Standard Test Method for Impact Attenuation of Playing Surface Systems, Other Protective Sport Systems, and Materials Used for Athletics, Recreation and Play[1]

This standard is issued under the fixed designation F355; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε[1] NOTE—Editorially corrected A1.9 in December 2016.

1. Scope

1.1 This test method measures the impact attenuation of surface systems and materials, specifically the peak impact acceleration ("impact shock") produced under prescribed impact conditions.

1.2 This test method is applicable to natural and artificial surface systems intended to provide impact attenuation, including natural and artificial turf sports fields.

1.3 This test method is applicable to impact attenuating mats and padding used in sports facilities, including stadium wall padding, gymnastic mats, wrestling mats, turf playing systems, pole vault landing systems, playground protective surfacing, and other systems.

1.4 This test method is used to measure the impact attenuation of materials and components used as protective padding on trampoline frames, goal posts, etc., provided the material or component can be tested separately from the equipment to which it is attached.

1.5 Without modifications, this test method shall not be used to test materials and components that are attached to structures or equipment or finished products, unless the impact attenuation of the whole system is of interest.

1.6 While it is widely believed that appropriate impact attenuation can reduce the risk of impact-related injuries, the relationships between the results of this test method and specific injury risk and outcomes have not been determined.

1.7 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1596 Test Method for Dynamic Shock Cushioning Characteristics of Packaging Material

E105 Practice for Probability Sampling of Materials

E122 Practice for Calculating Sample Size to Estimate, With Specified Precision, the Average for a Characteristic of a Lot or Process

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

F1292 Specification for Impact Attenuation of Surfacing Materials Within the Use Zone of Playground Equipment

F2650 Terminology Relating to Impact Testing of Sports Surfaces and Equipment

2.2 *SAE Standard:*

SAE J211/1 Instrumentation for Impact Tests - Part 1 - Electronic Instrumentation (rev. July 2007)[3]

3. Terminology

3.1 Definitions of terms related to impact testing of sports surfaces equipment can be found in Terminology F2650, except as noted.

3.2 *Definitions:*

3.2.1 *HIC interval, n*—the time interval within the acceleration-time history of an impact over which the HIC integral is evaluated.

3.2.2 *impact, n*—contact caused by a moving object (for example, an impact test missile) striking another object (for

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from SAE International (SAE), 400 Commonwealth Dr., Warrendale, PA 15096-0001, http://www.sae.org.

example, a surface) and during which one or both bodies are subject to high accelerations.

3.2.3 *impact test, n*—a procedure in which the impact attenuation of a playground surface or surfacing materials is determined by measuring the acceleration of a missile dropped onto the surface.

3.2.4 *free-fall impact test, n*—an impact test in which the trajectory of the missile is not restrained by rails, wires, or mechanisms or structures of any type.

3.2.5 *guided impact test, n*—an impact test in which the trajectory of the missile is restrained by rails, wires, or other mechanism or structure.

3.2.6 *impact test results, n*—one or more measured or calculated values from one or more impact tests used to define the impact attenuation of a playground surface or surfacing materials.

3.2.7 *impact test site, n*—point on the surface of an installed playground surface that is selected as the target of an impact test.

3.2.8 *impact velocity, n*—the velocity (V_0) of a falling body (for example, a missile) at the instant of impact.

3.2.9 *missile, n*—a rigid object of specified mass and dimensions; used to impart an impact to a surface.

3.2.10 *impact test system, n*—a device or system for performing an impact test in which an instrumented missile as described in Annex A1 and Annex A2 is used to impact the surface or surfacing materials as specified in the appropriate specification or test procedure.

3.2.11 *missile reference plane, n*—the plane of the flat circular face of the hemispherical missile.

3.2.12 *reference drop height, n*—a specification of the theoretical drop height of an impact test.

3.2.13 *reference MEP pad, n*—a modular elastomer programmer pad with consistent and known impact attenuation properties that is used to verify proper functioning of the impact test equipment.

3.2.14 *theoretical drop height, n*—the drop height (h) that, under standard conditions, would result in an impact velocity equal to a missile's measured impact velocity (V_0). The standard conditions assume that friction and air resistance do not affect the acceleration of the missile and that the acceleration due to gravity is equal to the standard value of g at sea level. In a free-fall impact test, the actual drop height will approximate the theoretical drop height. In a guided impact test, the theoretical drop height will be less than the actual drop height, due to the effects of friction in the guidance mechanism.

3.3 *Definitions of Terms Related to the Measurement of Acceleration Used in Annexes:*

3.3.1 *accelerometer, n*—a transducer for measuring acceleration.

3.3.1.1 *transducer, n*—the first device in data channel, used to convert a physical quantity to be measured into a second quantity (such as an electrical voltage) which can be processed by the remainder of the channel.

3.3.1.2 *triaxial accelerometer, n*—a transducer or combination of transducers used for measuring the three vector components of acceleration in three dimensions, relative to three orthogonal spatial axes.

3.3.1.3 *uniaxial accelerometer, n*—a transducer used to measure the component of acceleration relative to a single spatial axis.

3.3.2 *accelerometer data channel, n*—all of the instrumentation used to communicate information about the physical quantity of acceleration from its origin to the point of presentation. The data channel includes all transducers, signal conditioners, amplifiers, filters, digitizers, recording devices, cables and interconnectors through which the information passes and also includes the analytical software or procedures that may change the frequency, amplitude, or timing of the data.

4. Summary of Test Method

4.1 A test specimen is impacted at a specified velocity with a specific missile of given mass and geometry as stipulated in a specification or test method. An accelerometer mounted in the missile is used to record the acceleration-time history of the impact and the peak acceleration is used as a measure of impact severity. Optionally, the displacement history of the impact may also be recorded.

4.2 This test method defines three missiles for use in playing surface impact tests:

4.2.1 *Missiles A and D* are both cylindrical, with specified mass and geometry and a circular, flat, metal impacting surface. These missiles are used with a guidance mechanism.

4.2.2 *Missile E* has a hemispherical impacting surface of specified mass and geometry and is used with a guidance system or, if equipped with a triaxial accelerometer, without guidance ("free-fall").

4.2.3 The specific masses and geometries of the missiles are detailed in Annex A1.

5. Significance and Use

5.1 The results of this method quantify the impact attenuation of playing surface and system specimens under the specific test conditions.

5.2 The test method measures the outcome of impacts performed under specific conditions. It does not quantify the intrinsic material properties of the tested specimens.

5.3 Test results from different specimens obtained under the same conditions (that is, the same missile mass and geometry, drop height, etc.) are used to compare impact attenuation under those conditions.

5.4 Test results obtained under different conditions are not comparable. Specifically obtained with different missiles are not equivalent and cannot be directly compared. Similarly, test results obtained using the same missile, but using different drop heights, are not directly comparable.

6. Apparatus

6.1 The user is to select the appropriate apparatus as called for in the test method or specification for the testing.

NOTE 1—The apparatus is detailed in Annex A1.

7. Test Specimen

7.1 Test specimens shall represent the surface system or protective padding as it is intended to be used. The minimum distance between the outer dimension of the missile and the edge of the specimen shall be at least 25.4 mm (1 in.) and no less than the thickness of the specimen.

7.2 Where the sample is to be tested in a controlled laboratory a method of confinement for the sample is required when specified in the appropriate standard.

7.3 Where the test is to be performed on an installed surface or in a location where it is to be used, there will be a testing protocol in the system specifications that will state the test procedure. The procedure can include, the theoretical drop height, test locations, surface preparation, temperature and requirements for the collection, recording and reporting of data.

7.4 Where the missiles and Annex A1 and Annex A2 are used in the testing of surface systems, the appropriate specification shall provide any reference or confirmation procedures required.

8. Number of Specimens

8.1 The number of specimens tested as a sample can vary widely, depending upon the intended use of the data. It is recommended that at least two specimens be tested for each set of conditions. To obtain a specific quality assurance level, the sampling procedures of Practices E105 and E122 shall be followed.

8.2 The appropriate specification will have requirements for number and size of samples required for laboratory testing.

8.3 Where the testing is to take place at the site of installation or use, the appropriate standard will provide direction to the person performing the testing as to the number of test locations and how they are determined.

9. Conditioning Laboratory Testing

9.1 Do not stack the specimens during any conditioning. They shall be under the intended use condition or preconditioned at 50 ± 2 % relative humidity and 23 ± 2°C for a minimum of 4 h, or until desired temperature is attained. Samples to be tested at other than these conditions shall be stored in the desired environment for at least 4 h, or until they reach the desired temperature, before testing. Samples shall be tested (that is, impacted) within 10 s after removal from the environmental chamber. Samples shall be returned to the environmental chamber within 20 s after impact and stored for at least 2 h between drops. Testing at other than ambient precludes conducting successive drops at short time intervals.

9.2 The specification to which the sample is being tested will outline all requirements for conditioning of laboratory test samples.

9.3 The specification to which the surface system is being tested in the field will outline all requirements of conditioning or preparation requirements for the surface or the selection of the test location.

NOTE 2—Due to differing thermal conductivities and the extreme time dependence of temperature profiles in most materials exposed to extreme surface temperature changes there may be variability introduced by this type of testing.

10. Procedure

10.1 Perform an instrument check as described for the appropriate instrument in Annex A1 and Annex A2. Reference drops are performed appropriate to the test.

10.2 Place the specimen under the missile, or orient the dynamic test equipment over the playing surface system.

10.3 Determine the baseline by preloading the test specimen to 6.8 kPa (1.0 psi) for Procedure A and adjusting the recorder to read zero penetration. When testing at other than ambient conditions, determine the baseline with the sample at the desired test temperature.

10.4 Set the theoretical drop height to obtain the desired impact velocity.

10.5 Release the missile, and record the results in accordance with the recommended procedures of the equipment manufacturers.

10.6 Make three consecutive drops at intervals of 1 ± 0.5 min, unless otherwise specified (see Annex A1).

10.7 Ensure the measured drop height corresponds with the theoretical drop height.

11. Evaluation of the Data

11.1 Select the appropriate calculations as the relevant specification.

11.2 G_{max}—Determine the maximum deceleration in the time-deceleration history to the closest *G*.

11.3 The drop test data shall be reviewed at the time of testing and evaluated for G_{max}, velocity, and anomalies in the data, for example large variation in peak from one drop to the other for the same location, that could affect the validity of the data.

11.3.1 Where an anomaly is found, the testing shall be terminated and the device brought into compliance prior to proceeding.

12. Report

12.1 Report the following information:

12.1.1 Complete identification of material tested, including type, source, manufacturer's lot number (if appropriate), thickness (if measureable), and any other pertinent information,

12.1.2 Conditions of test, including temperatures, humidity, and any other pertinent data,

12.1.3 Date of test,

12.1.4 Procedure used and missile description, including mass and geometry,

12.1.5 Method of determining the baseline,

12.1.6 Impact velocity,

12.1.7 Average values of last two of three impacts or as specified,

12.1.8 G_{max}, and

12.1.9 Head Injury Criterion (HIC) depending on specification.

12.2 Where additional reporting requirements are called for in the standard that the test is being performed to, this shall be added to that report.

13. Precision and Bias

13.1 *Precision Procedure A*—The reproducibiltiy is estimated to be ±15 % between laboratories and ±2.5 % within a laboratory.

NOTE 3—This precision statement is based on a series of round-robin tests. The data were analyzed in accordance with Practice E691.

13.2 *Precision Procedure E*—In a preliminary inter-laboratory study, three samples (two reference MEP pads and a unitary surface sample) were tested by five laboratories, using a total of seven different impact test systems. Based on this study the inter-laboratory reproducibility limit of the test method is estimated to be ±5 % for g-max and ±10 % for HIC. The estimate assumes that laboratories will conform to the equipment requirements of this specification and that the tested specimen has minimal inherent variability.

13.3 Potential sources of error or deviations that were accounted for in the procedure are as follows:

13.3.1 Variations in the time between impacts required,

13.3.2 Variations in the impact velocity as a result of differences in drop height or friction in the drop guidance system, and

13.3.3 Variations in test laboratory temperatures.

14. Keywords

14.1 G_{max}; head injury criterion (HIC); impact; playground; playing surfaces; shock absorbing; surface materials

ANNEXES

(Mandatory Information)

A1. APPARATUS

A1.1 *Anvil*—For tests performed on surface samples in a laboratory, the surface sample shall be mounted on a rigid anvil or base having a mass at least 100 times that of the missile.

A1.2 *Missile:*

A1.2.1 The user is to select the appropriate missile as called for in the surface specification. The missile shall have one of the combinations of mass and geometry specified in Table A1.1. (See also Fig. A1.1.)

A1.2.2 The missile includes cavities and additional components required to accommodate the attachment of sensors or to attach a supporting assembly. The form of any cavities or additional components shall be generally symmetrical about the Z-axis of the level missile such that center of mass lies within 0.08 in. (2 mm) of the Z-axis and the moments of inertia about any two horizontal axes do not differ by more than 5 %. (See Fig. A1.2.)

A1.2.3 When a supporting assembly (for example, a handle or ball arm) is rigidly attached to the missile as a means of connecting it to an external guidance system the total mass of the drop assembly, which is the combined mass of the missile, accelerometer and supporting assembly shall be that defined in Table A1.1. The mass of the supporting assembly alone shall not exceed 30 % of the total mass.

A1.3 *Guidance Mechanism for Guided Impact Tests*—For guided impact tests, the missile is connected to low-friction guides (such as a monorail, dual rails, or guide wires) using a follower or other mechanism in order to constrain the fall trajectory of the missile to a vertically downward path. Missile A and D are guided using a ventilated tube. The guidance system must allow the missile to be leveled prior to a drop and must maintain the missile in a level (±5°) attitude during the drop. The guidance mechanism shall be constructed in a

TABLE A1.1 Missile Mass and Geometry

Missile	Impacting Surface Shape	Mass	Geometry
A	Cylindrical	9.1 ± 0.050 kg (20.0 ± 0.11 lb)	Circular face with an area of 129 ± 2.0-cm^2 (20 ± 1.0-$in.^2$) and a circumference-relieved radius of 2 ± 0.25 mm (0.08 ± 0.01 in.) to eliminate sharp edges
D	Cylindrical	2.25 ± 0.050 kg (4.95 ± 0.011 lb)	Circular face with a diameter of 50 ± 0.1 mm (1.97 ± 0.04 in.) and a circumference-relieved radius of 0.75 ± 0.25 mm (0.03 ± 0.01 in.) to eliminate sharp edges
E	Hemispherical	4.6 ± 0.02 kg (10.1 ± 0.05 lb)	Hemispherical face with a diameter of 160 ± 2 mm (6.3 ± 0.1 in.)

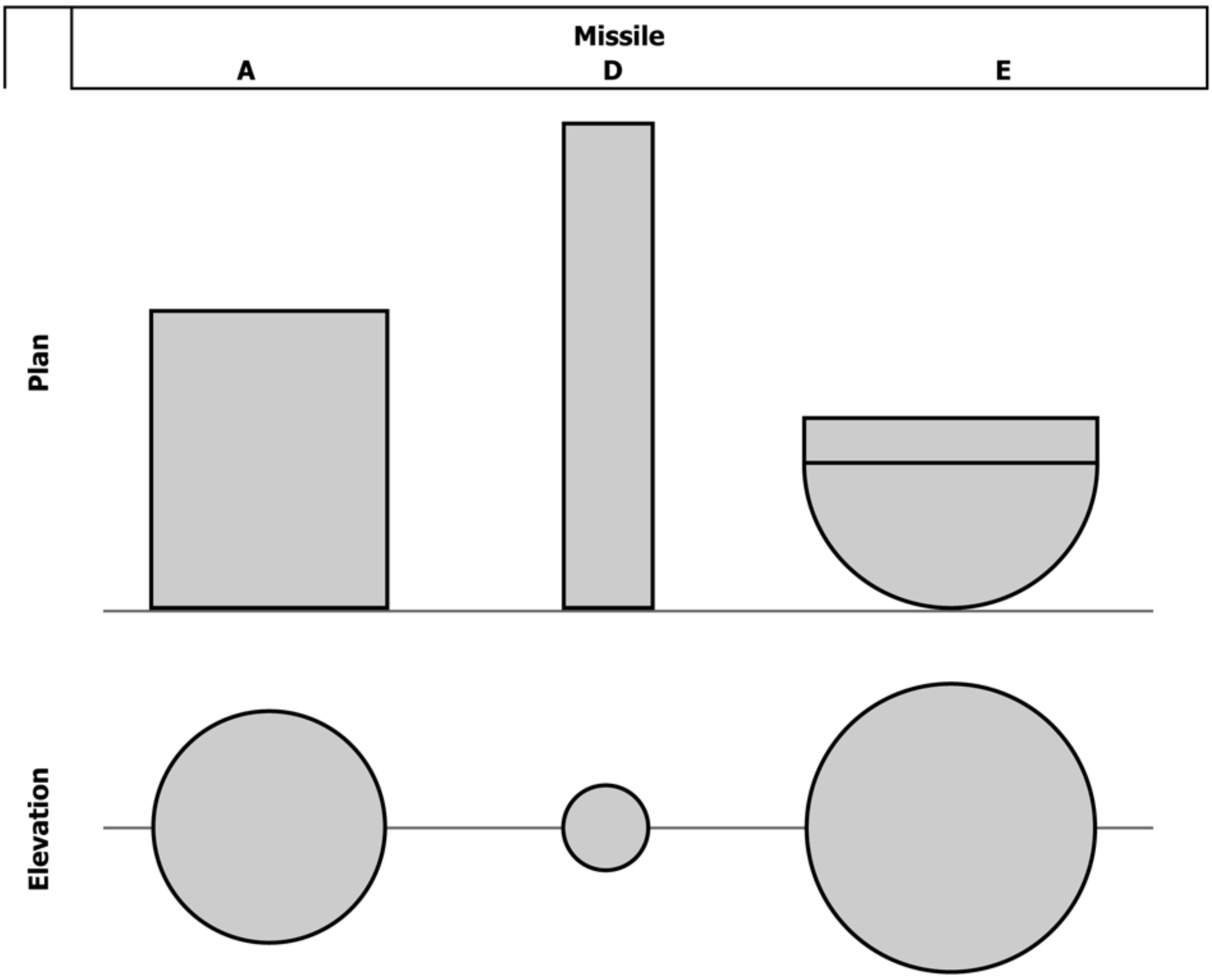

FIG. A1.1 Schematics Showing Approximate Relative Geometries of the A, D, and E Missiles

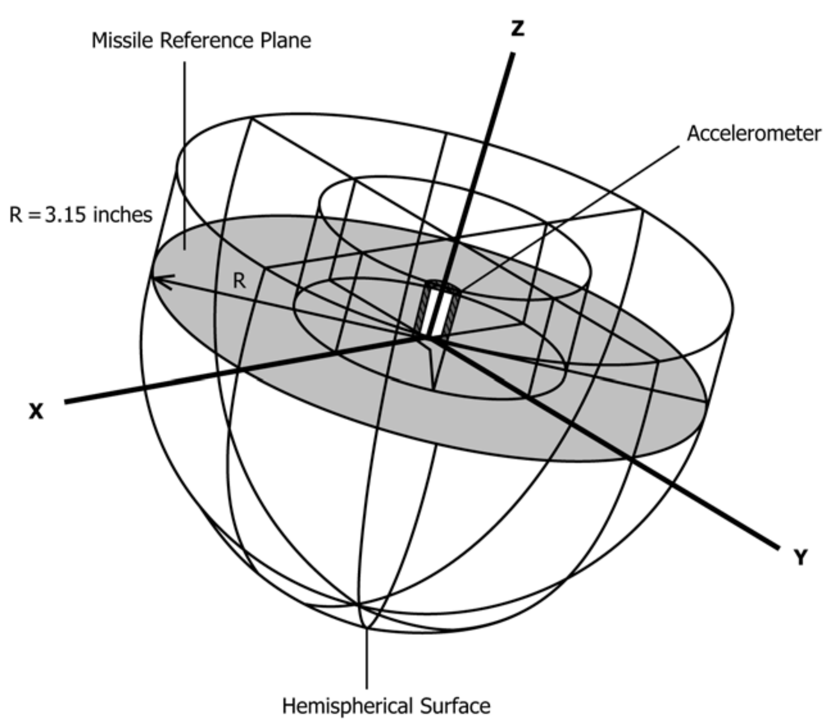

FIG. A1.2 Missile Reference Plane

manner that does not impede the trajectory of the missile during its fall or during its contact with the surface being tested; other than necessary impedance caused by friction in the guidance mechanism.

A1.4 *Support Structure for Free-Fall Impact Tests*—For free-fall impact tests, a support structure (for example, a tripod) shall be used to ensure repeatable drop height and location. The support structure shall be sufficiently rigid to support the weight of the missile without visible deformation. The support structure shall be erected in a manner that does not impede the trajectory of the missile during its fall or during its contact with the surface being tested.

A1.5 *Drop Height Control Mechanism*—The guidance mechanism of A1.19.2 or the support structure of A1.19.1 shall incorporate a means of repeatedly positioning the missile at a predetermined drop height.

A1.6 *Release Mechanism*—The operation of any release mechanism provided as a means of initiating a drop of the missile shall not influence the fall trajectory of the missile following release.

A1.7 *Acceleration Measurement System*—A transducer or transducers and associated equipment for measuring and recording the acceleration of the missile during an impact with an accuracy of within ±1 % of the true value.

A1.8 *Accelerometers*—An accelerometer shall be rigidly attached at the center of mass of the missile. The sensing axis or axes of the accelerometer shall pass through the center of mass of the missile.

A1.8.1 For a free-fall test, a triaxial accelerometer is required.

A1.8.2 For a guided test, a single uniaxial or triaxial accelerometer is used. The accelerometer shall be rigidly attached at the center of mass of the missile (±2 mm) with its axis of sensitivity aligned (±5°) with the missile's Z axis and passing through the center of mass of the missile.

A1.8.3 Accelerometers shall have a minimum sensitive range of ±500 g and be capable of tolerating accelerations of at least 1000 g along any axis.

A1.9 *Accelerometer Calibration*—Accelerometers shall be calibrated by reference to a National Institute of Standards and Technology (NIST) traceable standard using a shaker table to excite a range of frequencies and amplitudes determined suitable by the accelerometer manufacturer. The calibration procedure shall include, as a minimum, the range of frequencies from 20 to 2000 Hz.

NOTE A1.1—Accelerometer calibration is usually performed by the manufacturer.

A1.9.1 Accelerometers shall be recalibrated at a time interval recommended by the equipment manufacturer or every two years, whichever is the lesser time interval.

A1.10 *Accelerometer Connections*—The means of providing power and signal connections to the accelerometer (for example, a cable) shall be constructed in a manner such that the connecting devices do not influence the trajectory of the missile before or during the impact test.

A1.11 *Accelerometer Signal Conditioning*—Any signal conditioning of amplifying electronics required for proper operation of accelerometers shall be of a type recommended by the accelerometer manufacturer and shall have impedance and frequency response characteristics that are compatible with the accelerometer.

A1.12 *Accelerometer Signal Filtering:*

A1.12.1 *Anti-Aliasing Filter*—To prevent aliasing in the digitized acceleration data, the acceleration signals shall be filtered with an analog low pass filter prior to digitization. The anti-aliasing filter shall have a corner frequency of 5000 ± 500 Hz or a maximum of 0.25× the single channel sampling rate.

A1.12.2 *Data Channel Filter*—Digitized data shall be filtered in accordance with the specification for an SAE Channel Class 1000 data channel, using a 4th order Butterworth. An analog filter may be substituted provided it has 4-pole characteristics and conforms to the data channel specification.

A1.13 *Recording Device*—A digital recording device such as a digital storage oscilloscope, a dedicated waveform analyzer of a computer equipped with an analog to digital converter shall be used to capture the acceleration time signal produced during an impact. Analog oscilloscopes and other analog recording devices shall not be used.

A1.14 *Resolution*—The conversion from analog accelerometer signal to digital data shall be accomplished with a digitizer having a resolution of 0.25 g or less. (For example, a twelve bit digitizer spanning the range ±500 g has a resolution of 0.244 g.)

A1.15 *Sample Rate*—The minimum sampling rate of the recording device shall be 10.0 kHz per accelerometer channel. When a triaxial accelerometer is used, three individual digitizers (one per accelerometer axis), each with a minimum sampling rate of 10 kHz are required.

A1.16 *Capacity*—The digitizer shall be capable of recording and storing data continuously for a minimum of 50 ms, beginning at least 5 ms before onset of the impact and ending no earlier than 5 ms after the cessation of the impact.

A1.17 *Display*—The recording system shall have the capability of displaying the recorded acceleration-time data in order to allow inspection by the operator. A graphical display is recommended, but a tabular printout or other form of display is acceptable. The display shall allow inspection of all the data points recorded from at least 5 ms before the onset of impact until no less than 5 ms after cessation of the impact. The display shall show acceleration data in a manner that allows inspection of all data points lying in the acceleration range from –10 g to a value that exceeds the maximum recorded acceleration value.

A1.18 *Accelerometer Data Channels:*

A1.18.1 *Accuracy*—The accuracy of the each data channel shall be such that the maximum acceleration recorded during an impact is recorded is within ±1 % of the true value.

A1.18.2 *Frequency Response*—All acceleration data channels, before signal filtering, shall have a flat frequency response ±0.1 dB in a range extending from below a maximum of 1.0 Hz to above a minimum of 2000 Hz.

A1.18.3 *Channel Frequency Class*—All acceleration data channels, including signal filtering, shall, as a minimum, conform to the requirements of a Channel Frequency Class 1000 data channel, as specified by SAE J211/1.

A1.19 *Drop Height Measurement*—A means of repeatably determining the missile's drop height with a resolution of 1 in. (25 mm) and to an accuracy of ±1 % of the true value is required.

A1.19.1 For a free-fall impact test, the drop height shall be measured directly, prior to release of the missile, using a measuring stick, a steel tape or other appropriate means where possible. An indirect means of determining the theoretical drop height shall also be used. Such indirect means are the velocity measuring system described in A1.19.2, or a means of measuring the time interval between release of the missile and the onset of impact (the fall time), in which case the time interval shall be determined with a resolution and accuracy of 1.0 ms. Both the measured drop height and the theoretical drop height shall be reported.

A1.19.2 For a guided impact test, the theoretical drop height must be determined by measuring the velocity of the missile immediately prior to the onset of an impact; at a point in the missile's trajectory no more than 2.0 in. (51 mm) above the first point of contact between the missile and the surface under test. The velocity measuring system may consist of a light gate device to measure the time an opaque flag interrupts a light sensor or other appropriate means. The velocity measuring device shall not interfere with or impede the trajectory of the missile and shall be capable of recording impact velocity with a resolution of 0.1 ft/s–1 (0.03 m/s–1) and an accuracy of ±1 % of the true value.

NOTE A1.2—Since theoretical drop height is proportional to the square of impact velocity, the ±2 % tolerance on drop height measurement and the ±1 % tolerance on velocity measurement are equivalent. For a typical flag and light gate velocimeter to achieve ±1 % accuracy, the flag width must be known to an accuracy of ±0.5 % and the transit time measured with an accuracy of ±20 μs (that is, a timing device with a clock rate of at least 50 kHz is required).

A1.20 *Battery Operated Equipment*—Battery-operated equipment shall have a means of monitoring battery voltage (for example, a voltage gauge or indicator).

A1.21 *System Integrity Check*—Prior to and following each use, the test apparatus shall be checked for proper operation by performing a series of impact tests on a reference MEP pad. The reference MEP pad shall be provided by the equipment manufacturer or by another agency capable of ensuring reproducible reference pads and shall have been assigned a reference drop height and a nominal *g*-max score.

A1.21.1 Perform three impact tests on the reference MEP pad from the reference drop height with an interval of 1.5 ± 0.5 min between impacts.

A1.21.2 Determine the average g-max score by averaging the *g*-max scores from the second and third drops.

A1.21.3 Compare the average g-max score to the nominal *g*-max score provided with the reference MEP pad.

A1.21.4 If the difference between the recorded *g*-max score and the nominal g-max score exceeds either the manufacturer's specified tolerance or 5 % of the nominal *g*-max score, the equipment does not conform to the requirements of this specification and shall not be used.

A1.22 *Additional and Optional Testing Performed (relevant only on to Procedure A):*

A1.22.1 *Maximum Penetration*—Determine the maximum displacement to the nearest 0.254 mm (0.01 in.).

A1.22.2 *Time to Maximum Penetration*—Determine the time to maximum penetration.

A1.22.3 *Rebound Velocity*—Use a straightedge to draw a tangent line at the exit of the penetration-time trace. The slope of this line, multiplied by the appropriate distance and time calibration, is the rebound velocity. Alternatively, the rebound velocity is determined by other velocity-measuring devices that measure the coefficient of restitution or percent rebound of the missile.

A1.22.4 *Dynamic Hardness Index*—See calculations in Annex A2.

A2. CALCULATIONS

A2.1 If a triaxial accelerometer is used, the resultant acceleration at each point in the time history of the impact shall be calculated as $A_R=\sqrt{A_x^2+A_y^2+A_z^2}$ where A_R is the resultant acceleration and A_x, A_y, and A_z are the accelerations recorded by accelerometers aligned with the X, Y, and Z missile axes.

A2.2 The angle of impact of a free fall missile shall be calculated as in Eq A2.. In a free-fall impact test, the angle of the missile at the onset of impact and at the instant of maximum acceleration shall be calculated. For the purposes of this calculation, the onset of impact shall be the data sample at which the resultant acceleration first meets or exceeds a threshold value of 5 g. The angle shall be calculated from the component accelerations. The cosine of the missile angle shall be calculated as:

$$\cos\left(\theta_{headform}\right)=\frac{A_z}{A_R}$$

A2.3 For guided missile systems where frictional forces may affect the missile the theoretical drop height shall be calculated as:

$$H=V^2/2g \qquad (A2.1)$$

where:

H = theoretical height, mm (in.),
V = velocity, mm/s (in./s), and
g = acceleration of gravity, 9806 mm/s/s (386 in./s/s).

Ensure the measured drop height corresponds with the theoretical drop height for comparison to the velocity for the theoretical drop height.

A2.4 For free fall test system where the time from missile release to the time of onset of impact has been measured, impact theoretical drop height shall be calculated as:

$$H=\frac{1}{2}gt^2 \qquad (A2.2)$$

where:

t = time of fall (in seconds).

A2.5 *Severity Index*—The time integral of deceleration exponentiated 2.5 times is calculated by dividing the deceleration-time record into equally sized time subintervals of magnitude of 0.05 ms and summing the deceleration values (in *G*) exponentiated 2.5 times between the two intersections of the deceleration record and the time axis. Multiply this result by the time subinterval length (in seconds) and the result is the Severity Index in *G*-s.

A2.6 *Head Injury Criteria (HIC)*—Requires the maximization of a mathematical expression, involving the time-average acceleration by varying of the time interval over which the average is calculated. Numerical evaluation of the HIC requires analog-to-digital conversion of the acceleration time profile using a sampling rate sufficient to characterize the pulse accurately. These data are easily processed by a digital computer. The HIC number is determined by evaluating the equation for all iterative combinations of the integration limits that the time interval allows for the evaluation. The equation[4,5] for calculating the HIC value is as follows:

$$\mathrm{HIC}=\left[(t_2-t_1)\left(\frac{1}{(t_2-t_1)}\int_{t_1}^{t_2}a\,dt\right)^{2.5}\right]\max \qquad (A2.3)$$

A time interval of 0.05 ms shall be used.

A2.6.1 In the acceleration-time history of the impact, locate the time point T_0 at a point immediately preceding the onset of the impact and the time point T_1 at a point immediately following the cessation of the impact.

A2.6.2 For each time interval (t_1, t_2) calculate and record the trial HIC interval, $t_2 - t_1$.

A2.6.3 The HIC score for an impact is determined as the maximum value of all the Trial HIC (t_1, t_2) scores.

A2.6.4 The numerical procedures used to calculate HIC shall provide results that are within ±1 % of the true value.

A2.7 Review the drop data at the time of testing and evaluate the test data for velocity or anomalies, or both, in the graph.

NOTE A2.1—A computer algorithm for calculating HIC is provided in Appendix X1.

A2.8 *Dynamic Hardness:*

$$\text{Dynamic hardness index}=\frac{G_{max}\times S\times W}{A\times P} \qquad (A2.4)$$

where:

S = sample thickness, cm (in.),
W = missile weight, kg (lb),
A = missile area, cm^2 (in.^{2}), and
P = maximum penetration, cm (in.).

A2.9 *Conformity of Test Data:*

A2.9.1 Total sum of *G* values for each 0.05 ms.

A2.9.2 Test conformity to following relationship:

$$\left(|V_i|+|V_r|\right)\frac{20\,000}{g}=[\mathrm{sum}]G \qquad (A2.5)$$

where:

V_i = missile velocity at start of impact,
V_r = missile velocity upon rebound from surface of material,
G = acceleration of gravity units, and
[sum]G = sum of the G values at each 0.05 ms over the total duration of impact.

A2.9.3 Incongruity of greater than 5 % warrants search for errors in the apparatus or the instrumentation system, or both.

[4] Chou, C., and Nyquist, G., "Analytical Studies of the Head Injury Criterion," Society of Automotive Engineers (SAE), Paper No. 740082, 1974.

[5] See Specification F1292, Appendixes X1 and X2.

APPENDIXES

(Nonmandatory Information)

X1. COMPUTER ALGORITHM FOR CALCULATING HIC

X1.1 The following example pseudo-code computes the HIC score of an acceleration pulse to within 0.5 % of theoretical values. For clarity, the program has been written as a procedure, with filtered input data and results passed as global variables. It is also assumed that the data presented to the routine has already been filtered.

```
// GLOBAL VARIABLES
 var
 // Data Acquisition Information
   SampleFrequency: integer;   // Data acquisition rate, samples/second
   nSamples     : integer; // Number of acquired data samples
 // Input Data
   AccelData: array [0..nSamples] of real; // Array of acceleration data in g units
// Outputs
   HICmax   : real;      // HIC score
   HICinterval : real;      // HIC interval

// HIC CALCULATION PROCEDURE
 procedure HIC_Calculation;
 // LOCAL VARIABLES
 var
 // Intermediate Results
   integral     : array [0..nSamples-1] of real; // HIC Integral Values
   iHIC0,iHIC1  : integer;  // HIC interval boundaries
   HIC        : real;     // Intermediate HIC result
 // Counters
   i,j          : integer;

begin
// Initialise results
 iHIC0 := 0;
 iHIC1 := 0;
HICmax:=-1.0;
// Calculate Integral
integral [0]:=0.0;
for i:=1 to nSamples do integral [i]: =integral [i-1] +(AccelData [i]+AccelData [i-1])/2;

// Scan all possible HIC intervals for maximum score
for i := 0 to nSamples-1 do
for j := i+1 to nSamples do
begin
 HIC:=(integral [j]-integral [i])/(j-i);
 if HIC>0.0
   then HIC:=Power (HIC,2.5)
   else HIC:=0.0;
 HIC:=HIC*(j-i)/SampleFrequency;
 if HIC>HICmax then
   begin
     HICmax:=HIC;
     iHIC0:=i;
     iHIC1:=j;
   end;
end;

// Calculate the HIC interval
HICinterval := (IHIC1-IHIC0)/SampleFrequency;
end;

end.
```

X1.2 *Verification*—When correctly implemented, the algorithm computes the theoretical HIC scores for the cosine pulses described in Specification F1292 subsection A1.4.2.1 and Table X1.1, assuming a sample rate of 20 000 Hz.

TABLE X1.1 Theoretical and Calculated Values of Synthesized Cosine Pulses

Pulse Width (T) ms	Reference *g*-max	Theoretical HIC	Calculated HIC	Error	Error %
10.0	100	302.9	302.9	0.0	0.013
10.0	150	834.8	834.7	–0.1	–0.012
10.0	200	1713.7	1713.5	–0.2	–0.011
*20.0	100	605.9	605.9	0.0	0.004
20.0	150	1669.6	1669.5	–0.1	–0.006
20.0	200	3427.4	3427.2	–0.2	–0.005

X2. ALGORITHM FOR DIGITAL BUTTERWORTH FILTER

X2.1 This specification specifies the use of a Butterworth Digital Filter for smoothing acceleration data. Also, the response spectrum of modified Channel Frequency Class (CFC) 1000 acceleration data channels is defined in terms of the Butterworth digital response. The CFC 1000 data channel requires a fourth order (4-pole) Butterworth filter with a –3dB corner frequency of 1686.1 Hz. Instead of implementing a fourth order filter, it is recommended that the data be filtered twice, once forwards and once backwards using second order (2-pole) filter twice with a -3dB corner frequency of 2077.5 Hz. This approach eliminates phase shift in the filtered data.

X2.2 The 2-pole (second order) Butterworth Digital Filter is defined by:

$$F_t = \sum_{i=0}^{2} a_i A_{t-j\Delta} + \sum_{j=1}^{2} b_j A_{t-j\Delta} \tag{X2.1}$$

where:

F_t = filtered acceleration datum at time *t*,
A_t = input acceleration datum at time *t*,
Δ = sample interval, and
a_i = filter coefficient
b_j = filter coefficient

X2.2.1 The correct filter coefficients vary with the data sampling rate. Table X2.1 shows coefficients for a sample rate of 20 000 Hz. Fig. X2.1 shows the response function of the filter in relation to the specified limits of the modified CFC 100 data channel. Subsection X2.3 describes a computer algorithm for implementing the 4-pole filter using forward and reverse passes of the 2-pole filter.

TABLE X2.1 Second Order Butterworth Filter Coefficients for a CFC 1000 Data Channel Sampling Rate = 20000 Hz

Coefficient	a_0	a_1	a_2	b_1	b_2
Value	0.071893	0.143786	0.071893	1.111586	–0.399159

X2.3 *Computer Algorithm for 4th Order, Zero Phase Shift, Butterworth Digital Filter*—The example pseudo-code below implements a fourth order, zero phase shift on an array containing a single channel of acceleration data. For clarity, the program has been written as a procedure, with input data and filtered data passed as global variables.

```
// GLOBAL VARIABLES
const   nSamples;          // Number of acquired data samples
var
// Data Acquisition Information
   SampleFrequency: integer; // Data acquisition rate, samples/second
   nSamples      : integer; // Number of acquired data samples
// Input Data which will be replaced with the filtered data
AccelData: array [0..nSamples] of real; // Array of acceleration data in g units

// Butterworth Filter
procedure Butterworth_Filter
// LOCAL VARIABLES
var temp: array [0..nSamples] of real; // Intermediate results
   a,b:array [0..2] of real; // Filter coefficients
  i,j: integer; // Counters
begin
  a [0] = 0.071893;
  a [1] = 0.143786;
  a [2] = 0.071893
  b [1] = 1.111586;
  b [2] =-0.399159;

// First pass in forward direction
temp:=AData;
for i:=2 to ScanSize-1 do
     AData [i]:=a [0]*temp [i] + a [1]*temp [i-1] + a [2]*temp [i-2]
                    + b [1]*Adata [i-1]+ b [2]*Adata [i-2];

// Second pass in backward direction
  temp:=AData;
  for i:=ScanSize-3 downto 0 do
     AData [i]:=a [0]*temp [i] + a [1]*temp [i+1] +a [2]*temp [i+2]
                    + b [1]*Adata [i+1]+b [2]*Adata [i+2];
end;
```

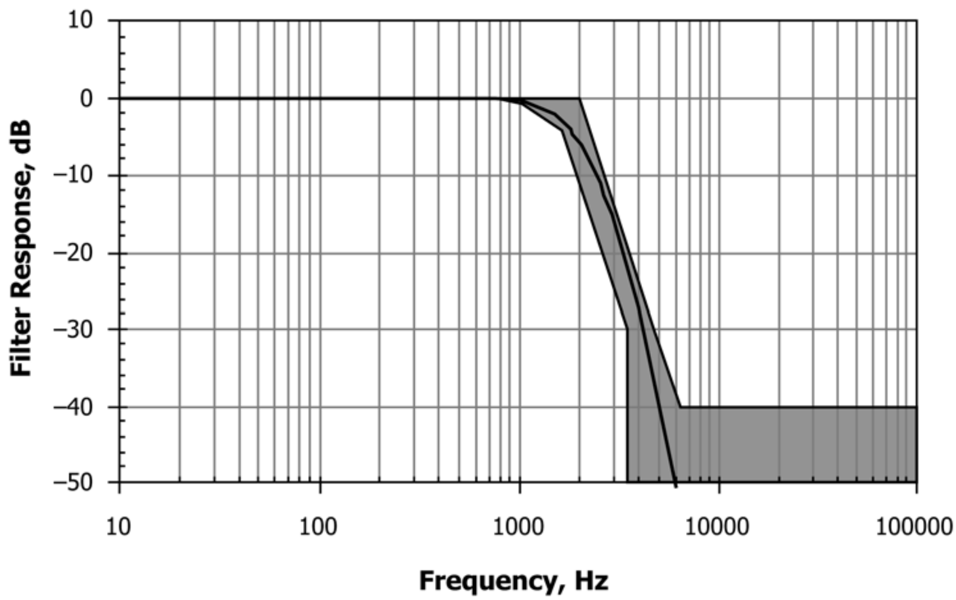

FIG. X2.1 Filter Response Function