# Appendix L

## Stray Voltage Supplement

# Literature Review and Synthesis of Research Findings on the Impact of Stray Voltage on Farm Operations

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For the

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## Executive Summary

This report synthesizes the main findings and conclusions of the body of scientific literature on the potential for tingle voltage (or stray voltage) or at power frequencies (50 to 60 Hz), to directly or indirectly affect farm output or productivity. The report includes:

- A review of scientific literature,
- A description of the symptoms indicative of the presence of tingle/stray voltage,
- Descriptions of the pathways whereby tingle/stray voltage can have an impact on farms,
- An indication, by animal type, of the minimum voltage and current level at which impacts on farm operations can be expected,
- A description of the on-farm measures available for mitigating tingle/stray voltage, and
- The range of regulatory measures that have been adopted to achieve the objective of ensuring that tingle/stray voltage does not unduly impact farm operations.

The direct effect of animal contact with electrical voltage can range from:

- Mild behavioral reactions indicative of sensation, to
- Involuntary muscle contraction – or twitching, to
- Intense behavioral responses indicative of pain,

The indirect effects of these behaviors can vary considerably depending on the specifics of the contact location, level of current flow, body pathway, frequency of occurrence, and many other factors related to the daily activities of animals. There are several common situations of concern in animal environments:

- Animals avoiding certain exposure locations which may result in,
    - Reduced water intake that may result if painful exposure is required for animals to access watering devices,
    - Reduced feed intake that may result if painful exposure is required for animals to accesses feeding devices or locations,
- Difficulty of moving or handling animals in areas of annoying voltage/current exposure,
- The release of stress hormones produced by contact with painful stimuli.

The review of literature in this study used published studies that included data from controlled experiments and field studies. This review synthesizes these studies and summarizes the conclusions of hundreds of researchers to provide the basis for a consensus view of the scientific community.

The majority of tingle/stray voltage research has been done on dairy cows. The accepted practice by researchers and regulators has been to assume worst-case (lowest practical values) for cow contact resistances. Studies done to measure more typical body + contact resistances that would occur on farms have shown that 500 Ohms to 1000 Ohms is a reasonable range to use in a measurement circuit to estimate the current that would flow through a cow's body. The most sensitive dairy cows may experience mild behavioral modifications at current exposures exceeding 2 milli-Amps (60 Hz AC rms) corresponding to 1 Volt to 2 Volts (60 Hz, AC rms) of cow contact exposure in farm exposure situations. Aversion and metabolic changes have been documented to require substantially higher voltage and current exposures. It has also been shown that the equivalent to 2 mA of 60 Hz AC current (2 Volts of 60 Hz AC rms voltage) is about 2.8 mA of DC current (2.8 Volts DC). In addition dairy cows are much less sensitive to high frequency or short duration electrical exposures than for 60 Hz rms AC current (A much

higher current is required to elicit the same response). Numerous studies have documented that cows rapidly acclimate very quickly to even very high levels of voltage/current exposure and behavioral modifications become less pronounced in a matter of several days.

Research suggests swine respond to voltage/current exposure in a similar way to cows. Behavioral modification has been observed at about 5 Volts with avoidance behaviors at exposures of 8 V. The body + contact resistance for swine appears to be somewhat higher than for cows and 1000 Ohms appears to be a conservative value for measurement purposes.

Neuro- electric principles suggest that the current sensitivity of sheep is lower than for cows, but that their body resistance is higher than cows. Ewes have been shown to avoid electrified feed bowls when exposure levels exceed 5.5 V while Lambs showed this same preferential behavior when exposure levels exceeded 5 V.

Exposures to voltages as high as 18 V had no effect on the hens' production and behavior. This is likely due to the very high electrical resistance of poultry which has been documented to be between 350,000 and 544,000 Ohms.

The source of stray voltage is a voltage that is developed on the grounded neutral wiring network of a farm and/or the electric power delivery system. The magnitude of the voltage source is a product of the current flowing on the neutral system and the resistance of that neutral system. Grounding is provided to keep the voltage potential between the neutral system and the ground below levels that could be harmful to people or animals. Neutral-to-earth, or stray voltage can be reduced in three fundamental ways:

- reduce the current flow on the neutral system,
- reduce the resistance of the neutral system, or
- Improve the grounding of the neutral system

The first step in a competent stray voltage investigation is to determine the major sources of neutral-earth voltage. Any major faults or code violations in the wiring system that could pose an electrocution hazard or are a major source of neutral to earth voltage should be corrected immediately. If the wiring systems (farm and utility) are operating correctly then the above three actions can be assessed to determine which is most practical, safe and efficient way to reduce neutral-earth voltage. Equipotential planes are effective in eliminating contact potentials even if substantial levels of neutral-to-earth voltage are present.

Several jurisdictions have conducted scientific and technical reviews and held public hearings to address concerns and inform public policy on stray voltage issues. Some States have adopted regulations dealing with stray voltage while others have developed multi-agency and stakeholder groups to develop guidelines and standard practices. State regulations generally relate to the maximum utility contribution to on-farm voltage levels (since most only have regulatory authority over investor owned utilities) while stressing the importance of reducing on-farm sources of neutral voltage through compliance with wiring codes and good management practice.

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# 1 Introduction

## 1.1 Scope of this Report

The general scope of this report is to synthesize the main findings and conclusions of the body of literature on the potential for tingle voltage, or stray voltage to directly or indirectly affect farm output or productivity. The specific elements of this report include:

- A **literature review** on the effects of stray voltage on farm animals Including;
    - A review and synthesis of academic, industry, government agency and other sources of information, with publications from 1990 onwards being the main focus. Earlier publications have been included where important and appropriate.
    - These publications form a comprehensive review of all studies in which farm animals have been exposed to voltage or current sources and are divided into two general categories; controlled studies in which exposure (or dose) levels and responses have been documented and field studies in which exposures and responses have not been recorded as accurately (or at all). A discussion of conclusions that can be drawn from each type of study anda comparison of these studies is included in this report
- A description of some common **symptoms** associated with the presence of stray voltage is provided along with a discussion of other causes that can give rise to these same symptoms is presented.
- A description of the exposure **pathways** whereby stray voltage can have an impact on farm operations.
    - Details are provided, where available, as to variations in the electrical components of various contact pathways
    - Differences in impacts associated with variations in exposure duration, exposure level, contact pathway and animal type are discussed.
- An indication, by animal type, of the **minimum voltage (or current) level** at which impacts on behavior, health, reproductive success and productivity and overall farm operations would be expected.
- A description of the on-farm measures available for mitigating stray voltage with their respective level of effectiveness at reducing or eliminating impact of stray voltage from all sources (on- and off-farm) on farm operations.
- The range of regulatory measures that have been adopted to achieve the objective of ensuring that stray voltage does not unduly impact farm operations.

## 1.2. Ways That Stray, or Tingle, voltage Can Impact Farm Operations

The terms stray voltage and tingle have been used for about the past 40 years to describe a special case of voltage developed on the grounded-neutral system of a farm. The definition of stray (or tingle) voltage accepted by the scientific community is that it is a low-level electrical shock that can produce sensation or annoyance in farm animals[1].

### 1.2.1. Direct effects

The direct effect of animal contact with electrical voltage and the resulting current flowing through their bodies can range from:

- Mild behavioral reactions indicative of sensation, to
- Involuntary muscle contraction – or twitching, to
- Intense behavioral responses indicative of pain,

The severity of response will depend upon the amount of electrical current (usually measured in milliamps, mA) flowing through the animal's body, the pathway it takes through the body and the sensitivity of the individual animal.

### 1.2.2. Indirect effects

The indirect effects of these behaviors can vary considerably depending on the specifics of the contact location, level of current flow, body pathway, frequency of occurrence, and many other factors related to the daily activities of animals. There are several common situations of concern in animal environments:

- Animals avoiding certain exposure locations which may result in;
    - Reduced water intake that may result if painful exposure is required for animals to access watering devices,
    - Reduced feed intake that may result if painful exposure is required for animals to accesses feeding devices or locations,
- Difficulty of moving or handling animals in areas of annoying voltage/current exposure,
- The release of stress hormones produced by contact with painful stimuli.

The levels of voltage exposure and current flow through animals required to produce these various behaviorally mediated responses are identified in the summary of research studies in section 3.

A number of studies have been done to investigate direct physiological effects that may be produced at levels **above** those that produce behavioral changes, as well as potential detrimental physiological responses that may result from animals' exposure to voltage/current **below** levels which may produce

[1] Stray voltage is defined in a Handbook published by the United States Department of Agriculture as a small voltage (less than 10 V) measured between two points that can be contacted simultaneously by an animal. Because animals respond to the current produced by a voltage and not to that voltage directly, the source of the voltage must be able to produce current flows greater than the threshold current needed to elicit a response from an animal when an animal, or an equivalent electrical load, contacts both points (Lefcourt, 1991).

sensation and behavioral response. These studies have shown that increased concentrations of the stress hormone cortisol do not occur at levels below behavioral response levels and only become apparent in some, but not all cows, at substantially higher voltage/current exposures than the threshold required for behavioral modification, and typically at levels that produce severe behavioral changes and probably at current levels that produce discomfort and/or pain. Furthermore, the failure of several experimental and field studies to demonstrate detrimental effects of current exposure on the incidence of mastitis (an infection of the mammary gland) and immune function response indicate that the levels of voltage/current exposure that elicit behavioral changes do not compromise the immune function of dairy cows.

# 2. Overview of Electrical Exposure and the Physiology of Animal Contact voltage and Current

## 2.1. Basic concepts of voltage, current, and resistance

The relationship between voltage exposure and current conducted through the animal is described by Ohms Law[2]. This simple relationship has been a source of much confusion and resulting controversy in the stray voltage debate. One way to think about electricity is that voltage is the driving force and current is the resulting movement of electrons through the resistance of the wire (or animal). It **is possible** to have a voltage source with no resulting current flow if the resistance value is infinite (as is the case when a switch is turned off, or a valve is shut). It is **not possible** to produce current flow in the absence of voltage, regardless of the resistance of the circuit.

While the contact voltage is often used to describe animal exposure conditions, it is the resulting current flowing through animals' bodies that determines the 'dose' and the resulting type and degree of nerve stimulation. The exposure (voltage) and the dose (current) are related by the resistance (measured in Ohms) of various parts of the electrical circuit.

It is critically important to use a realistic value of animal resistance (or impedance[3]) to relate voltage exposures to the level of current conducted through an animal and the resulting effects on nerve stimulation, sensation and behavioral reaction. Figures 1 and 2 illustrate the elements of the electrical circuit that occurs when an animal comes into contact with a voltage source.[4]

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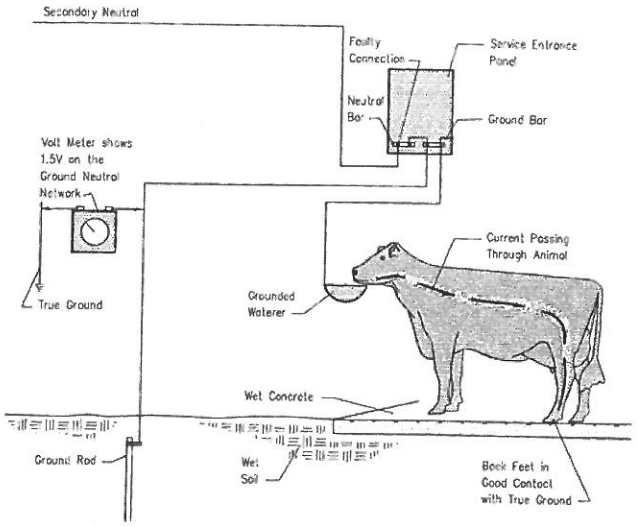
[2] Ohm's law expresses the relationship between voltage, Current and Resistance in an electrical circuit.

A common form of Ohm's Law is: $\textit{Current (Amps)} = \frac{\textit{Voltage (Volts)}}{\textit{Resistance (Ohms)}}$

Ohms law indicates that if the voltage (across animal contact points) is increased, the current flowing through the animal will increase. Likewise, if the resistance (of contact points) is increased, the current flowing through the animal will decrease. The current measure used in many stray voltage studies is milli-Amps or 1/1000$^{th}$ of an Amp. The measurement circuit used for field investigations uses a 500 Ohm Resistor to simulate the combined resistance of a cow's body + conservative estimates of the resistance of the two contact points. Using these values a cow contact current of 2 mA would result from a cow contact voltage of 1 V and a cow+contact resistance of 500 Ohms.

$$\textit{Current}\left(\frac{1}{500}\ \textit{Amps} = \frac{2}{1000}\textit{Amps} = 2\ \textit{Milliamps}\right) = \frac{1\ \textit{Volt}}{500\ \textit{Ohms}}$$

[3] Resistance refers to the physical properties of materials while impedance incorporates capacitive and inductive elements. Impedance is a more technically specific term for AC circuits but resistance will be used here for simplicity. There are some special cases in which capacitive and inductive elements must be considered and these will be noted.



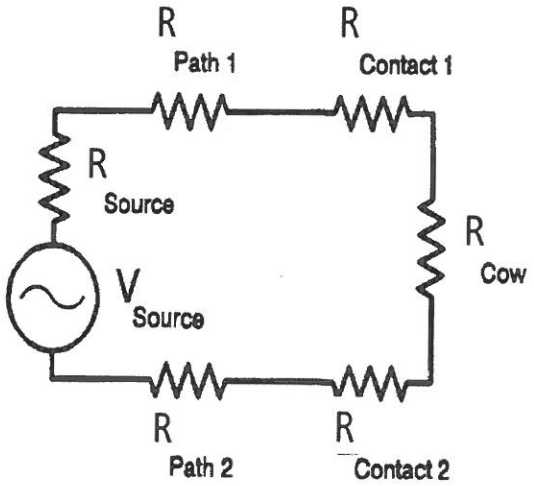




**Figure 1. Cow drinking from a water bowl.** **Figure 2. Elements of the electrical circuit.**

The source circuit is represented by the left half of Figures 1 and 2.

- $V_{source}$ = the source voltage, usually a voltage drop developed by current flowing through the resistance of neutral wires. $V_{source}$ is also referred to as open circuit voltage and is the voltage between two animal contact points/areas measured without a shunt resistor.
- $R_{source}$ = the internal resistance of the source, in our example, the resistance of the neutral wire. The three resistances in the source circuit are commonly grouped together into a single source resistance ($R_{source} = R_{path1} + R_{path2} + R_{source}$).
- $R_{path1}$ = the resistance of the path from the voltage source (neutral wire) to the water bowl. If the farms grounding system is well bonded (or electrically connected) this resistance will be very low. If the farm is not well bonded this resistance can be very high.
- $R_{path2}$ = the resistance of the path from the floor back to the source, in this example the resistance of the concrete floor, the earth itself, and the grounding connection back to the neutral wire. If the farm has an equipotential plane that is bonded to the grounded neutral system this value can be very low. If the farm does not have an equipotential plane this value can be very high.

The animal circuit is represented by the right half of Figure 2 and the Cow and its muzzle and hoof contact points in Figure 1. The three elements of the animal circuit are commonly grouped together to form an equivalent animal+contact resistance (500 Ohms for cows) for measurement purposes. This is the value of the shunt resistor used to estimate current flow though an animal.

- $R_{body}$ = the body resistance of the animal across the contact pathway, in our example muzzle to 4 hooves.
- $R_{contact1}$ = the resistance of contact point 1, usually the animals mouth/muzzle or front hooves/feet. This resistance value can be quite low in the case of a wet muzzle in firm contact with a wet metal plate. There are other situations in which this resistance value is quite high such as muzzle contact through feed on a metal feed bowl or an animal's muzzle in a water tank, without making contact with the walls of the tank.
- $R_{contact2}$ = the resistance of contact point 2, usually the animals 4 hooves/feet or rear hooves/feet. This resistance value is also quite variable from relatively low values for animals standing on clean water pooled surfaces to very high values for animals standing on surfaces covered with debris, manure, bedding, etc.

Correct measurement technique involves cleaning the contact surfaces and wetting them with a conductive solution to eliminate the contact resistances. These contact resistances are then added back into the animal body resistance to provide a realistic animal+contact resistance value that is used as the 'shunt' resistor in the measurement circuit. Scenarios illustrating the importance of understanding the resistive components of the electrical circuit are presented in Table 1.

Table 1. Examples of Cow Contact Circuit Resistance Values.

| V(source)[1] | R(Source)[2] | R(cow + contact)[3] | V(cow contact)[4] | Current through cow[5] |
|---|---|---|---|---|
| 1 V | 100 Ohms[6] | 500 Ohms[7] | 0.8 V[8] | 1.7 mA |
| 1 V | 100 Ohms[9] | 1,000 Ohms[10] | 0.9 V[8] | 0.9 mA |
| 1 V | 1,000 Ohms[12] | 1,000 Ohms[10] | 0.5 V[11] | 0.5 mA |

*Notes:*

*[1] Vs, Also referred to as open circuit voltage measured without a shunt resistor.*

*[2] Rs, combining internal resistance of the source and path resistances to contact points*

*[3] Rcc, combining animals body resistance and 2 contact resistances (muzzle to water bowl and hooves to floor, or front hooves to floor and rear hooves to floor)*

*[4] Vcc, Also referred to as the exposure level. Vcc = Rcc / (Rs + Rcc)*

*[5] Ic, or the dose level which determines nerves stimulation. Ic = Vcc / Rcc*

*[6] A farm on which conductive elements are well connected to the grounding system.*

*[7] Rcc = 350 Ohms cow + 150 Ohms, or a cow standing on a clean wet concrete floor and drinking from a metallic water bowl.*

*[8] Cow contact voltage is somewhat less than the source or open circuit voltage.*

*[9] A farm on which conductive elements are well connected to the grounding system.*

*[10] Rcc = 350 Ohms cow + 650 Ohms Contacts, or a cow standing on dry concrete with minimal debris.*

*[11] Cow contact voltage is considerable lower than the source or open circuit voltage.*

*[12] A poorly bonded farm, metallic objects in animal areas not grounded.*

The examples in Table 1 illustrate that for the same source voltage (measured 'open circuit' with no shunt resistor) the resulting animal current (or dose) varies by a factor of 3. Changes in the contact resistance, resulting from small differences in the animal environment, changed the current dose by a

factor of 2. While a poorly bonded farm, in which metallic objects in animal areas are not connected to the farms grounded neutral system, produced less current through an animal, there is also a much higher risk of electrocution because the lack of proper grounding can cause breakers to fail, and expose people and animals to lethal voltage in the event of an electrical fault.

Source resistance values also show variability depending on the quality of bonding and local soil conditions on each individual farm. Measurement of the source resistance is essential in assessing voltage/current exposure risk and is an essential part of stray voltage measurement technique. Once these source resistance values have been measured on an individual farm they show relatively little variation, unless the farm wiring system is altered.

### 2.1.1. The Problem of Contact Resistance

The body resistance of several species of farm animals through various body pathways has been measured in several studies. Measures of an animal's body resistance depends on the pathway between the contact points (e.g. muzzle-hoof or hoof-hoof) and the way in which the contact is made including factors such as the area over which the contact is made, pressure applied to the contact, and use of conductive liquids or gels on the measurement connection.

Some studies have tried to isolate the body resistance of animals using contact conditions not encountered in normal farm operations such as:

- removing contact resistance by injecting voltage/current under the skin (Gorewit, 1985)
- Applying current through EKG patches applied to shaved skin (Lefcourt, 1985)
- Minimizing contact resistance by providing extremely low contact points at the hoof (such as wetted expanded metal plates) and/or muzzle (bits or nose clips) (Norell, 1983; Currence, 1990; Reinemann, 1999; Aneshansley, 1999).

The lowest body resistance values have been reported when the skin of the animal was pierced using needles. The next lowest category of body resistances include measurement electrodes affixed to shaved patches of skin. The majority of body resistance measurements have been made with cows coming into contact with a metallic device such as: standing on a metal plate, standing on a metallic mesh, metallic bit in the animals' mouth, metallic clip applied to the animals' nose. Definition of the body pathway and mode of contact will allow a reasonable estimate to be made of an animals' body resistance and reasonable population estimates are available for cows and swine for typical pathways (mouth-feet, foot-foot).

Contact resistances are the most difficult value to predict in real-world farm situations. Fewer studies have been done to characterize real-world contact resistances. It is clear from these studies as well as physical principles that real-world contact resistances have enormous variability. The lowest contact resistances would be expected if a clean, wet body part (such as a cow's muzzle) comes into contact with a clean, wet, metallic object with a substantial mutual contact area and substantial contact pressure. Contact resistances will increase with:

- smaller contact surface area (e.g. a point contact the size of a pencil eraser compared to a metal plate applied over a surface the size of your hand)

- reduced contact surface pressure (e.g. a light touch versus a contact applied with the weight of an animal)
- drier contact surfaces
- the amount of debris on either the animal contact point (e.g. bedding/manure impacted in hooves or feed at the muzzle)
- the resistance value of the debris at the contact margin (e.g. dry straw compared with wet manure)

The accepted practice by researchers and regulators has been to assume worst-case (lowest practical values) for contact resistances. Studies done to measure more typical body+contact resistances that would occur on farms (Lefcourt, 1991; Reinemann, 2005) have shown that 500 Ohms to 1000 Ohms is a reasonable value to use in a measurement circuit to estimate the current that would flow through a cow's body. Although the resistance of the cows body is typically less than 500 Ohms for the muzzle to hoof pathway (other pathways have a higher resistance), it has been shown to be a 'worst case' or minimum resistance value for the combination of a dairy cows body + real-world contact resistance in the farm environment.

There have been fewer studies on other species, but the same principle will apply to any animal contact situation. A review of each species and common contact points is included in section 4 of this report.

## 2.2 – Nerve Stimulation and Response

### 2.2.1 The Bio-mechanics of Nerve Stimulation

Behavioral responses are the result of nerve stimulation that elicits a sensation and/or muscle contraction in an animal. The bio-mechanics of nerve stimulation with electrical exposure has been widely studied and is well understood[5]. Nerve stimulation is characterized by a current threshold. Current applied below the threshold will not produce nerve excitation, and hence no sensation, motor response or behavioral response can occur (Figure 3). At the current level just above the threshold of nerve excitation sensation will result, which may be perceived but is not painful. As the current level is increased above the threshold involuntary muscle contraction begins to occur. This lower margin of muscle contraction is not painful. Pain can be experienced at as current exposures are increased further due to both increased sensory stimulation and more intense muscle contraction.

[5] *The 1998 text Applied Bioelectricity: from Electrical Stimulation to Electropathology by J.P Reilly is a definitive reference on the biomechanics of nerve stimulation and resulting pathologies. This text summarizes the vast body of research on electrical stimulation over the past 100 years or more. Electrical properties animal tissues are described. The use of electrical stimulation for beneficial medical purposes is covered as well as pathological exposures that may result in injury, death or other undesirable conditions. It has been shown that the broad body of research on nerve excitation in humans also applies to nerve excitation in animals. Both sensation and muscle reactions can be elicited with electric currents conducted through the skin... These effects occur when nerves (or neurons) are excited – sensory neurons in the case of sensation, or motor neurons in the case of muscle reactions. Sensory effects are usually elicited with lower stimuli than are motor effects.*

### 2.2.2. Behavioral Responses to voltage exposure

Studies have shown that each animal will have a threshold of current exposure for a particular contact pathway. Levels of current exposure just above the threshold will result in mild behavioral reactions, such as the blink of an eye, which tend to become less pronounced over time as animals become accustomed to the sensation. As current exposure is increased above this threshold, behavioral responses become more pronounced and more persistent, indicative of annoyance, pain or involuntary muscle contraction (twitches).

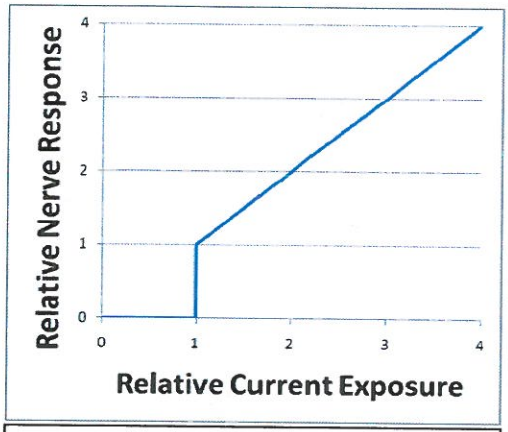



**Figure 3. Example of threshold response.** Below the threshold there is no nervous response. Response begins at the threshold value (in this example, one arbitrary 'unit' of current) and the intensity of response increases as the current level is increased further.

Stray voltage studies have used a variety of animal responses to characterize these threshold phenomena. Some studies have tried to use the most sensitive behavioral indicators of perception as a threshold of response (Norell, 1983; Reinemann, 1995, 1999; Rigalma, 2007). Researchers have noted that these very sensitive thresholds show high variability because cows rapidly acclimate to an unfamiliar sensation and cease to show any behavioral response.

Other studies have attempted to develop a more repeatable response in order to more accurately compare different types of stimuli (Aneshansley, 1997; Reinemann, 1999, 2003). These studies typically rely on involuntary muscle contraction, or stimuli with goes beyond subtle sensation to moderate annoyance as a threshold. Current applied in a periodic manner (e.g. a short burst of current repeated every 3 seconds for 1 minute) appear to produce more repeatable behavioral response thresholds than continuously applied stimuli (e.g. current applied continuously for 1 minute). This is probably because repeated stimuli produce a repeated series of 'startle' behaviors when each stimulus is applied whereas there may be only one such response at the start of continuous current exposure.

Further studies have used avoidance of water intake as a response threshold (Gorewit, 1989; Reinemann, 2004). Because of an animal's powerful drive to satisfy their water demand, this threshold is logically a higher value than those designed to detect moderate or pronounced (repeatable) behavioral changes. Studies have shown that animals are not deterred from drinking if only a mild sensation results from contact with a drinking device, while they are only temporarily deterred from drinking when a moderately annoying sensation results.