltages over 1 V with faulty wiring as the most significant cause. There was no definite relationship between voltage levels and herd production. This study also provides an insight into the occurrence and sources of neutral to earth voltage levels on Canadian farms although it is unclear if appropriate cow-contact measurements were made.

Winter (1984) reported on a field survey of 40 farms that had installed a mitigation device called the Electronic Grounding Systems® or EGS. Initial exposure levels were not reported. There were self-reported changes in milk production, somatic cell count, frequency of mastitis, time required to milk, breeding efficiency and labor productivity. The authors noted that numerous other factors affect dairy herd performance and therefore may have influenced the results reported by the operators and that in some cases with good reductions in voltage there were no significant changes reported in herd performance. This study suffers from selection bias (only those farms purchasing a particular device included), lack of appropriate exposure verification, and lack of appropriate response verification (self reported).

Appleman (1987) reported on a statistical analysis of 84 Minnesota farms that had neutral isolators installed over the period of one year. Milk production 12 months after isolation was reported to be higher than prior to isolation and increasing more rapidly than regional averages. No other parameters studied showed significant change after isolation (average SCC, % of cows with high SCC, % of cows leaving the herd, heat detection, conception rate, calving interval). Initial exposure levels were not recorded, nor were exposure levels after isolation. This study suffers from possible selection bias (those farms that had neutral isolators installed may have been more likely to be experiencing problems and searching for solutions to these problems beyond isolation).

Albright (1991) reported on a study in which 30 Indiana dairy farms in 21 counties were checked for suspected stray voltage problems. Initial neutral-earth voltage levels at the service panel averaged 0.5 V. With all apparent electrical equipment turned on, the neutral-earth voltage levels averaged 1.1 V. Continuous monitoring on nine farms showed peak levels of 1.5 V. The installation of a Tingle voltage

Filter (TVF) on ten problem dairy farms was reported to have reduced neutral-earth voltage levels 11-fold. Major differences were found from farm to farm regarding dairy management abilities, as well as the state of electrical wiring and grounding. Nine of ten TVF herds were reported to have shown improvement in individual cow and group behavior although it was not clear how these behaviors were measured or reported or which specific behaviors improved. When comparing 12 months post installation to pre-TVF milk production data, herds were reported to show a slight increase in milk production, however, the time of year of intervention was not indicated and there did not appear to be a comparison with a 'control' group of farms. This study suffers from lack of appropriate exposure verification (only neutral-earth voltages, not cow-contact voltages measured). Many of the responses were not appropriately verified (either methods not described or self reported).

Hendrickson, (1991) conducted a field study in which cow contact voltage and current exposures were monitored 4 times/year on 110 randomly selected Wisconsin dairy farms. Dairy herd management practices were also analyzed and related to both production and voltage findings. Farms were grouped into low level and high level voltage exposure groups (greater than 0.5 V steady state or greater than 1.0 V spikes in cow contact locations = high level exposure) as well as low, middle and high milk production groups. Conclusions of this study included:

- *High level exposure was found on 34% of the survey farms on at least 1 of the quarterly checks.*
- *The high level exposure group included farms in all production groups (low, middle, and high) suggesting that rolling herd averages of greater than 18,000 lbs. can be achieved at this high exposure level.*
- *High level voltage was more common in the low and middle production groups than the high production group.*
- *The high production group displayed a significantly higher level of management intensity than the middle and low production groups suggesting that proven dairy herd management factors is key to achieving high levels of milk production regardless of the voltage exposure levels measured during the survey.*

This study had a reasonable sample size and farms were randomly selected. Exposure and response verification appear to be appropriate. The study cannot be used to establish cause and effect relationships but is a useful comparison to the types of responses observed in controlled studies.

3.10. USDA-ARS Handbook 696: Effects of electrical voltage/current on farm animals

USDA Handbook 696, issued in December 1991 is the result of a review of available research by 15 scientists. Most of the research relates to 60 Hz AC steady state voltage/current exposures. Figure 4 is reproduced from that publication and summarizes the researcher's conclusions regarding the levels of voltage and current that affect dairy cows.

The following specific conclusions are the consensus opinions of all contributors to the Handbook.

- Currents up to 4.0 mA do not appear to inhibit the milk ejection reflex, depress milk production significantly, or increase the incidence of mastitis or other diseases of the cow.
- It is doubtful that the milking machine plays a role in the exposure of cows to stray voltage. The voltage necessary to override the resistance of the milking path would be well in excess of neutral-to-earth voltages.
- Cows experience various health problems, including mastitis. Mastitis is a fact of life in the dairy industry, and it is caused by infection of the udder and not electricity.
- Factors such as milking machine problems, disease, poor sanitation, and nutritional disorders may cause cows to manifest any of the symptoms that are sometimes attributed to stray voltage/current exposure.
- While some pathway resistances approach 1000 ohms or more, worst-case resistance may be as low as 500 ohms.
- Cow contact voltages from low impedance sources should be kept less than 2 V to 4 V. (2 V corresponds to 4 mA, assuming 500 Ohm cow + contact resistance, 4V corresponds to 4 mA, assuming 1000 Ohm cow + contact resistance

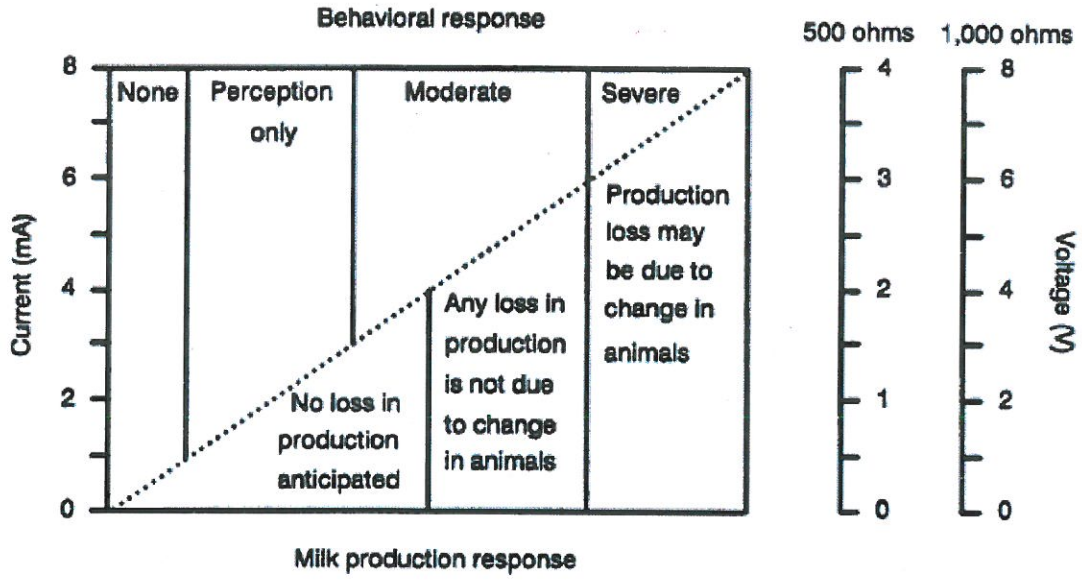

Figure 4. Behavioral and milk production responses to increasing current levels. The corresponding voltage scales on the right were estimated using a worst case circuit impedance (500 Ohms) and a more realistic impedance (1000 Ohms). (From USDA Handbook 696, Lefcourt 1991)

3.11. Studies after publication of USDA 696

In the 1990's the focus of research shifted to the effects of 'transient' 60 Hz voltage and currents and high frequency stimuli by research groups at Cornell University and the University of Wisconsin.

3.12. Cornell University II

A useful categorization of voltage/current exposures was developed based upon on-farm measurements (Aneshansley, 1997),

- Steady state 60 Hz AC voltages, greater than 1 second duration, typically 60 Hz power frequency. These steady state events can also have some harmonic content as well due to nonlinear loads.
- Momentary 60 Hz events of from 1 to 60 cycles of 60 Hz voltage/current, as occurs when a motor starts.
- Transients are events have a duration of less than 1 cycle of 60 Hz and are caused by arcing as switch contactors bounce, electric fence controllers which produce short duration pulses and other high frequency 'noise' produced by the operation of a variety of electrical devices.

A set of water bowl experiments were used to determine the current levels needed to cause a cow that was drinking, to stop drinking. These experiments examined the effect of different voltage waveforms and frequencies (Aneshansley, 1997; Aneshansley, 1999). All current levels for a response are given as the average of 16 cows with 4 replications of each treatment per cow. Events studied were

- steady state AC current from 60 to 30,000 Hz
    - higher frequencies required increased current to elicit response
- combinations of 60 and 180 Hz with different phase shifts (harmonics)
    - extreme waveform distortion can influence cow sensitivity
- short duration DC pulses
    - pulse duration less than 400 microseconds required higher current to elicit response
- DC offset combined 60 Hz current
    - DC offset had no effect on current sensitivity

The results of these studies agree well with neuro-electric theory (Reilly, 1998) and other experiments on high frequency exposures (Reinemann, 2005).

Holstein cows with a history of subclinical mastitis (cultured positive for *staphylococcus aureus*), were used to determine if seven day exposure to steady state voltages could trigger clinical mastitis (Gorewit, 1997). Cows were divided into four treatment groups of four cows each with constant voltage treatments of 0 V, 1 V, 2 V and 4 V applied continuously between water bowls and metal floor mats. Animals perceived voltages as evidenced by delays in drinking, which increased with voltage exposure

levels. Voltage exposure did not significantly influence milk production, milk composition, water intake, feed intake, blood chemistry, or blood serum concentrations of immune gamma globulins or cortisol. A trend existed for higher cortisol levels in those cows receiving voltage treatments, however. Milk production, somatic cell counts, milk fat and protein and IgM[8] levels were higher in the 0 V and 1V groups compared with the 2V and 4 V treatment groups. This was most likely caused by the subclinical *staph*. infections present in the cows at the start of experimentation.

In a second mastitis experiment 16 lactating Holstein cows (8 receiving Bovine somatotropin [bST] and 8 bST free cows) were divided in to four treatment groups of four cows each and exposed to 0 V, 1 V, 2 V or 4 V of 60 Hz rms constant voltages applied continuously between water bowls and metal floor mats for seven days (Gorewit, 1999). All cows were exposed to *streptococcus uberis*[9], as a post teat dip after milking. Voltage exposure did not significantly influence milk production, feed intake, water intake, SCC, milk fat or milk and protein. The authors concluded that steady state voltages of up to 4V, applied to water bowls, for 7days, did not promote clinical mastitis in dairy cattle predisposed to mastitis during or after direct exposure of live bacteria to teat ends.

3.13. University of Wisconsin

A research program at the University of Wisconsin was initiated at the request of the Wisconsin Department of Agriculture, Trade and Consumer Protection (WDATCP) in 1991. A citizen's advisory board to the WDATCP, composed of parties with concerns about stray voltage, established the priorities for this research. The highest priority at the time this research was initiated was dairy cow response to short duration or 'transient' voltages.

Experimental procedures were developed by an animal behavior specialist to measure and detect behavioral responses to applied current pulses. A number of suspected behaviors were monitored by human observers. Computer-based data acquisition equipment was also used to monitor animal activity. For studies in which current pulses were applied from muzzle to 4-hooves, facial activity was the most sensitive behavioral response followed by front hoof lifting. Human observers' measurements of hoof lifting agreed well with automated recording of animal motion. Tail motion showed no statistically significant response to the current stimulus (Reinemann, 1999b).

The distribution of responses at 60 Hz and higher frequencies showed remarkable agreement neuro-electric models and numerous other studies that used a variety of methods to detect behavioral response thresholds (Reinemann 1999b). The range of sensitivity to a single-cycle, 60-Hz, current pulse for 120 cows ranged from 2.8 to 19 mA (measured from zero to peak) with a median response threshold of 9.6 mA. Cows were less sensitive (e.g., more current was required to elicit a response) to shorter duration or higher frequency waveforms over the frequency range from 60-Hz to 50,000 Hz. The median sensitivity for a single-cycle, 50-kHz pulse increased to 1308 mA (measured from zero to peak). The waveform and number of cycles of the stimulus for high frequency pulses also affected sensitivity. Cows did not respond to magnetic fields of up to 4 Gauss produced by current flow in metal structures

[8] *IgM or Immunoglobulin M, is by far the physically largest antibody in the human circulatory system. IgM antibodies in serum indicates recent infection*

[9] A highly contagious mastitis pathogen.

(Reinemann, 1995a). The maximum magnetic field exposure used in this study (4 Gauss) is extreme and hundreds of times higher than any conceivable farm exposure.

A series of experiments was performed to examine the sensitivity of dairy cattle to current pulses with multiple frequency components, specifically shorter duration pulses superimposed on a 60 Hz waveform (Reinemann, 2003b). Involuntary muscle contraction thresholds were determined for cows using the muzzle-hooves exposure pathway. There was no significant interaction between the longer duration component (1 cycle of 60 Hz current or a phase duration 1/120 of a second or 8.3 ms) and the shorter duration components (pulses with durations of 1.8 ms , 1.4 ms and 0.7 ms). The authors concluded that peak-to-peak and zero-to-peak measurements of current with multiple frequency components may over-estimate the sensitivity of dairy cattle to current pulses.

Further studies were conducted to determine the level of current, relative to the behavioral reaction threshold, required to affect cows' feed and water intake and milk production. Groups of eight cows were monitored for a 14-day pretreatment period followed by a 21-day treatment during which a single-cycle, 60-Hz transient current was applied to water bowls once every second, and a 14-day post treatment period (Reinemann, 2005). Cows in these experiments were exposed to the transient current whenever they attempted to drink. In practice, transient events are not typically present every time an animal attempts to eat or drink. Exposure levels were set relative to the sensitivity of individual animals to short duration exposure to take into account the wide range of sensitivities among cows. The exposure levels ranged from 7 mA to 20 mA (measured from zero to peak). Feed and water intake, milk production, somatic cell count, blood composition, and activity level were monitored during the experiment. Average changes in feed and water intake and milk production during the 21 day treatment period were not significant when compared with the 14-day pre-treatment period. No change in SCC was found for the animals at the highest exposure level. Animals showed an acclimation to the transient current exposure with avoidance behaviors most prominent immediately after exposure and reduced avoidance response with increasing exposure time.

Significant reductions in water and feed intake, and milk production were measured on the first three days of exposure for cows exposed to 150% of their reaction threshold current level. The current level required to elicit this short term reduction in water and feed intake and milk production was thus considerably higher than that to produce a behavioral response. Behavioral effects, as indicated by delay to drink and gross observation, were apparent during the first day of exposure at levels lower than those required to cause measurable changes in daily total water and feed intake or milk production. On average, an increase in the reaction threshold (cows became less sensitive) was observed between pre-treatment and post-treatment periods. This confirms results of previous studies and field observations noting rapid acclimation to voltages as well as changes in animal behaviors with no measurable decline in water or feed intake or milk production.

Short-term aversion to water was also observed in a second study when a single-cycle 6000 Hz current pulse (ranging from 60 to 150 mA zero-peak current) was applied to the water bowl (Reinemann, 1996). Reduced water consumption was again observed for current exposure levels 150% of the behavioral response threshold. Predictability of aversive response was improved over previous studies by taking into account individual animal sensitivity. This result clarifies previous experiments in which animals had

to be removed from experimental trials because of dramatic response. More consistency in behaviors was observed, and greater response was obtained when using a multiplicative current exposure scheme (150% of behavioral response threshold), than with an additive scheme (1.5 mA or 3 mA + behavioral response threshold). The responses were all explainable by avoidance of water bowls associated with the presence of an annoying stimulus rather than direct physiological effects.

A subsequent study investigated aversive response of a continuously-applied stimulus to intermittently-applied stimulus (Reinemann, 2004). A continuously applied current pulse at 150% of each cow's behavioral response threshold resulted in reduced the water consumption, while the intermittently applied pulse at the same current level did not result in reduced water intake. In order for current exposure to affect cows, the applied current must first be of sufficient level to cause avoidance behavior. In addition, these events must also occur often enough to cause animals to avoid water and/or feed.

The relationship between cow impedance and cow sensitivity was also examined in these studies. There was a trend for more sensitive cows to have higher resistance. Thus using the minimum threshold current for the population of cows combined with the minimum impedance from that same population will result in an overly conservative estimation of the minimum threshold contact voltage for that population. Measurement of cow contact voltage and current using a 500-Ohm shunt resistor have been shown in these laboratory studies as well as field studies to be a conservative estimate (worst case) of the current likely to flow though a cow.

There was no evidence from these studies that there was any direct physiological effect of voltage and current exposures below the levels at which a behavioral response could be documented nor at levels at which aversion to water and/or feed are first observed. The short term decreases in water and feed intake that was documented were consistent with aversive response to an unpleasant stimulus.

3.14. AgroParisTech

The most recent series of studies to examine the effects of stray voltage on farm animals was begun at the French Agricultural University, AgroParisTech, in 2005. Roussel (2007) determine the threshold level at which heifers perceive the electric shock, using an avoidance test. Twenty Holstein heifers were exposed in steps of 0.3 V up to 5 V applied to a feeding cup. Twenty additional heifers followed the same avoidance test but without any electricity applied. For exposures of 2.3 V or greater, the percentage of total feed eaten from the electrified feeder and the time spent eating in the electrified feeder decreased. Above 3 V heifers changed more quickly to the non-electrified feeder. Above 2 V heifers performed more muzzle-grooming and head shaking than the control group. The authors concluded that a voltage of 2.3V appeared to be the threshold at which avoidance behavior starts. Further research is underway study whether individual electrical resistance may explain some of the variability in the voltage threshold.

Rigalma (2007) reported on a 3-week period of 3.3 V exposures at metallic feeders in either a continuous or unpredictable manner with twenty electricity-naïve heifers or twenty heifers that had experienced voltage exposure previously. Heifers with unpredictable exposure tended to spend more time eating in the electrified feeder, made more abrupt head movements and more muzzle-grooming

behaviors than those in the continuous exposure group. Although no behavioral differences were observed between naïve and experienced heifers, the naïve heifers had higher cortisol concentrations on the first day when the voltage was applied. Naïve heifers with continuous exposure ate more and changed feeder quicker than the naïve heifers in the unpredictable exposure group. They concluded that heifers with unpredictable exposure had more difficulty in adapting and that past-experience seemed to reduce the response. Preliminary results (to be presented by Rigalma in 2008) suggest that unpredictable exposure may not offer sufficient time to the heifers to learn how to adapt.

A study has been initiated to examine behavioral and endocrine responses for a large sample size of lactating cows (about 100) in a free-stall barn environment. Studies have also just begun at Limoges University to remotely measure current flowing through cows in their normal farm environment. The results of these studies will be a valuable contribution to better understand the level and time patterns of current exposures in real-world farm conditions. Work is also being conducted on mitigation methods (personal communication with researchers at stray voltage conference in Limoges, France, November 2007).

3.15. Minnesota Science Advisors Study

In 1994 the Minnesota Legislature authorized the Minnesota Public Utilities Commission (MPUC) to establish a committee of science advisors in response to claims by The Electromagnetic Research Foundation (TERF) that electric currents in the earth from electric utility distribution systems are somehow responsible for problems with animal behavior, health and production problems of dairy cows. The Science Advisors were a multidisciplinary group with expertise in the fields of agricultural engineering, animal physiology, biochemistry, electrical engineering, electrochemistry, epidemiology, physics, soil science and veterinary science. These science advisors were assigned the following tasks:

- Review any evidence that might support the proposal that earth currents adversely affect dairy herd health and production.
- Determine whether further research in this area is warranted.
- Oversee any research proposed to resolve questions related to possible earth current effects.
- Provide recommendations to the PUC based on available evidence and the results of any research conducted with funds appropriated under the legislation.

A progress report was issued in January 1996 in which it was noted then that currents in the earth can only interact with dairy cows through their associated electric fields, magnetic fields and voltages, and that these parameters should be the focus of analysis, rather that earth currents per se. A survey of Minnesota and Wisconsin dairy operators was designed to obtain information on the specific types of herd health and production problems and to assess the extent to which owners of dairy herds attribute such problems to stray voltage or other causes. A field study was conducted to assess possible associations between selected electrical and non-electrical parameters and the presence or absence of persistent problems associated with dairy cow health and milk production. The MPUC also funded follow-up laboratory research at the University of Wisconsin.

Based on their study and analysis the science advisors reached the following conclusions (MPUC, 1998):

1. *"We have not found credible scientific evidence to verify the specific claim that currents in the earth or associated electrical parameters such as voltages, magnetic fields and electric fields, are causes of poor health and milk production in dairy herds."*

2. *"At the present time, there is no basis for altering the PUC-approved standards by which electric utilities distribute power onto or in the vicinity of individual dairy farms."*

3. *"There are many well-documented non-electrical factors that are known and accepted by the scientific community, and by most farmers as well, to cause dairy cow health and production problems. Among the most noteworthy stressors are poor nutrition, poor cow comfort and hygiene, and low or no use of vaccinations and related preventive veterinary practices. Those who want to improve performance of dairy herds should always address these factors."*

Other Notable conclusions were:

> *"It is important to note here that there is a difference between what is conceivable or possible and what is likely or probable. For example, a National Institute of Environmental Health and Safety committee concluded that there is a possible not a probable association between the presence of 60 Hz magnetic fields of 2-3 milliGauss or higher and childhood leukemia. In the 19-farm field study described in this report, the average AC magnetic fields measured inside the dairy barns were on the order of 0.5 milliGauss. Thus with the present body of evidence, it is our best judgment that magnetic fields from earth currents or any other contributory sources in the dairy barn are not of sufficient levels to cause any health or production problems in dairy cows."*
>
> *"At the present time, there is only one electrical condition that is well documented in the peer reviewed, published literature to influence adversely cow behavior, health or milk production under specific circumstances. That is cow contact stray voltage."*

While each of the Science Advisors accepted the final report and recommendations, one of the science advisors published a paper with his personal follow-up analysis of the Science Advisors Report (Polk, 2001). Some of the conclusions from this paper were:

- *At present it is not known whether and how the long-term exposure to step voltages above 9 mV can affect health and/or milk production of dairy cows. This can only be established by laboratory experiments where major variables known to affect animal health can be controlled.*

- *It appears desirable to measure soil resistivity when a dairy farmer reports possible electricity related cow health and production problems*

- *The author alone is responsible for the analysis presented here and the conclusions drawn.*

The analysis in this paper consists of a series of more than twenty T-tests was done on a limited data set. Statistical theory indicates that if a p value of 0.5 is used as a test of significance, one of 20 tests would show significance due to chance correlation. The correlation between Milk/per/cow/day and

voltage exposure during low use hours was claimed to be significant (p=0.0418) but is highly influenced by one outlier in the rather small data set and when this outlier is removed the correlation is not significant. The correlation is in the best case extremely weak, and in the reasonable case is nonexistent. Many other differences in management factors were more significant than voltage exposure during the low voltage period. Dr. Polk's paper does not refute any of the original science advisors conclusions and there is insufficient evidence in the 2001 analysis to challenge the original conclusions of the Science Advisors Report, of which he was an author. Another Science Advisor published a statement (Stetson, 2003) in which he indicated that Polk (2001) apparently used a limited selection of data from the Science Advisor Report and misinterpreted the data from the farms with the stall mats. Dr. Polk died in 2000 so he is not able to defend his published comments.

3.16. University of Wisconsin II

Controlled laboratory studies at the University of Wisconsin were commissioned by the MPUC to investigate a hypothesis developed by the Science Advisors. In these studies stress hormones and immune function response of dairy cows exposed to low-level step potentials were examined. A first series of experiments was performed to measure behavioral responses and changes in blood cortisol concentration of cows exposed to 60-Hz electrical current applied from front to rear hooves (Reinemann, 2003c). Cortisol levels did not increase in response to short-term current exposure at levels up to 150% of the behavioral reaction threshold. Cortisol concentrations were found, however, to increase in response to hoof trimming. These results confirm several previous studies indicating that behavioral changes are a more sensitive indicator of response to short-term electrical current exposure than blood cortisol levels.

Milking performance of cows subjected to electrical current during milking and two common milking machine problems were documented (Reinemann, 2003a). The first experiment used 32 cows in a 2x2 factorial design with exposure to 1 mA (60-Hz rms) of electrical current from front to back hooves during milking and a pulsation failure (no massage phase) as treatments. A second experiment used 16 cows in a 2x2 factorial design with exposure to 1 mA (60-Hz rms) of electrical current from front to back hooves during milking and excessively aged milking machine liners as treatments. The main effect of current exposure was not statistically significant for milk yield, average milk flow rate, maximum milk flow rate, cow activity, and strip yield. The main effect of pulsation failure was significant for cow activity (5.8 fewer weight shifts during a milking). The main effect of aged liners was significant for milk yield (2.2 kg increase), average flow rate (0.3 kg/min reduction), maximum flow rate (1.2 kg/min reduction), and liner slips (26 more per milking). The significance of some interactive effects appeared to indicate that current exposure had a mitigating effect on the changes caused by the milking machine problems. These interactions were not consistent across experiments, however, and in some cases were highly influenced by a few observations. This study adds further evidence to the body of literature showing that exposure to low-level step potential resulting in less than 1 mA rms of 60-Hz electrical current during milking is not a cause of cow discomfort or poor milking performance.

A third series of experiments were performed in which twelve mid-lactation dairy cattle were subjected to intermittent 60 Hz electrical currents of 1 mA rms from front to rear of stall for a period of 14 days (Reinemann, 1999a). An additional 12 cows were housed in identical stalls with no treatment. Electrical

monitoring indicated that achieved current was within 10% of target. Feed intake, water intake, milk production and rectal temperature were monitored daily and were unaffected by treatment. Behavioral measurements, including percentage of time lying and time to re-enter stalls after milking, were unaffected by treatment. Immune function was assessed by analyzing blood samples taken twice a week for thirteen different response variables. There was no statistically significant difference between control and treatment cows for any of the main response variables. The difference between the control and treatment cows was statistically significant for one of the secondary response variables but did not appear to be consistent with other observations. Collectively, these results suggest that exposure to 1 mA of current for two weeks had no significant effect on the immune function of dairy cattle.

3.17. Recent Dairy Field Studies.

Southwick (1992) reported on a dairy farm located in central New York State that was visited following complaints of electrical shock in the farmhouse shower and the milk house sink. As much as 2 V AC of potential difference was measured between the waterline and the cow platform (cow-contact voltage) and attributed mainly to a utility source. The farm's electrical service was modified so that the farmstead could be connected or disconnected from the primary neutral wire at 2-week intervals for 12 weeks. When connected to the primary neutral wire, voltage between waterline and floor ranged between 0 and 1.8 V. When disconnected from primary neutral wire, voltage between waterline and floor was less than 0.1 V. There was no difference in mean milk production, bulk tank milk somatic cell count, or water consumption among periods when cows were exposed or unexposed to voltage. Although not statistically significant the values for somatic cell count were lower and water consumption was higher when cows were exposed to voltage than when they were not. This field study is notable in that the exposures and responses were appropriately verified and a switchback design was used to avoid confounding with time (to reduce the influence of the many other factors that can affect dairy cow health and production).

Reines (1998) presented data from more than 2900 stray voltage investigations performed in Wisconsin. The data collected includes electrical characteristics of both the distribution and on-farm wiring systems as well as rolling herd average milk production and bulk tank average somatic cell counts. More than 85% of the first investigations reported maximum primary and secondary neutral-to-earth voltages less than 2 V. More than 90% of investigations reported maximum cow contact voltages less than 1 V. The correlation between electrical parameters was as expected from electrical theory. However, specific measurement of each parameter is required because predictive ability is low. Indicators such as ground per mile, primary neutral or secondary neutral-to-earth voltages are not good predictors of cow contact voltage. This is probably due to the prevalence of on farm sources, which can either add or subtract from primary sources. It is imperative to properly identify the voltage sources and their interaction before implementing mitigation. There was no meaningful correlation between primary neutral-to-earth voltage, secondary neutral-to-earth voltage, cow contact voltage, or ground rod current and either rolling herd average milk production or somatic cell count ($r < 0.02$). The correlation between the monthly average somatic cell count reported by stray voltage investigators and by the USDA for all farms in the Midwest ($r = 0.58$) was an order of magnitude higher than for any electrical parameter.

Inappropriate conclusions about changes in somatic cell count and milk production can be drawn if these seasonal trends are not taken into account.

The Public Service Commission of Wisconsin has continued to collect data from stray voltage investigations. The most recent report (PSCW, 2007) presents charts and statistics form 8388 farm investigations. Only about 7% of these farms had cow contact voltage in excess of the PSCW level of concern of 1 V measured across a 500 Ohm resistor. Both cow contact current and primary neutral-to-earth voltages have decreased substantially since the early 1990's as the result of efforts by the PSWC and electric power suppliers. These data show no meaningful correlation between:

- current return ratio and elevated somatic cell count
- current return ratio and rolling herd average milk production levels
- cow contact current level and somatic cell count
- cow contact current level and rolling herd average milk production

This lack of correlation is consistent with experimental studies which indicate no expected cause and effect relationship between herd health and production at exposure levels below 1 V at animal contact locations. This continuing field survey is notable in its very large sample size. If voltage and/or current exposures did have a causal influence on dairy cow animal health and production, it should be apparent in this large sample. Because the vast majority of farms (93%) are below the 1 V (2 mA) level of concern, it is not surprising that there is no apparent trend in milk production or somatic cell count with increasing voltage exposure. This data set presents strong evidence of the lack of a dose/response relationship from extremely low exposures up to 1 V (2mA) exposures, confirming results from controlled studies indicating that dairy cow responses would not occur at these low exposure levels.

3.18. Other Species

The vast majority of stray voltage studies have been performed on dairy cows; however there are also a number of studies that have been performed on other species that have been summarized below.

3.18.1. Swine[10]

Gustafson (1986) reported that eight growing/finishing pigs exposed to 60 Hz electrical currents administered through a mouth-to-all-hooves showed a preference for a water source with no current

[10] *The studies reported here are published works in which sheep were exposed to voltage and current levels typical of stray or tingle voltage. There have been other studies on swine with extremely high level of current exposure: Ziecik (1993) foot-shocks increased cortisol concentration in blood during the first hours of stimulation but at the end of treatment cortisol was even lower than in control animals. Sein (1994) transcranial electro-stimulation during 3 days shortened the pubescence period and increased the quantity of ovulated follicles in swine.*