Low Electrical Energy Post-Crash Compliance Option in FMVSS No. 305a

1. Background

Capacitors store electrical energy and may be connected directly to the chassis in some electric power trains. In fuel-cell electric vehicles (FCEVs), the high-voltage systems may contain capacitors which are connected to high voltage buses and are not electrically isolated. Such capacitors may be high voltage sources post-crash (because a charged capacitor may not discharge quickly) and may not be able to comply with post-crash electrical safety requirements using the direct and indirect contact protection option or the electrical isolation. However, capacitors may not pose a safety hazard when contacted, even though they may be high voltage sources post-crash, because they are low energy high voltage sources.

The Federal Motor Vehicle Safety Standard (FMVSS) No. 305, "Electric-powered vehicles: electrolyte spillage and electrical shock protection," currently requires that the vehicle manufacturer shall select and fulfill one of the following three criteria post-crash:

1. Electrical Isolation (S5.3a)
2. Absence of high voltage (S5.3b)
3. Physical Barrier Protection (S5.3c)

Global Technical Regulation (GTR) No. 20, "Electric vehicle safety," provides a fourth post-crash electrical safety compliance option, known as the "low electrical energy" option for high voltage sources with unidirectional single impulse currents.[1] It specifies an electrical energy limit of 0.2 Joules (J) for unidirectional single impulse currents that can pass through the human body without any long-term or irreversible effects.

1.1 NHTSA's Previous Position on a Post-Crash Low Energy Compliance Option

In a 2007 notice of proposed rulemaking (NPRM)[2] responding to petitions for rulemaking from the Alliance of Automobile Manufacturers (Alliance) and the Association of International Automobile Manufacturers (AIAM),[3] NHTSA sought comments regarding the

[1] GTR No. 20, https://unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a20e.pdf.
[2] 72 FR 57260, October 9, 2007
[3] In January 2020, the two industry associations merged to form the Alliance for Automotive Innovation (generally referred to as the Auto Innovators).

inclusion of 0.2 J as an appropriate low energy threshold for electrical safety compliance post-crash; however, at that time a safety need for a low energy option was not yet clear and the Agency expressed concerns regarding the practicality of measuring the residual energy in a crash test environment. Given those unknowns, a low energy option for post-crash electrical safety was not proposed. AIAM and Alliance submitted comments to the NPRM[4] arguing that the option is necessary due to the presence of y-capacitors in fuel cell vehicle systems.

Capacitors, like batteries, store electrical energy and pose similar electrical safety hazards, in particular shock hazards. In electrical power distribution, x-capacitors are commonly placed across high voltage buses, while y-capacitors are commonly used across a high voltage bus and chassis. A common application of x- and y-capacitors is filtering of electromagnetic or radio frequency interference, where they are directly connected to an alternating current (AC) or direct current (DC) power line. They may also be used to suppress electrical noise generated by motors and other components, such as harmonics from semiconductor switches. In comments to the 2007 NPRM and ex-parte communications, the Alliance/AIAM noted that capacitors (x- and y-capacitors) used for current filtering application in fuel cells. When coolant flows in a fuel cell, the voltage across individual y-capacitors in the fuel cell becomes asymmetrical. This asymmetry in the voltage is, directly related to the coolant loop in a fuel cell. When x-capacitors in the fuel cell system discharge in the event of a crash, that discharge will leave a residual voltage (sometimes in excess of 60 volts direct current (VDC)) on the y-capacitors. The Alliance commented that as y-capacitor asymmetry increases in fuel cell electric vehicles (FCEV) designs with more efficient coolants, it could take as much as 10 to 20 seconds (s) for the voltage to dissipate below the low voltage threshold of 60 VDC. However, the Alliance argued that this residual voltage on the y-capacitors would not pose a safety risk because the total energy levels would be very small.[5]

The Alliance and AIAM provided an analysis to justify the 0.2 J low energy limit and provided a method of determining the energy in a capacitor, after the crash test, that is based on knowing the capacitance value. A low energy option for post-crash electrical safety was not included in the June 14, 2010,[6] final rule because NHTSA was not convinced that a low energy

[4] NHTSA-2007-28517-0004
[5] 75 FR 33515
[6] 75 FR 33515, 33519

option was needed and had concerns about the possible disparity between the level of safety provided by 0.2 J of energy and the electrical isolation requirement. NHTSA also did not consider the low energy post-crash compliance option in the 2017 final rule,[7] which incorporated electrical safety requirements in GTR No. 13, "Hydrogen and fuel cell vehicles," into FMVSS No. 305, because the petitioner (Alliance) requested that the low energy compliance option in GTR No. 20 be considered, which was still in development at that time.

2.0 NHTSA's Updated Assessment of the Post-Crash Low Energy Compliance Option

GTR No. 20 contains a detailed analysis of the 0.2 Joules energy limit for the low energy post-crash electrical safety compliance option. This section presents NHTSA's analysis of the low energy post-crash compliance option and appropriate performance limits which is based on the analysis detailed in GTR No. 20.

According to IEC-60479-1, the initial resistance of the human body, referred to as R_i, is a variable that is based on a variety of factors including surface conditions (wet vs. dry vs. saltwater wet), and current path (e.g., hand-to-foot vs. hand-to-hand). The IEC 60479-1 asserts that the minimum value of R_i of a human body is 500 ohms.[8]

The following evaluation assumes worst-case conditions. Specifically, among the following environmental conditions: dry, water-wet, and saltwater-wet conditions, the lowest total body impedances for a current path hand-to-hand with 50/60 Hertz (Hz) current for large surface contact areas, are realized in saltwater-wet conditions. Furthermore, IEC 60479-1 notes that some measurements indicate that the total body impedance for the current path hand-to-foot is 10 to 30 percent lower than for a current path hand-to-hand. Additionally, impedances for the 5th percentile of the population are used in this analysis to capture the lowest impedances possibly experienced by the entire population. Applying a 0.8 factor (to reflect the mean impedance for the current path hand-to-hand as captured in Note 1 of Table 1), the total body impedances for the hand-to-foot current path are estimated. The results are shown in Table 2.

[7] 82 FR 44950, September 27, 2017

[8] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980

Table 1 - Total Body Impedances Z_T for a current path hand-to-hand AC 50/60 Hz, for large surface areas of contact in saltwater-wet conditions[9]

Touch voltage V	Values for the total body impedances Z_T (Ω) that are not exceeded for		
	5 % of the population	50 % of the population	95 % of the population
25	960	1 300	1 755
50	940	1 275	1 720
75	920	1 250	1 685
100	880	1 225	1 655
125	850	1 200	1 620
150	830	1 180	1 590
175	810	1 155	1 560
200	790	1 135	1 530
225	770	1 115	1 505
400	700	950	1 275
500	625	850	1 150
700	575	775	1 050
1 000	575	775	1 050
Asymptotic value = internal impedance	575	775	1 050

NOTE 1 Some measurements indicate that the total body impedance for the current path hand to foot is somewhat lower than for a current path hand to hand (10 % to 30 %).

NOTE 2 Due to low skin impedances in this case it may be assumed that Z_T depends little on the duration of current flow; Z_T approaches the internal body impedance Z_i.

NOTE 3 For the standard value of the voltage 230 V (network-system 3N ~ 230/400 V) it may be assumed that the values of the total body impedance are the same as for a touch voltage of 225 V.

NOTE 4 Values of Z_T are rounded to 5 Ω.

[9] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980

Table 2 - Total Body Impedance Z_T for hand to hand and hand to foot current path with AC 50/60 Hz for 5th percentile population and large contact surface areas under saltwater-wet conditions

Touch Voltage (Volts)	Body Resistance for Hand-to-Hand Path (Ohms)	Body Resistance for Hand-to-Foot Path (Ohms)
25	960	768
50	940	752
75	920	736
100	880	704
125	850	680
150	830	664
175	810	648
200	790	632
225	770	616
400	700	560
500	625	500
700	575	500
1,000	575	500

For the touch voltages of 700 V and 1,000 V, the resistance of hand-to-foot path would be 460 ohms after applying the 0.8 correction factor to reflect the hand-to-foot path. However, the IEC-60479-1 states that the minimum total body impedance is limited to 500 ohms because the initial body resistance of the 5th percentile of the population is 500 ohms and the total body impedance cannot be less than the initial resistance.[10]

The IEC 60479-1 standard defines various hazard levels for both AC and DC current. These levels are defined by intensity of involuntary muscle contractions, threshold for ventricular fibrillation, sensory perception of current in the human body, and the threshold for irreversible damage to the human body.

[10] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980

Figure 1 and Figure 2 below provide the time (in milliseconds (ms)) versus current (in milli Amperes (mA)) zone plot which maps the physiological effects experienced by the human body, based on the magnitude of the discharge current and duration for DC and AC currents respectively.

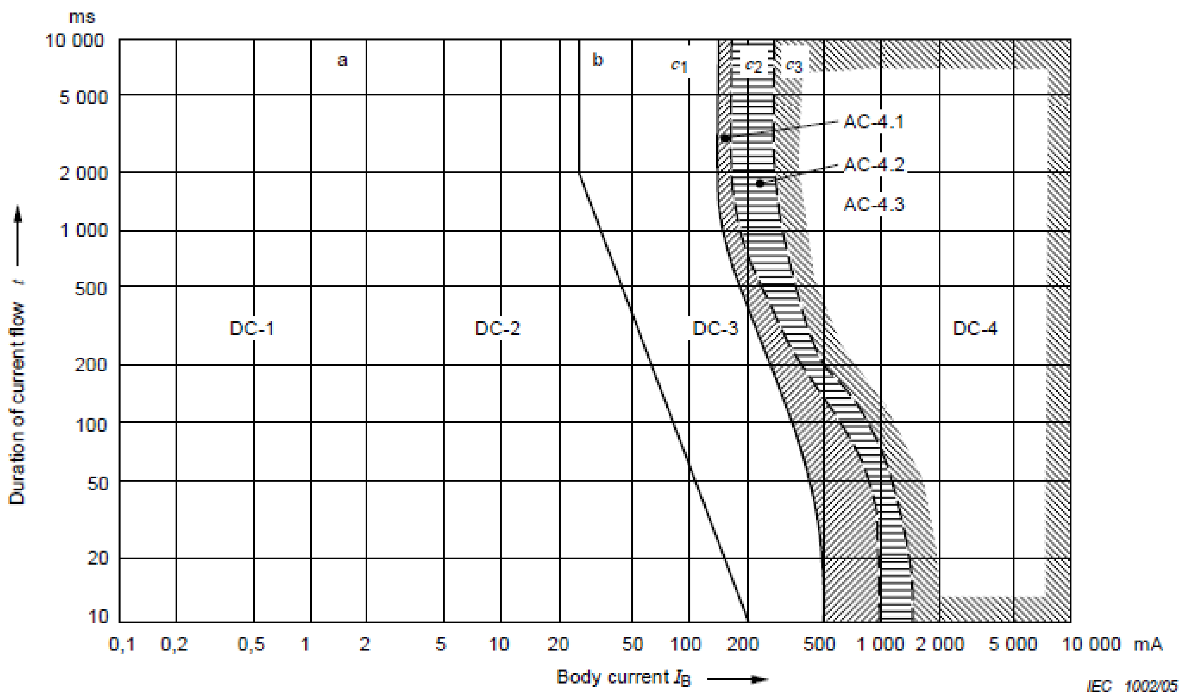

Figure 1 – Conventional time/current zones of effects of DC currents on persons for a longitudinal upward current path[11]

The values shown in Figure 2 only apply to AC currents at frequencies of 15 Hz to 100 Hz for the left hand-to-foot current path and for discharge durations greater than 10 ms. Below the c_1 curve in Figure 1 and Figure 2, the IEC 60479-1 states that ventricular fibrillation is unlikely to occur. The curves indicated by c_2 and c_3 in the two figures have a 5% and 50% probability of ventricular fibrillation, respectively.

[11] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980

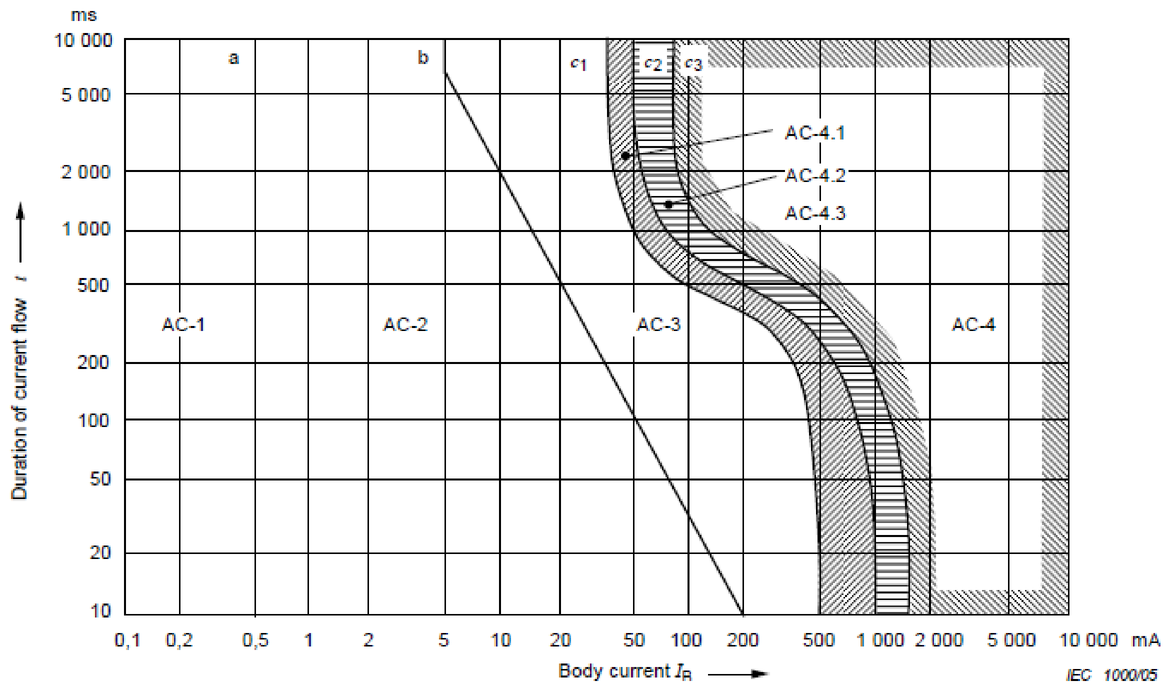

Figure 2 – Conventional time/current zone of effects of AC currents (15 Hz to 100 Hz) on persons for a current path corresponding to left hand-to-feet [12]

Table 3 and Table 4 below present the physiological effects in different zones (e.g., DC-1, DC-2, etc. and AC-1, AC-2, etc.) that the human body experiences when exposed to DC and AC current. In the DC-1 zone per Table 3, there is a slight prickling sensation possible when making, breaking, or altering the current flow which can be perceived up to 2 mA. In the DC-2 zone, there are involuntary muscle contractions likely, but there are no harmful electrical physiological effects. In DC-3, there are strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, but there is usually no organic damage.

[12] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980

Table 3 – Time/Current zones for DC for hand to feet pathway[13]

Zones	Boundaries	Physiological effects
DC-1	Up to 2 mA curve a	Slight pricking sensation possible when making, breaking or rapidly altering current flow
DC-2	2 mA up to curve b	Involuntary muscular contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects
DC-3	Curve b and above	Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected
DC-4 1)	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	DC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	DC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	DC-4.3 Probability of ventricular fibrillation above 50 %
1) For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation this figure relates to the effects of current which flows in the path left hand to feet and for upward current. For other current paths the heart current factor has to be considered.		

In the AC-1 zone in Table 4, the perception by the human body is possible and usually without any "startled" response. In the AC-2 zone, the perception and involuntary muscle contractions are likely, but without harmful or irreversible electrical physiological effects. The physiological effects in the AC-3 zone increase in severity, including strong involuntary muscular contractions, difficulty breathing, and reversible disturbances of the heart function. Above curve c_1, cardiac arrest, burns and the probability of ventricular fibrillation increase with increasing current, magnitude, and time. These curves help define safe regions of current exposure for the human body, and therefore can be used to help define safe regions of operation in post-crash conditions.

[13] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980

Table 4 – Description of Time/current zones for AC 15 Hz to 100 Hz for hand-to-feet pathway[14]

Zones	Boundaries	Physiological effects
AC-1	Up to 0,5 mA curve a	Perception possible but usually no 'startled' reaction
AC-2	0,5 mA up to curve b	Perception and involuntary muscular contractions likely but usually no harmful electrical physiological effects
AC-3	Curve b and above	Strong involuntary muscular contractions. Difficulty in breathing. Reversible disturbances of heart function. Immobilization may occur. Effects increasing with current magnitude. Usually no organic damage to be expected
AC-4 [1)]	Above curve c_1	Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time
	c_1-c_2	AC-4.1 Probability of ventricular fibrillation increasing up to about 5 %
	c_2-c_3	AC-4.2 Probability of ventricular fibrillation up to about 50 %
	Beyond curve c_3	AC-4.3 Probability of ventricular fibrillation above 50 %
[1)] For durations of current flow below 200 ms, ventricular fibrillation is only initiated within the vulnerable period if the relevant thresholds are surpassed. As regards ventricular fibrillation, this figure relates to the effects of current which flows in the path left hand to feet. For other current paths, the heart current factor has to be considered.		

IEC-60479-2 highlights unidirectional single impulse currents of short durations, either in rectangular, sinusoidal impulses, or capacitor discharges, as an electric shock hazard in the event of a ground fault or isolation fault as shown in Figure 3 below.[15] For a shock duration of 10 ms or more, the physiological effects experienced by the human body is determined by that shown in Figure 1 and Figure 2. For impulse currents of duration less than 10 ms, the physiological effects of ventricular fibrillation is determined by that shown in Figure 3.

[14] IEC-60479-1, "Effects of Current on Human Beings and Livestock." https://webstore.iec.ch/publication/62980
[15] IEC-60479-2, "Effects of Current on Human Beings and Livestock - Special Aspects." https://webstore.iec.ch/publication/63392

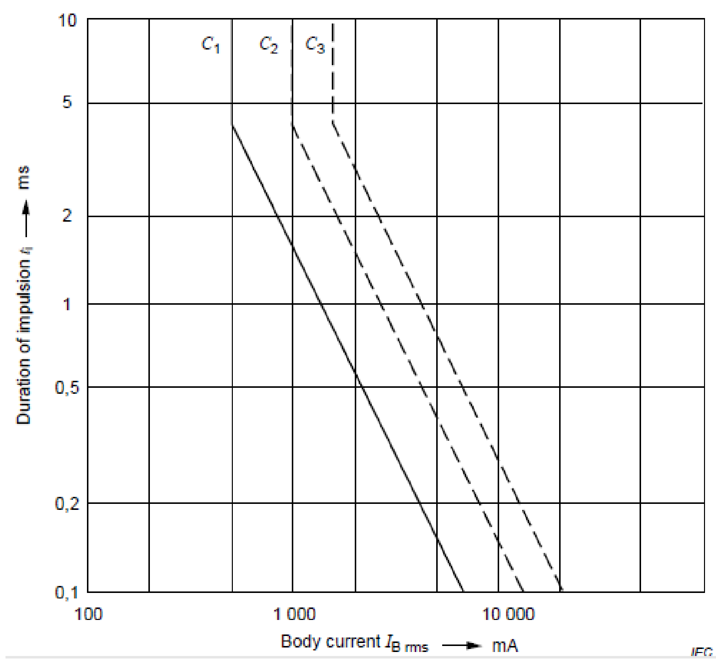

Figure 3 – Threshold of ventricular fibrillation for current flowing from hand to both feet.[16]
Below *C*1: no fibrillation;
Above *C*1 up to *C*2: low risk of fibrillation (up to 5% of probability);
Above *C*2 up to *C*3: average risk of fibrillation (up to 50% of probability);
Above *C*3: high risk of fibrillation (more than 50% probability).

The following analysis evaluates whether 0.2 J is a safe energy limit for capacitive discharge as proposed by the GTR No. 20.

In a discharging RC circuit, the capacitor with a time-constant T, will discharge exponentially as shown in Figure 4 below. $I_{C(p)}$ is the peak current value of the capacitor discharge, I_{Crms} is the root mean square of the current of the capacitor discharge for a duration of 3T. 3T is the time it takes for the discharge current to decay to 5 percent of $I_{C(p)}$, where T is the time constant equal to the product of the capacitor's capacitance in Farads, and the discharge resistance in ohms. Therefore, at time equal to 3RC, the discharge current equals 5 percent of $I_{C(p)}$.

[16] IEC-60479-2, "Effects of Current on Human Beings and Livestock - Special Aspects." https://webstore.iec.ch/publication/63392

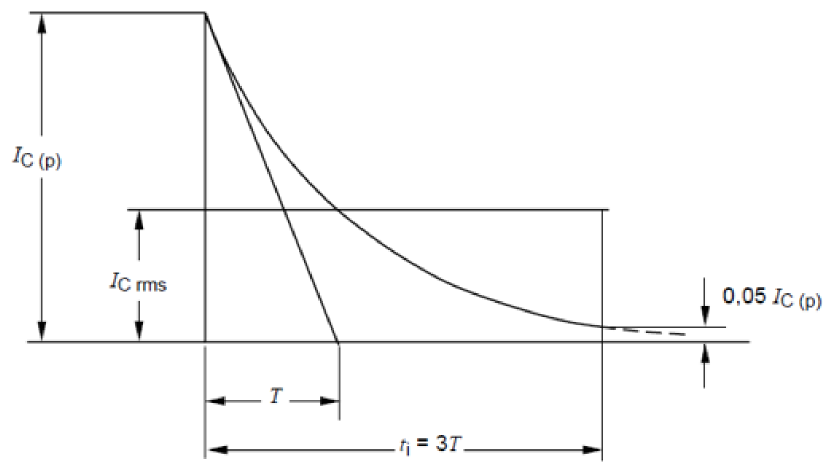

Figure 4 – Forms of Current for Capacitor Discharges[17]

The discharge current of a capacitor can be represented by the exponential decay shown in Equation 1. The heat dissipated is the product of the resistance of the resistor and the integral of the square of the discharge current, which is equal to the product of the resistance, the square of the I_{Crms} current, and the time at 3T, shown in Equation 2.

Equation 1 – Discharge Current of a Capacitor

$$i(t) = I_{C(p)} \times e^{\frac{-t}{RC}}$$

Equation 2 – Heat Dissipated

$$R \times \int_0^{\infty} \left(I_{C(p)} e^{-\frac{t}{RC}}\right)^2 dt = R \times I_{Crms}^2 \times 3T$$

Equation 3 – Relationship between I_{Crms} and $I_{C(p)}$

$$I_{Crms} = \frac{I_{C(p)}}{\sqrt{6}}$$

For capacitors, the dischargeable energy is described as half of the product of capacitance, C, the touch voltage (V_T) squared.

[17] IEC-60479-2, "Effects of Current on Human Beings and Livestock - Special Aspects." https://webstore.iec.ch/publication/63392

Equation 4 – Dischargeable Energy as a relationship between V_T and C

$$E = \frac{1}{2}CV_T^2$$

Equation 5 – Dischargeable Energy as a relationship between I_{rms} and RT

$$E = I_{rms}^2 x\ 3RT$$

For a touch voltage, V_T, the discharge resistance R can be obtained from the third column in Table 2. Should the touch voltage not match exactly, the discharge resistance is interpolated using the values in Table 2.

In NHTSA's analysis, the sample discharge scenarios were constructed by (1) using a range of touch voltage values (60V – 1000V), (2) applying the associated discharge resistance values from the third column in Table 2 (interpolating between values as needed), (3) using a constant energy value of 0.2J, (4) using Equation 4 to calculate the capacitance (C) and (5) using Equation 5 to calculate the current I_{rms}. The computed I_{rms} discharge current at a discharge time period of 3T is then compared to the ventricular fibrillation thresholds defined in Figure 1, Figure 2, and Figure 3 above.

As an example, consider a capacitance voltage of 60V. In accordance with the steps described above,

1. Touch voltage V_T = 60 V
2. Resistance for 60 V touch voltage from the third column in Table *2*:

$$R = 736\ ohms + \left(\frac{75V - 60V}{75V - 50V}\right) \times (752\ ohms - 736\ ohms)$$

$$R = 745.6\ ohms$$

3. Energy = 0.2 J
4. Using Equation 4, we get:

$$C = \frac{2 \times E}{{V_T}^2} = 111.11\ microfarads\ (uF)$$

Equating the discharge duration to 3T we get:

$$t = 3 \times T = 3 \times R \times C = 248.53\ ms$$

5. Using Equation 5, we get:

$$I_{rms} = \sqrt{\frac{E}{3T \times R}} = 32.85\ mA$$

The I_{rms} and discharge duration for different touch voltages of discharge energy of 0.2 J are shown in Table 5.

Table 5. Computed Discharge Current (I_{rms}) and Discharge Duration for Different Voltages for a Discharge Energy of 0.2 Joules.

Voltage (V)	Resistance (ohms)	Capacitance (uF)	Discharge Duration (ms)	I_{rms} (milli Amperes (mA)
60	746	111.1	248.5	32.9
100	704	40.0	84.5	58.0
125	680	25.6	52.2	75.0
150	664	17.8	35.4	92.2
175	648	13.1	25.4	110.3
200	632	10.0	19.0	129.2
225	616	7.9	14.6	149.1
400	560	2.5	4.2	291.6
500	500	1.6	2.4	408.2
700	500	0.8	1.2	571.5
1,000	500	0.4	0.6	816.5

Figure 5 below displays NHTSA's results for discharge current and discharge duration plotted on the combined graph of Figure 2 and Figure 3 above. For a limit of 0.2 J of discharge energy, the results are below the c_1 boundary curve for a duration of 10 ms or less and are within the AC-2 region for discharge durations exceeding 10 ms, but less than 10 s. Discharge events below the c_1 curve have no risk of ventricular fibrillation or harmful physiological effects.

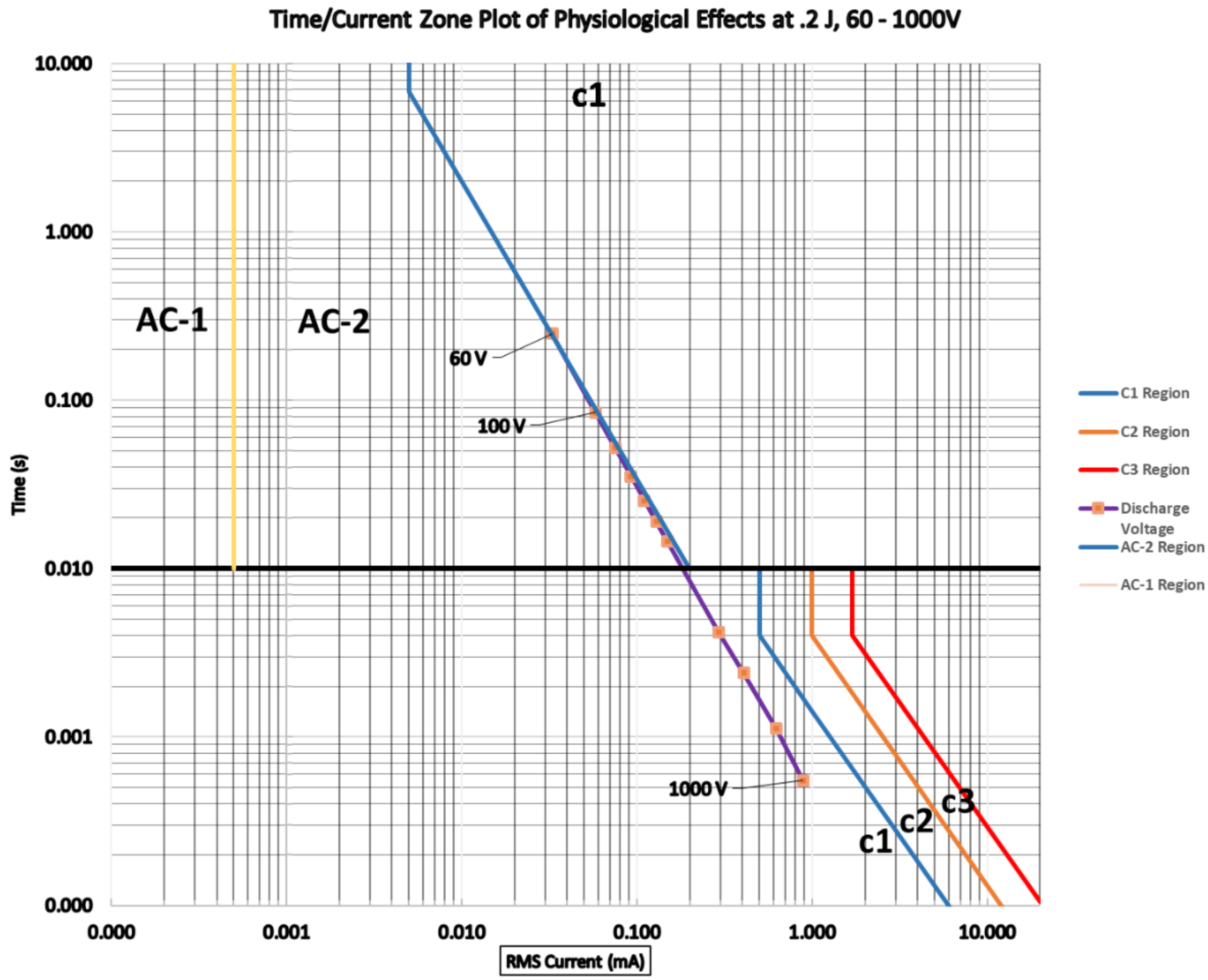

Figure 5 – NHTSA's Analysis transposed onto IEC 60479-1 for AC current (Figure 2 of this document) and IEC 60479-2 (Figure 3 of this document)

For DC current, the results are also below the C1 curve and within the DC-2 region, as shown in Figure 6. IEC-60479-1 notes that measurements of the total body impedance for large surface areas of contact with direct current were only performed in dry condition, but none were performed at saltwater-wet conditions. The IEC-6079-1 states for large surface areas of contact in water-wet and saltwater-wet conditions the total body resistance may be determined with sufficient accuracy from total body impedance for AC current in water-wet and saltwater-wet conditions, while neglecting small differences of impedances between AC and DC which may exist in the voltage range below 100 V. The AC impedances can be used for a conservative estimate, which were implemented in the DC analyses of safe energy limits.

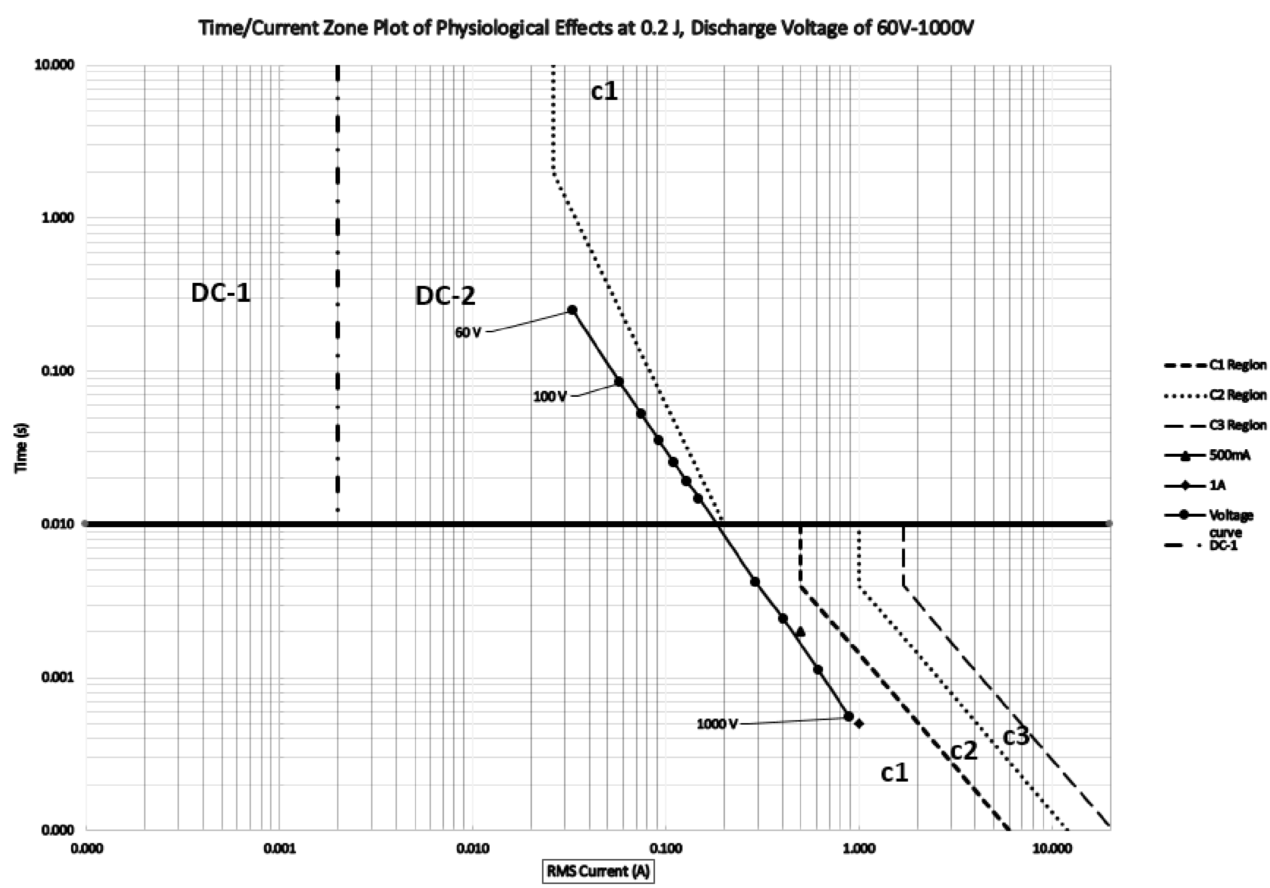

Figure 6 – NHTSA's Analysis transposed onto IEC 60479-1 for DC current (Figure 1 of this document) and IEC 60479-2 (Figure 3 of this document)

3.0 NHTSA's Assessment of a Low-Energy Post-Crash Compliance Option

Based on NHTSA's analysis of the low electrical energy option, the Agency agrees that 0.2 J is a safe energy limit for capacitors that are not electrically isolated. Including a low electrical energy compliance option for post-crash electrical safety for capacitors and high voltage sources with unidirectional impulse currents (e.g., y-capacitors in FCEVs which are directly connected to the chassis and cannot be electrically isolated) does not reduce safety.

This compliance option for meeting post-crash electrical safety is only available to capacitors and high voltage sources in the electric powertrain with unidirectional impulse currents, such as capacitive discharge. All other high voltage sources will not be able to use this post-crash option and instead, will have to meet one of the following: protective barriers, electrical isolation, or absence of high voltage post-crash.

Before the crash tests, manufacturers must identify the capacitors, type of capacitors (x-capacitors and y-capacitors) and their respective capacitance (C_x and C_y) in the electric power train for which they indicate compliance with the post-crash electrical safety requirements using the option for low energy of less than or equal to 0.2 J. Voltages Vb, V1, and V2 are measured in a similar manner as that in S7.7 of FMVSS No. 305 between 10 and 60 seconds after impact. The energy in a x- capacitor (TEx) and that in a y-capacitor (TEy) is calculated by the formulas below:

$$TEx = 0.5 \times Cx \times Vb^2$$

$$TEy = 0.5 \times Cy \times (V1^2 + V2^2)$$