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An Assessment of the Space Station Freedom Program's Leakage Current Requirement

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AN ASSESSMENT OF THE SPACE STATION FREEDOM PROGRAM'S LEAKAGE CURRENT REQUIREMENTS

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SUMMARY

The Space Station Freedom Program requires leakage currents to be limited to less than human perception level, which NASA presently defines as 5 mA for dc. This paper traces the origin of this value and surveys the literature for other dc perception threshold standards. It shows that while many varying standards exist, very little experimental data is available to support them.

1.0 INTRODUCTION

An important aspect of the shock hazard on Space Station Freedom (SSF) is the hazard associated with excessive leakage current. For the purpose of this discussion, we define two kinds of leakage current:

Chassis Leakage Current is any current which flows through the chassis in the absence of a faulted condition.

Connector Leakage Current is current that flows through a connector in the "power-off" state when a circuit is completed at the connector.

Excessive chassis leakage current creates a shock hazard whenever a crewperson touches the energized chassis with one part of the body and a grounded surface with another part, completing the circuit. This can happen during almost any operation. Excessive connector leakage current can shock a crewperson who is performing maintenance on a powered-down ORU (Orbital Replacement Unit). He or she must first break the connection, which may cause an arc; and afterwards he or she may inadvertently touch the exposed connector with one hand while contacting grounded chassis with another body part (most likely a hand or foothold), completing the circuit.

Both leakage currents create a more severe hazard on SSF than on past manned programs, due to the Station's higher currents and voltages, and its requirement for on-orbit maintenance.

The Remote Power Controllers (RPCs) on the NSTS Orbiter are required to leak no more than one ten thousandth of their rated current. Thus the 20 A RPCs leak no more than 2 mA and the 10 A RPCs leak no more than 1 mA. The Space Station design includes RPCs rated at 50 A and 25 A.

Leakage currents are almost always present to some degree in electrical equipment. System designers can control the resultant shock hazard by several means[1]. Before they can do this, however, SSFP System Safety must specify the maximum amount of current to which a crewperson can be safely exposed: this is tantamount to specifying the perception level of direct current and is the purpose of this paper.

2.0 THE PERCEPTION LEVEL OF DIRECT CURRENT

The "perception level" of current at a given frequency is the level at which a human placed in the circuit can just begin to sense current. Current of this magnitude is far too small to cause any physical damage, or even pain, but it may be enough to surprise an individual and cause him or her to jerk away, leading to injury and/or damaging equipment. This is particularly true in the on-orbit environment, where rapid, jerky movements can cause injuries due to impact and particularly since workspace is often somewhat confined.

Near the perception level, lower frequency (on the order of 60 - 400 hz) alternating current produces a slight tingling sensation which is continuous for the duration of contact. Perception level direct current manifests itself as a slight "kick" when contact is made and another when contact is broken. In between the two "kicks" there may be a small sensation of warmth.

2.1 SSFP Requirements

Few people have undergone electric shock in a situation where an accurate measurement of the current magnitude through their body was available. Therefore most discussions of the minimum dc perception level proceed without much "feel" for what the numbers imply. How many people could distinguish 1 mA dc from 2 mA dc? 3 from 4? etc.

The best reference within NASA documentation is NASA-STD-3000, Man Systems Integration Requirements, November 1986. Volume IV of this document is baselined for Space Station[2]. Volume IV, section 6.4.3, "Electrical Hazards Design Requirements", references "Figure 6.4.3-1" of Volume 1, which is reproduced in this paper as figure 1. This figure shows a number of constant current lines and states their effects on humans for 60 hz currents.

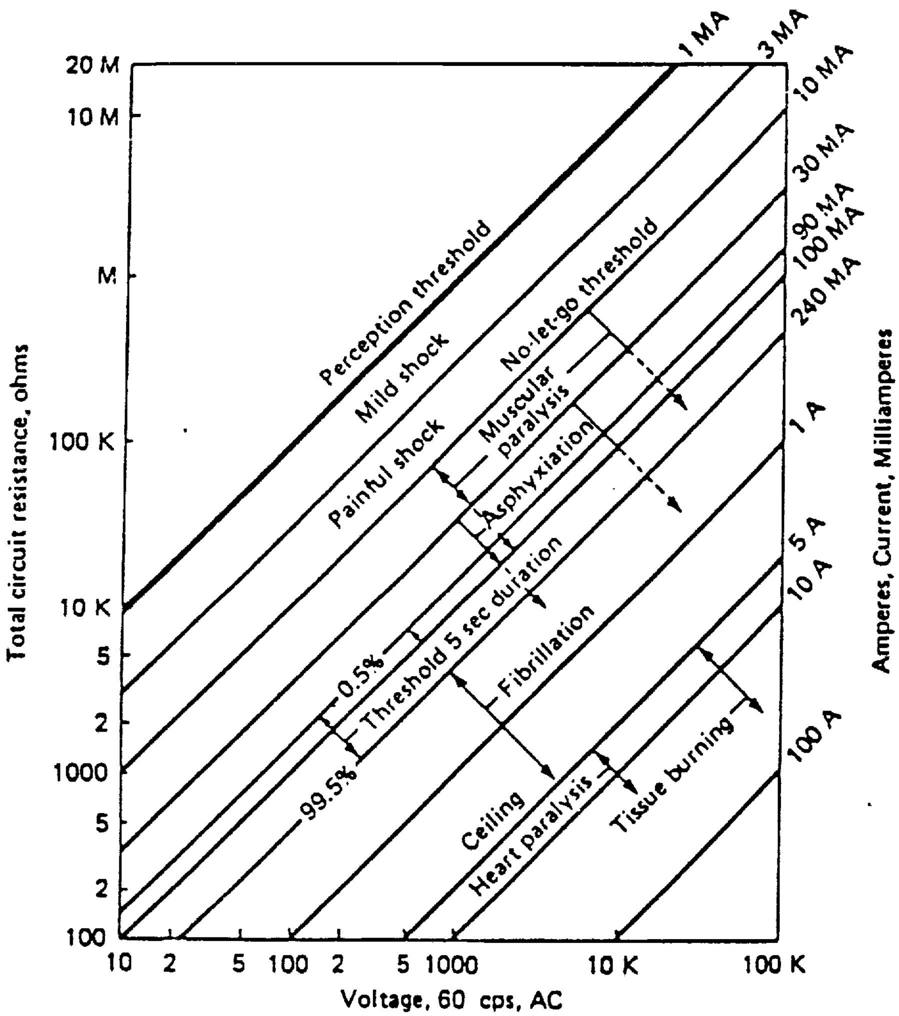
"Perception threshold" is given as 1 mA. "Note 2", after stating that 60 hz is about the worst possible current for shock, gives scaling factors for normalizing the 60 hz effects to currents of different frequencies. For 0 hz (direct current), the scaling factor is 0.2, and hence the 1 mA perception current at 60 hz translates into a 5 mA perception current for dc.

There are some who believe that this number is far too high - that currents below 5 mA dc can be felt and could present a hazard. Indeed, in a recent draft version of NASA-STD-3000 Rev A, 100 microamperes (0.1 mA) is proposed for maximum leakage current! Because proposed values vary so widely, and because so few people have a "feel" for perception current, it is important to investigate the sources of "Figure 6.4.3-1" and "Note 2" in NASA-STD-3000, and assess their applicability to the Space Station Freedom Program.

2.2 Sources of "Figure 6.4.3-1" and "Note 2"

2.2.1 NASA-CR-1205

Figure 2 of this paper illustrates the origins of



Notes:

1. Data are based on current flow from arm-to-arm or arm-to-leg of 60 Hz AC on 150 lb human.
2. 60 Hz is about the worst possible frequency as far as human safety is concerned. Relative effect of different frequencies normalized to 60 Hz = 1.0 is as follows:

f (Hz)	Effect
0	0.2
10	0.9
60	1.0
300	0.8
1000	0.6
10000	0.2
RF	0.01

Figure 1. NASA-STD-3000, Vol. 1, "Figure 6.4.3-1", including "Note 2".

NASA-STD-3000 "Figure 6.4.3-1" and "Note 2". They are taken directly from NASA-CR-1205, Compendium of Human Responses to the Aerospace Environment, by E. M. Roth[3]. NASA-CR-1205 is a large compendium of reports by various authorities on different medical aspects of space flight compiled for NASA in 1968. Section 5, by Finkelstein & Roth, deals with the effects of electricity on humans. It contains a small section on "Frequency Factors" (p. 5-11) which puts forth several statements comparing the effects of direct current and alternating current. They are listed here, with their sources:

"Other factors equal,

alternating current is approximately three times more injurious than direct current." - Aita, J. A., Neurologic Manifestations of

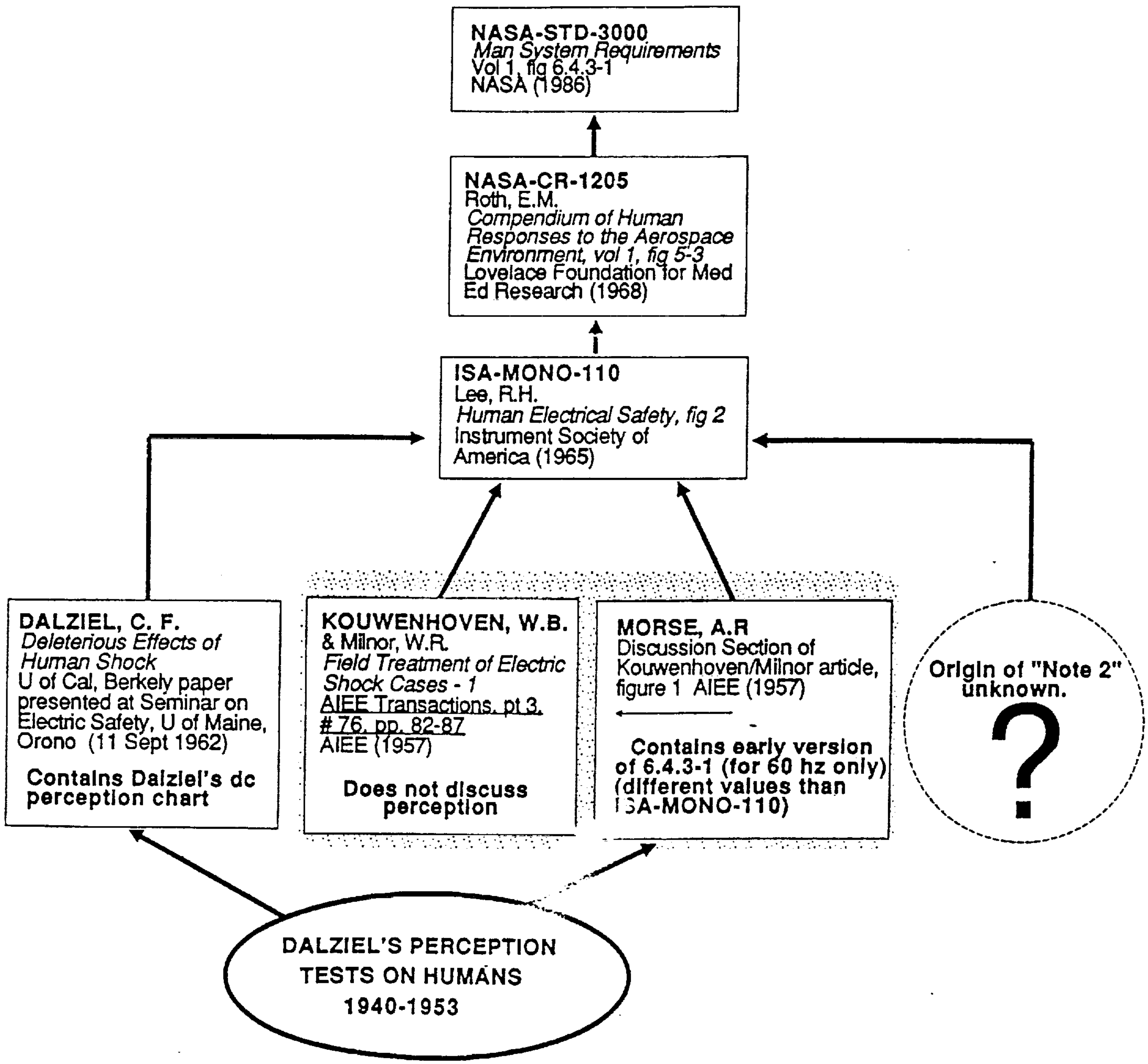


Figure 2. Origin of NASA-STD-3000, Vol 1, "Figure 6.4.3-1" and "Note 2". "Figure 6.4.3-1" and "Note 2" did not appear in the same paper until NASA-CR-1205, and were not combined until NASA-STD-3000.

Electrcial Injury, Nebraska State Medical Journal, 50: 530-533, Oct 1965.

"The median threshold of sensation for direct current of over 100 adult men and women is 1.43 milliamperes as compared to 1.0 for 60 Hz AC." - Kouwenhoven, W.B., Johns Hopkins University, Baltimore, MD, personal communication on unpublished data, 1968.

and

"It appears that humans are about five times as sensitive to 60 to 400 Hz as to DC, but more studies are in progress on this point." - Kouwenhoven, W.B., Johns Hopkins University, Baltimore, MD, personal communication on unpublished data, 1968.

Statement one tells us that for injury, 60 hz is three times worse than dc. Statement two says that for perception, people are 1.43 times as sensitive to 60 hz as they are to dc. But statement three seems to contradict the first two....it says that people are FIVE TIMES as sensitive to 60 hz as they are to dc, without specifying whether this pertains to perception, injury, or both! The "five times as sensitive" scaling factor for dc is reflected in NASA-CR-1205 table 5-6, which eventually became "Note 2" of NASA-STD-3000.

A check on the sources reveals that Kouwenhoven (cited in statements 2 and 3) was also one of the reviewers of Section 5 of NASA-CR-1205. We do not know whether Kouwenhoven's "unpublished data" was ever published. It seems strange that the same source would give both "1.43 mA as compared to 1.0" AND "five times as sensitive". Statement 3, "five times as sensitive", could well be cited incorrectly, because the same sentence, as well as the table which eventually became "Note 2", appear in ISA-MONO-110 by R. H. Lee.

One question stands out: Why did NASA choose to incorporate the "five times as sensitive" statement into NASA-STD-3000 while ignoring the "three times more injurious" and "1.43 mA as compared to 1.0" statements?

2.2.2 ISA-MONO-110

NASA-STD-3000 "Fig 6.4.3-1" and "Note 2" cite NASA-CR-1205. This, in turn, cites Instrument Society of America Monograph 110 (ISA-MONO-110), Human Electrical Safety, by R.H. Lee[4]. Lee, a Senior Electrical Engineer from DuPont, wrote this "guideline" type of article in 1965. Sadly, it contains no citations or references[5]. It does provide the following on the figure, which corresponds to "Figure 6.4.3-1" of NASA-STD-3000:

"The results are based on tests on guinea pigs, then dogs, then sheep, then calves."

but it does not reference a specific study.

This statement, and a note[6] in NASA-CR-1205, imply that Lee got his data from three sources:

- Kouwenhoven, W. B., & Milnor, W. R., <u>Field Treatment of Electric Shock Cases - 1</u>, 1957;

- Morse, A.R., discussion section of the above Kouwenhoven & Milnor article, 1957;

and

- Dalziel, C. F., <u>Deleterious Effects of Human Shock</u>, 1962;

It is not clear, then, that both "Figure 6.4.3-1" and "Note 2" of NASA-STD-3000 came from the same original source.

Though there are no clues as to the origin of "Note 2", the next three subsections examine the sources of "Figure 6.4.3-1".

2.2.2.1 Kouwenhoven & Milnor

W. B. Kouwenhoven and W. R. Milnor, MD, ran a number of experiments at Johns Hopkins University in the 1950s. The paper referenced by Lee, <u>Field Treatment of Electric Shock Cases - 1</u>, is primarily concerned with the treatment of cardiac fibrillation, a lethal condition induced by high currents in which the heart stops beating and flutters uselessly. Fibrillating currents begin at around 100 mA, and experiments in this range are done exclusively on animals. Hence, there is no data in this paper on dc perception current.

<u>Field Treatment of Electric Shock Cases - 1</u> was published in 1957 by the AIEE Safety Committee. It prompted a response from A. R. Morse of the National Research Council of Canada. It is in this discussion that the first version of "Figure 6.4.3-1" of NASA-STD-3000 appears.

2.2.2.2 Morse

A. R. Morse of the NRCC responded to Kouwenhoven and Milnor's paper by preparing a chart, shown in figure 3 of this paper[7]. Two observations are important: (1) the data for this chart is for 60 hz with no mention of other frequencies or dc, that is, it did not show up in the same paper as "Note 2" until ISA-MONO-110, and was not combined with "Note 2" until NASA-CR-1205; (2) the data for different levels (perception, fibrillation, etc) were obtained through several different sources, specifically Dalziel, Kouwenhoven & Milnor, Maclachlan, and Massagolia.

We believe the "perception" line in this

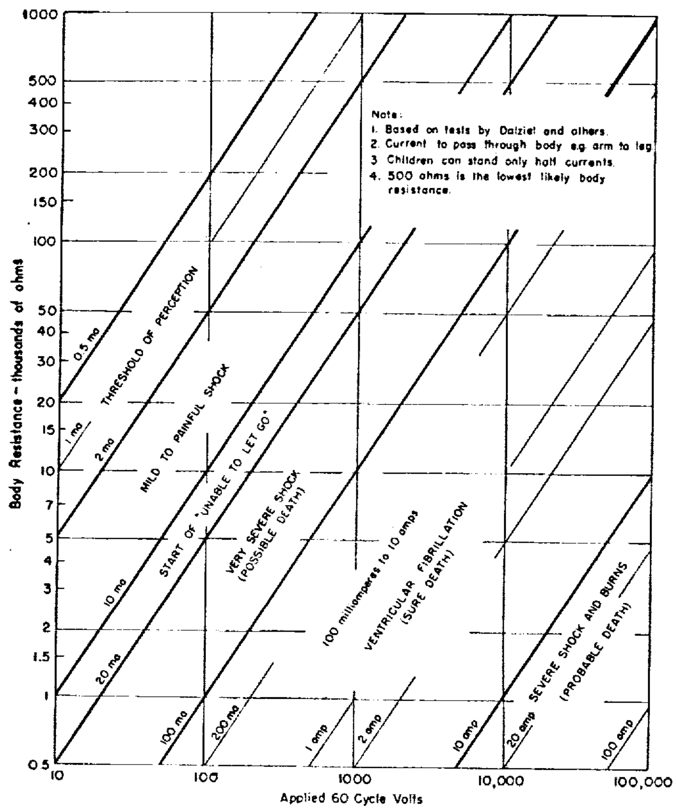


Figure 3. "The 60 cycle shock hazard to adult males", from A. R. Morse.

figure came from a series of experiments run by Charles F Dalziel, since the Kouwenhoven & Milnor source does not discuss perception currents, the Maclachlan source cited is a summary of field notes on electric shock, and the Massagolia source deals with the hazards of open-circuited current transformers.

We have come, then, to the original source of the perception current line in "Figure 6.4.3-1". Like most investigators of electric shock, we are ultimately led back to the experiments of Dr. Charles F. Dalziel[8].

2.2.2.3 Dalziel

Dalziel performed a number of experiments on live humans from the late 1930s to the mid 1950s, mostly centering around perception and let-go levels. Experiments since that time have all been with animals or cadavers, presumably for legal or insurance reasons[9]. A search through the literature reveals that almost all quantitative data on perception and let-go current can be traced back to Dalziel's experiments.

Perception tests for 60 hz were run on 167 healthy, young men - mostly college students. The 60 hz data was collected in three separate test series run several years apart, with different subjects and wires of different sizes[10]. Nonetheless, data from all three test series form a normal distribution, shown in figure 4 of this paper[11]. The median[12] value for this curve is 1.086 mA, which is probably the reason Morse gave 1 mA as the "perception level" in his chart (fig 3 of this paper), which eventually evolved into the perception line of "Figure 6.4.3-1".

There was another test, however - this one specifically for <u>direct current</u> perception. In 1940, at the University of

California, Berkeley, Dalziel tested the dc perception level of 115 healthy, young men. The subjects rested each hand lightly on a no. 7 copper wire. Current was controlled by a potentiometer and energized from batteries[13]. The results are shown in figure 5 of this paper[14]. Again the curve follows a normal distribution and this time the median value is 5.2 mA. This could be the source of Lee's "Relative Effect of Frequencies on perception and paralysis", which evolved into "Note 2". A search through

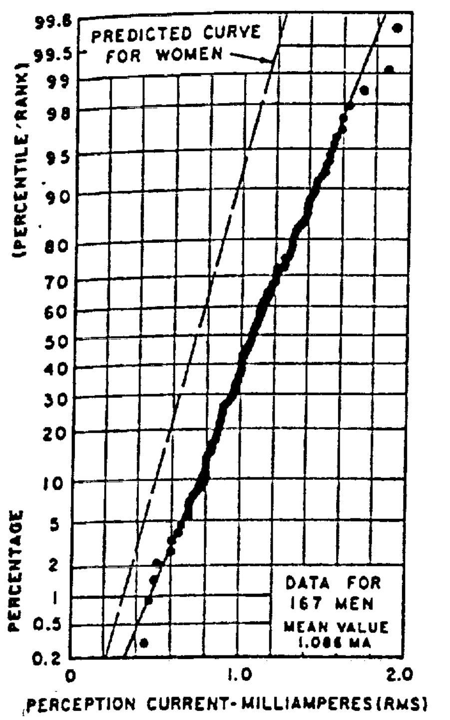


Figure 4. Dalziel's original data for 60 hz perception current.

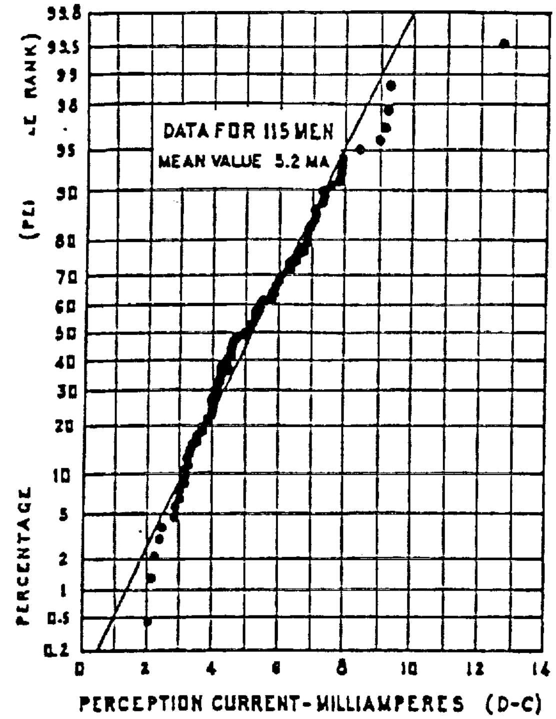


Figure 5. Dalziel's original data for dc perception current.

the literature has revealed no other original test data on human perception of direct current.

2.3 Other Standards & Requirements

There are few standards that do not reference Dalziel. Some which were located in the course of this investigation are given here. They are not baselined for the Space Station, and we did not make an effort to trace their sources.

1. European Space Agency (ESA). At the SSFP Work Package Four/ESA Technical Interchange Meeting in October, 1990, Mr. Bernhard

Glaubitz presented 2 mA as the current requirement being considered by ESA for the Columbus Attached Pressurized Module and Man Tended Free Flyer programs. This is the standard being considered by the European Community nations for the unified electric code they are preparing for 1992.

2. IEC 479-1. The International Electrotechnical Commission published this report, titled Effects of Current Passing Through the Human Body, in 1984. Chapter 3, paragraph 4.1 states: "Under conditions comparable to those applied in studies with a.c., the threshold of perception was found to be about 2 mA." The specific studies are not named but reference is made to a work by Antoni & Biegelmeier[15].

3. MIL-STD-454. This standard, titled Standard General Requirements for Electronic Equipment, is referenced in figure 6.4.2-1 of NASA-STD-3000. Section 5, table 1-I, gives a range of 0 to 4 mA as the "perception" region, and 4 to 15 mA as the "surprise" region for direct current. The section is labeled "Information and guidance only", and no source for the numbers is cited.

4. AAMI Electromedical Standards. The Association for the Advancement of Medical Instrumentation (AAMI), in their AAMI Safety Standard for Electromedical Apparatus, Safe Current Limits, April, 1974, limits leakage currents to 100 microamperes (100 uA) for equipment likely to contact hospital patients, and 10 uA for equipment that deliberately applies current to the patient. These standards are very tight due to the fact that sick people often have low sensitivity to and lower tolerance of electric current. Limiting leakage current to 100 uA is very difficult in a space system, especially in power conditioning and switching equipment[16].

The Air Force and Army adopted this standard for their AF Regulation 160-3, Prevention of Electrical Shock Hazards in Hospitals.

5. ANSI C101.1-1973. This ANSI standard, American National Standard for Leakage Current for Appliances, applies to chassis leakage current for consumer appliances. This document gives a very specific test setup. It uses Dalziel's data[17] and "normalizes" the perception curve to 0.5 mA at 60 hz, probably to introduce a safety factor.

3.0 SUMMARY

It is not absolutely provable without references from Lee, but the evidence above indicates that the following might be the source of NASA's 5 mA dc leakage current requirement. All references to figures apply to the figures in this paper.

1940 - 1956: Dalziel runs perception experiments on humans. Median values: 1.086 mA for 60 hz (fig 5) and 5.2 mA for dc (fig 5).

1957: Morse creates chart, "The 60 cycle electric shock hazard to adult males" (fig 4), from several sources. Perception line at 1 mA comes from Dalziel's chart (fig 5).

1965: Lee includes modified version of Morse's chart in ISA-MONO-110. Perception threshold for ac still at 1 mA. Elsewhere in same publication Lee presents table, "Relative effects of frequencies", which states that dc's effect is 0.2 times that of 60 hz - possibly based on Dalziel's dc perception level (fig 5).

1968: Finkelstein & Roth reproduce Lee's chart and Lee's table separately in NASA-CR-1205; quote Lee's statement that humans are 5 times as sensitive to 60 hz as to dc, but also include another statement that dc perception = 1.43 mA.

1986: NASA-STD-3000, Volume 1, reproduces Lee's chart as "Figure 6.4.3-1" (fig 1) and includes Lee's table as "Note 2" to the chart. The perception threshold in "Figure 6.4.3-1" and "Note 2" become baselined requirements for Space Station.

5 mA becomes the requirement for maximum safe leakage current.

4.0 RECOMMENDATIONS

Our investigation of NASA's 5 mA dc leakage current requirement has shown that although many varying dc perception threshold standards exist, very little data which supports these standards is readily available. Implementing the following two recommendations would clarify the requirement and increase its credibility.

Recommendation 1: State the leakage current requirement directly, and put "Figure 6.4.3-1" in the reference section.

Paragraph 6.4.3.a of NASA-STD-3000 states that "Crewmembers shall not be exposed to voltages and currents that exceed the 'PERCEPTION THRESHOLD' line in figure 6.4.3-1, using the frequency normalization factors given in Note 2 of the figure."

If the requirement is only concerned with perception level, why include the whole chart, with all its data on let-go, fibrillation, burning, etc, in the requirements section? Additionally, the chart only gives median values and does not include any safety factors. It only summarizes information, and therefore belongs in section 6.4.2, Electrical Hazards Design Considerations. Separate requirements for the different frequencies should be stated in Section 6.4.3, Electrical Hazards Design Requirements. This section should also give a means of verification, including the size of the resistor used in the test setup. 500 ohms is traditionally assumed to be the worst case human resistance - this simulates a person with broken skin.

Recommendation 2: Consider repeating Dalziel's test.

While Dalziel's work is still widely accepted after four decades, some have questioned it on the grounds that it has never been replicated in an independent laboratory - a basic criterion for complete acceptance of experimental research by the scientific community. Few, if any, people have a "feel" for the perception current numbers, including those people who are responsible for setting a safe standard within NASA.

While let-go testing on humans might introduce an unacceptable safety risk by today's standards, perception testing by definition involves extremely low current levels and does not have to include the heart or other vital organs in the current path. NASA's Man Systems organization might consider repeating Dalziel's test in a safe, controlled environment. Since there is really no pain involved at these levels, astronauts, design engineers, and safety engineers responsible for developing a reasonable standard could use such a test as an opportunity to enhance the quality of their discussions.

More importantly, NASA could test the perception level of populations other than young, healthy males. Dalziel predicted, for example, that women's perception current level would be significantly lower than that of men but never actually tested it.

The medical personnel within the Man Systems organization might begin by investigating the legality of such a test.

1. For example, the shock hazard due to connector leakage current can be controlled by placing a mechanical relay in series with the connector, shunting leakage current with a bleeder resistor, or making the connector highly inaccessible. Chassis leakage current can be controlled by shielding leaky components or placing leaky components away from structure.

2. SSP 30000, Space Station Program Definition and Requirements, Section 3: Space Station Systems Requirements, Revision I, Paragraph 3.2.10. NASA SSFPO, November 1989.

3. Roth, E. M., NASA-CR-1205, Compendium of Human Responses to the Aerospace Environment: Vol I, Section 5, figure 5-3 and table 5-6. Lovelace Foundation for Med Ed & Research, NASA, November 1968.

4. Lee, R. H., ISA-MONO-110, Human Electrical Safety, Instrument Society of America, Pittsburgh, 1965, figure 2 and sheet 3, table III.

5. This was confirmed by Victoria Fletcher, Reprints Administrator of the ISA.

6. Roth, figure 5-3.

7. Morse, A. R. Discussion Section of "Field Treatment of Electric Shock Cases - I" by Kouwenhoven & Milnor, AIEE Transactions, pt 3, 76: 85-86, AIEE 1957.

8. Banks, Robert S., An Assessment of the 5-mA 60-hz Contact Current Safety Level, IEEE Power Engineering Society, 84 WM 036-0, February 1984.

9. ibid., p. 4.

10. Dalziel, Charles F., The Threshold of Perception Currents, AIEE Transactions, 73: 990-996, August 1954.

11. ibid., figure 1.

12. Since the data are nearly a normal distribution, we use "mean" and "median" interchangeably.

13. Dalziel, p.993.

14. ibid., figure 5.

15. Antoni, H., and Biegelmeier, G.: Ueber die Wirkungen von Gleichstrom auf den Menschen, E und M, Vol 96 (1979), No. 2, p.71.

16. Conversation with Mr. Sina Javidi, Systems Integration Branch Chief, Space Station Directorate, Lewis Research Center. October, 1990.

17. Footnote #2, page 7 of ANSI C101.1-1973.

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16. Abstract

The Space Station Freedom Program requires leakage currents to be limited to less than human perception level, which NASA presently defines as 5 mA for dc. This paper traces the origin of this value and surveys the literature for other dc perception threshold standards. It shows that while many varying standards exist, very little experimental data is available to support them.

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