# Impact Attenuators: A Current Engineering Evaluation

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**This study, sponsored by the Federal Highway Administration (FHWA) and conducted by ENSCO, Inc., used full-scale crash testing of small and large test vehicles to investigate the impact performance of inertial barrel and energy absorbing impact attenuator systems. Special emphasis was placed on impact performance of minicompact sedans. In all, 20 tests were performed: 16 with inertial barrels and 4 with an energy absorbing system. The 16 inertial barrel tests studied the effects of the following crash scenarios: large car versus small car, angled versus head-on positions, pea gravel versus sand fill material, frozen versus nonfrozen sand fill, loose sand versus bagged sand and two different brands of attenuator barrels. The four energy absorbing system tests used a six-bay Guard Rail Energy Absorbing Terminal (GREAT) system and studied the effects of head-on versus angled positions and large car versus small car impacts. All tests used instrumented dummies and all tests generated a National Highway Traffic Safety Administration (NHTSA) digital data tape. Results of the program showed large and small car performance to be generally acceptable when using NCHRP 230 and dummy analysis procedures. In one test (C-04) the large car exhausted the capacity of a six-bay GREAT system.**

Past testing and analysis of impact attenuators has been based on vehicles weighing 2,250 pounds (1023 kg) or greater. Because of the recent increase in sales of minicars (1,800 lb, 818 kg, range), this class is becoming a significant portion of the vehicle population. This raises new vehicle collision concerns. The small size and weight of the mini cars reduces the dimensions of the wheel base, track width, and crush space, and lowers the mass moments of inertia when compared to larger cars. These differences affect the behavior of the car in a collision.

To better understand the behavior of mini cars in impact attenuator collisions, a series of 20 full-scale crash tests were studied under a Federal Highway Administration (FHWA) contract entitled "Impact Attenuators—A Current Engineering Evaluation." For comparison, seven of the 20 tests were conducted with large cars. The major objectives of this project were as follows:

- To investigate the dynamics of mini-sized and full-sized vehicles colliding with impact attenuators currently deployed on our nation's highways.
- To determine the problems associated with frozen sand in inertial type impact attenuators.
- To investigate the performance of inertial type impact attenuators using alternate fill materials and techniques.

Four series of 60 mile per hour (26.8 m/s) tests were conducted using mini-sized and full-sized vehicles and different impact attenuator systems and configurations. The first series consisted of four vehicle tests using the Guard Rail Energy Absorption Terminal (GREAT) impact attenuator system configured at three different angles and positions. The second series consisted of eight vehicle tests colliding into an unfrozen inertial type impact attenuator system. Sand and pea gravel were used as fill material and two attack angle positions were used. Further, two different types of barrels (Fitch and Energite) were used, but never mixed in one array. The third test series consisted of six head-on collision tests into frozen inertial impact attenuators. For these tests, the two different types of barrels were also employed. The fourth test series consisted of two head-on collision tests into Energite III systems filled with bagged sand.

The overall matrix of the 20 full scale tests is shown in Table 1.

## TEST PROCEDURES

The tests conducted under this contract were performed using the guidelines specified in NCHRP Report 230. Test types 50, 52, 53, and 54 were conducted on the two impact attenuator models. Tests 53 and 54 were conducted with 1,800 pound vehicles to explore snagging and abrupt deceleration potential. These test types are described in Table 2.

## TEST APPURTENANCES

Test appurtenances consisted of a six-bay Guard Rail Energy Absorption Terminal (GREAT) system manufactured by Energy Absorption Systems, Inc. (EAS) and a 15-barrel inertial system composed entirely of barrels manufactured by EAS or Roadway Safety Service, Inc. The following sections describe the selection criteria, design, and configuration of the systems.

### GREAT Impact Attenuator Layout

Figure 1 shows the three configurations used to test the GREAT impact attenuator:

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TABLE 1 FULL-SCALE CRASH TEST MATRIX

| Series No. | Test No. | Fill Material | Condition | Impact Angle | Speed (mi/h) | Impact Point | Vehicle | Attenuator Brand |
|---|---|---|---|---|---|---|---|---|
| 1 | 1625-C-01-84 | - | - | 0° | 60 | Nose | Honda Civic | EAS GREAT |
| | 1626-C-02-84 | - | - | 15° | 60 | 1' Offcenter off nose | Honda Civic | EAS GREAT |
| | 1625-C-03-84 | - | - | 20° | 60 | Mid-terminal | Honda Civic | EAS GREAT |
| | 1625-C-04-85 | - | - | 0° | 60 | Nose | Ford LTD II | EAS GREAT |
| 2 | 1625-B-01-84 | Pea Gravel | Not Frozen | 0° | 60 | Nose | Ford LTD II | Energite III |
| | 1625-B-02-84 | Sand | Not Frozen | 0° | 60 | Nose | Honda Civic | Energite III |
| | 1625-B-03-84 | Sand | Not Frozen | 0° | 60 | Nose | Mercury Cougar XR7 | Energite III |
| | 1625-B-04-85 | Sand | Not Frozen | 15° | 60 | Corner of Gore | Honda Civic | Energite III |
| | 1625-B-05-84 | Sand | Not Frozen | 15° | 60 | Corner of Gore | Honda Civic | Fitch |
| | 1625-B-06-84 | Sand | Not Frozen | 0° | 60 | Offcenter | Honda Civic | Fitch |
| | 1625-B-12-85 | Sand | Not Frozen | 0° | 60 | Nose | Honda Civic | Fitch |
| | 1625-B-07-85 | Sand | Not Frozen | 0° | 60 | Nose | Mercury Cougar XR7 | Fitch |
| 3 | 1625-B-08-85 | Sand | Frozen | 0° | 60 | Nose | Honda Civic | Energite III |
| | 1625-B-09-85 | Sand | Frozen | 0° | 60 | Nose | Mercury Cougar XR7 | Energite III |
| | 1625-B-10-85 | Sand | Frozen | 0° | 60 | Offcenter | Honda Civic | Fitch |
| | 1625-B-13-85 | Sand | Frozen | 0° | 54 | Nose | Honda Civic | Fitch |
| | 1625-B-14-85 | Sand | Frozen | 0° | 60 | Nose | Honda Civic | Fitch |
| | 1625-B-11-85 | Sand | Frozen | 0° | 60 | Nose | Ford LTD II | Fitch |
| 4 | 1625-E-01-86 | Sand | Bagged | 0° | 60 | Nose | Mercury Cougar XR7 | Energite III |
| | 1625-E-02-86 | Sand | Bagged | 0° | 60 | Nose | Honda Civic | Energite III |

TABLE 2 NCHRP REPORT 230 TEST TYPES

| No. | Vehicle Size | Speed (mi/h) | Angle (deg) | Location |
|---|---|---|---|---|
| 50 | 4500 lb | 60 | 0 | Center of Nose |
| 52 | 1800 lb | 60 | 0 | Center of Nose |
| 53* | 4500 lb | 60 | 20 | Along Mid-length |
| 54* | 4500 lb | 60 | 15 | 1 ft Offset from Nose |

*Tests 53 and 54 were conducted with 1800 lb vehicles to explore snagging and abrupt deceleration potential.

- 0° Impact Angle, Vehicle Centered on Nose of Device
- 15° Impact Angle, Vehicle Offset one foot from Center of Nose of Device
- 20° Impact Angle, Vehicle Directed Toward Midpoint of the Side

The GREAT system consists of crushable Hexfoam cartridges surrounded by a framework of triple-corrugated-steel guardrail. When hit head-on, the cartridges absorb the energy of the impact, while the steel guardrail side panels telescope. Only the cartridges are expended. When hit from the side, the steel side panels are restrained by leg pins and a center guidance cable to redirect the errant vehicle. After these tests were conducted, the Hexfoam cartridges were replaced with Hexfoam II cartridges by EAS.

Discussions were held with EAS to select the appropriate GREAT system, given the vehicle, speed, and position requirements of the test. The GREAT system selected was a six-bay configuration 2 feet wide and 22 feet long of the "Median Barrier Protection; Bi-Directional Traffic" unit. The six-bay size was selected because it is standard on today's Interstate highway system.

### Inertial Impact Attenuator Layout

Because of the technical requirements of this test program, all Energite or all Fitch barrels were used for crash testing in the following two configurations:

- 0° Impact Angle, Vehicle Centered on Nose of Attenuator (see figure 2),
- 15° Impact Angle, Vehicle Centered on Corner of Gore (see figure 2).

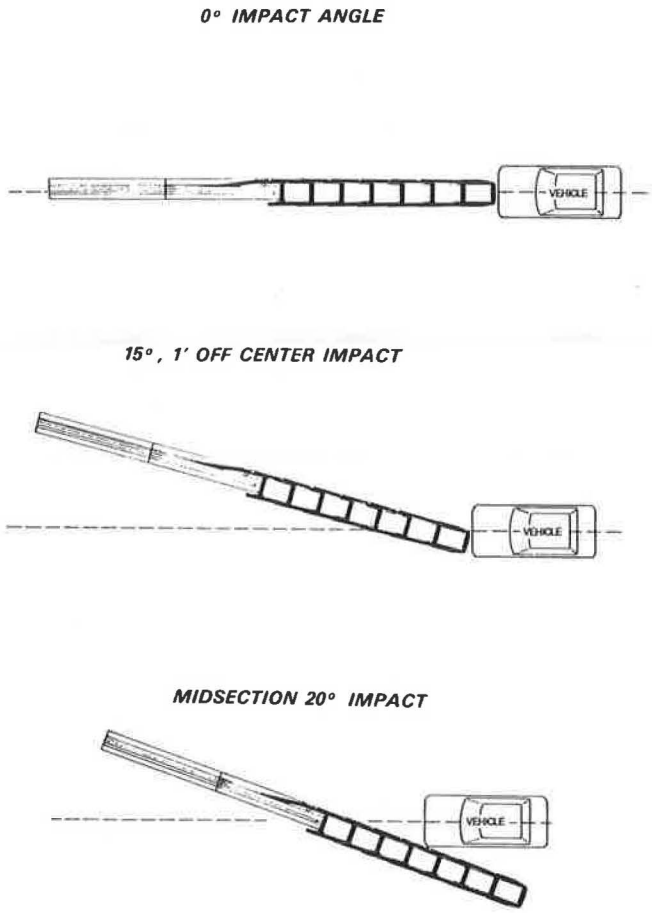


**FIGURE 1 Three test configurations for the GREAT system.**

Selection of the barrel configuration for the test program was based on the following requirements:

- shielding of a 5-foot wide (1.5 m) gore,
- overlapping barrels 30 inches (0.8 m) on each side of gore,
- using 7 rows of barrels or less to minimize length of installation,
- using 2,100-pound (955 kg) barrels in last row,
- leaving a 6-inch (0.2 m) longitudinal space between barrels,
- composing each test array of all Energite or all Fitch barrels, and
- using the same configuration for all tests.

The method for arriving at the configuration consisted of discussions with EAS personnel, Roadway Safety Service, Inc., personnel, FHWA personnel, and the use of a computer program to predict expected behavior. EAS and Roadway Safety Service personnel agreed on the selection of the configuration used for both the large and small car test. All barrels are approximately 3 feet in diameter and barrel weight layout is depicted in Figure 3. Figures 4 and 5 illustrate the Fitch and Energite III barrel systems.

Drainage tests were performed on Energite II, Energite III, and Fitch barrels for the 700-pound (318 kg) and 2,100-pound (955 kg) sizes. Figure 6 provides moisture content measurements made for each of the barrel configurations for a period of 61 days.

Overall, the Energite III and Fitch barrels showed similar results when filled with sand for the 700-pound (318 kg) and 2,100-pound (955 kg) sizes with initial moisture content of 17 to 18 percent. When filled with pea gravel the Energite III 2,100-pound (955 kg) barrel drained slightly faster than the Fitch barrel because the Fitch barrel has a plastic liner. However, the moisture content for pea gravel is low enough so that freezing action is not considered important.

The key finding of the drainage test was that the 700-pound (318 kg) Energite II barrel drained much better than either the 700-pound (318 kg) Energite III barrel or the Fitch barrel. This is because of a fundamental difference in design. The Energite II barrel uses whole piece inserts with drainage holes while the Energite III barrel uses sand support cores without drainage holes. Under the sand, the cores of Energite III seal most of the water in the barrel. Thus, very high moisture contents remain. It should be pointed out that, despite the difference in the two barrels with initial moisture contents of 17.7 percent, both Fitch and Energite III barrels filled with sand could still freeze solid after 1 to 2 months of free drainage.

## TEST VEHICLE

The test vehicles consisted of 1979 Honda Civics corresponding to the NCHRP 230 classification of 1800S and 1979 Ford LTD IIs or Mercury Cougar XR7s corresponding to the NCHRP classification of 4500S. Before testing, the vehicles were prepared by removing the gas tank, battery, and back seat (small car only). After incorporating the instrumentation and ballast necessary to meet the test inertial limits of NCHRP 230, instrumented anthropomorphic dummies (part 572) were installed. The weight limits of the vehicle with occupant(s) prior to test were 1,950 ± 50 pounds (886 ± 23 kg) for the minicompact sedan and 4,500 ± 300 pounds (2,046 ± 136 kg) for the large sedan.

## TEST RESULTS

An overall summary for all tests is provided in Table 3. The table summarizes the test and impact conditions, and test results (using vehicle and dummy analysis).

### Comparison of Force-Displacement Data

Force-displacement curves for each test were generated and documented in the technical volume of the final report. These curves are derived from the vehicle longitudinal acceleration signal. Force is derived by multiplying the acceleration signal by the mass of vehicle; displacement is derived by double integration of the acceleration signal. The major problem with this approach is that noise (e.g., ringing) in the accelerometer produces large oscillations in the force-time history. To overcome this, the data were subsequently smoothed with a 1.6-foot spacial filter (distance-based as opposed to time-based).

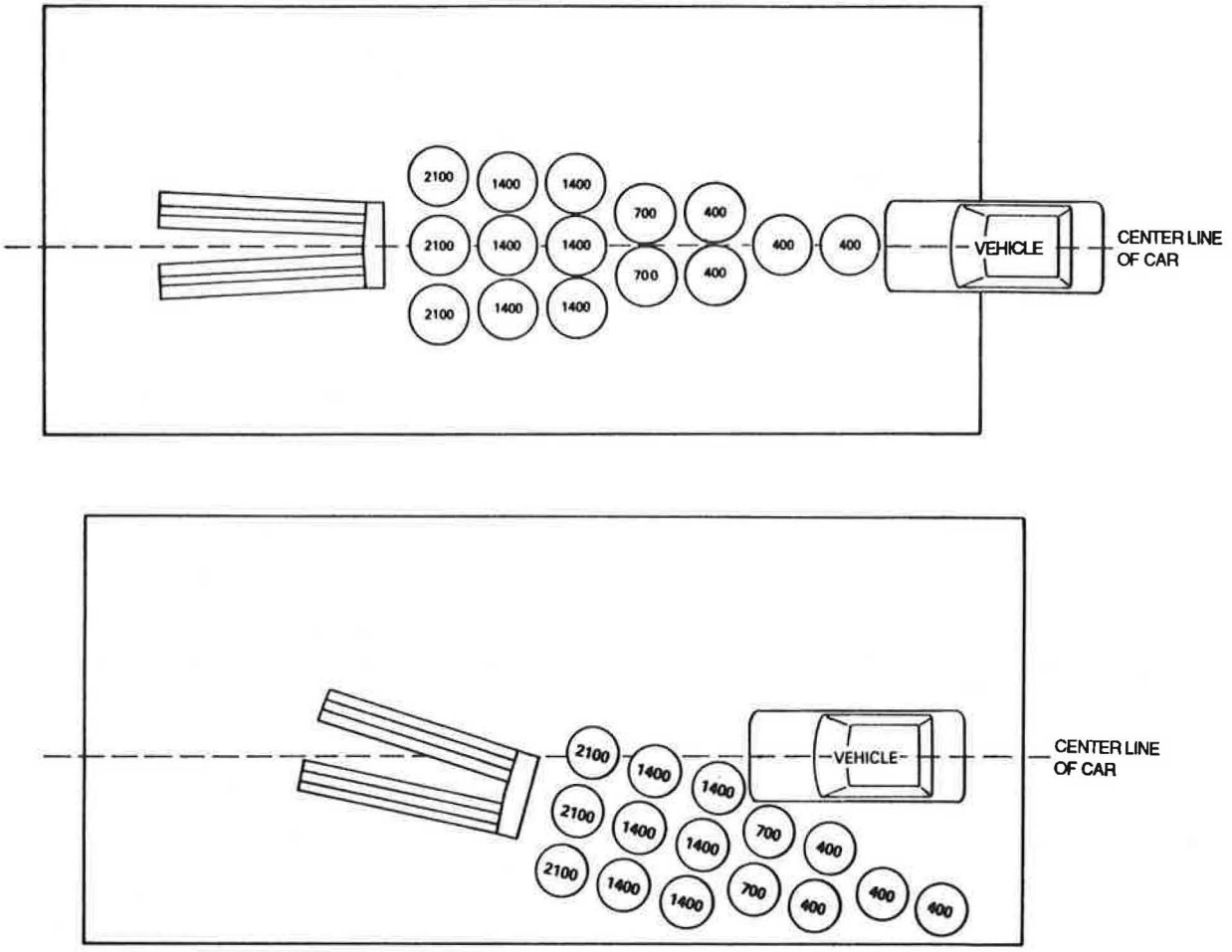


**FIGURE 2 Inertial attenuator: 0° impact angle and 15° corner of gore.**

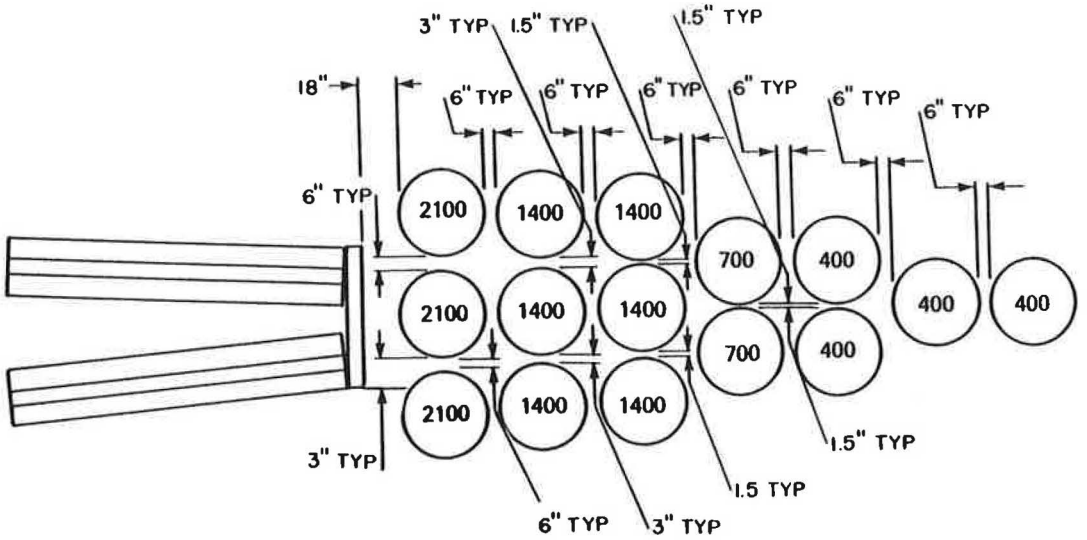


**FIGURE 3 Barrel weight layout.**

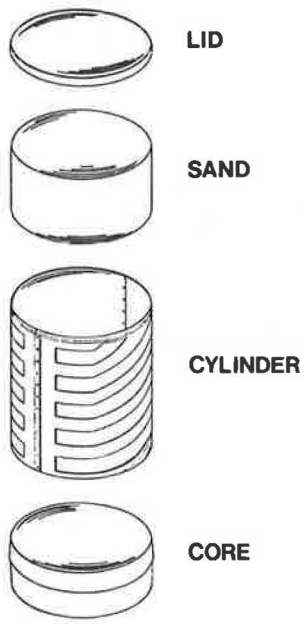


**FIGURE 4 Fitch inertial barrier system.**

### Comparison of Test Results

Head-to-head comparisons of all test results were performed to explore the effects of the following:

- vehicle weight,
- sand barrel attenuator type,
- attenuator configuration,
- frozen versus nonfrozen test conditions,
- sand versus pea gravel fill material,
- nonbagged versus bagged sand fill material, and
- passenger versus driver response.

Table 4 lists observations from these comparisons. Pass/fail criteria used in this paper are based on the NCHRP 230 design values of 30 feet per second for delta-V and 15 g for ridedown acceleration.

Design values were selected to better discriminate among configurations. The limit values recommended by NCHRP 230 are 40 feet per second for delta-V and 20 g for ridedown acceleration. It should be noted that the limit values were exceeded in only four tests.

## CONCLUSIONS

The following sections provide the key conclusions of this impact attenuator testing project.

### Barrel Attenuators (Nonfrozen Sand)

The systems tested worked as designed, showing good correlation with design predictions based on momentum transfer. The 15-barrel system selected appears to provide a safe design for stopping vehicles weighing 1,800 to 4,500 pounds (818 kg to 2,045 kg) at distances of 25 feet (7.6 m) or less.

### Barrel Attenuators (Frozen Sand)

This series of tests demonstrated that sand in barrels can freeze and produce large (400 lb, 182 kg) blocks that remain intact during an impact. These blocks were thrown up to 60 feet during the impact and could lead to additional accidents involving oncoming traffic. Complete freezing of the 15-barrel system was found to require low temperature for a period of several days. The frozen configuration showed reduced performance and safety when compared to nonfrozen tests. Reduced performance and safety resulted because freezing caused the last several rows of barrels to be pushed into the gore wall. These barrels then get squeezed between the impacting vehicle and gore wall. Instead of disintegrating, the barrels rupture. This effectively moves the

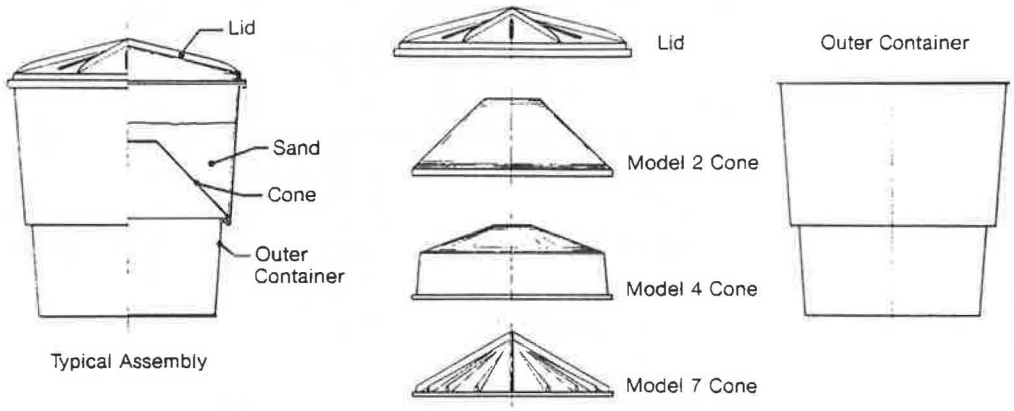


**FIGURE 5 Energite barrel system.**

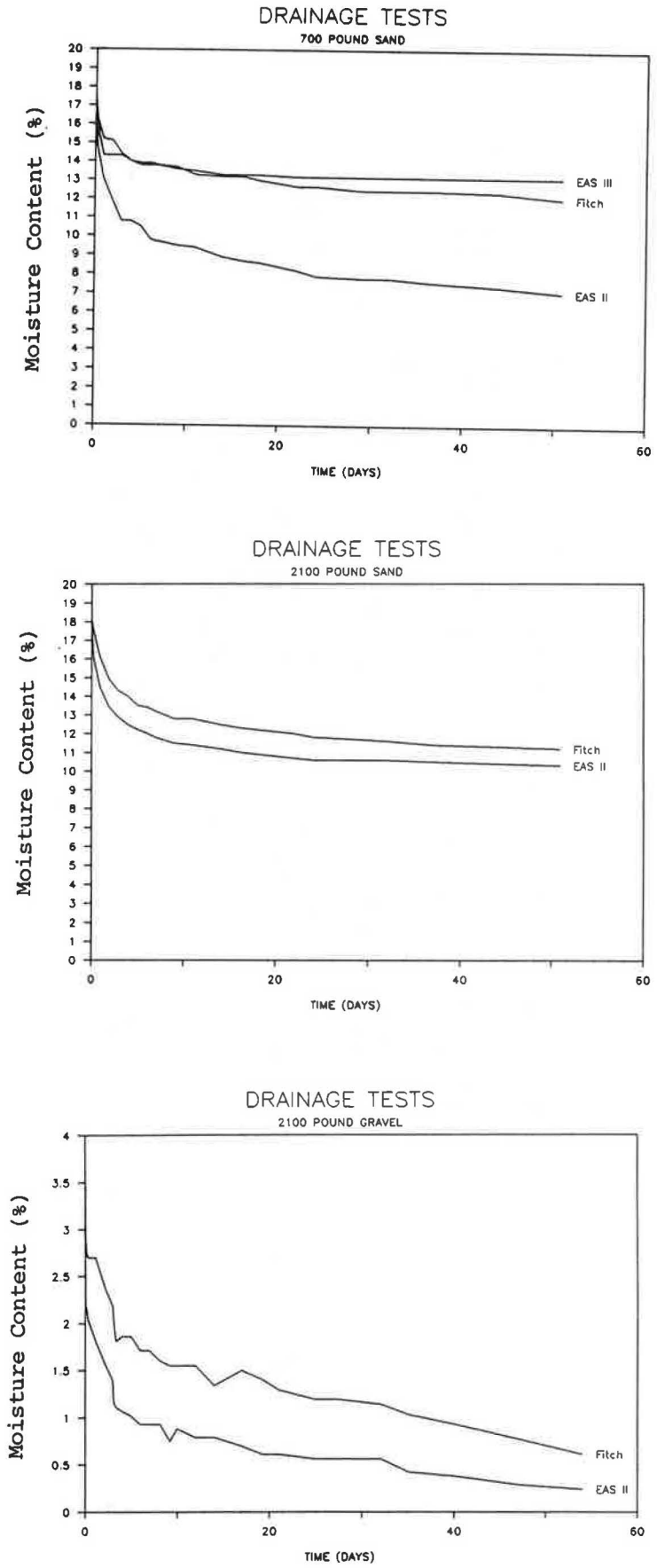


**FIGURE 6 Moisture content measurement.**

TABLE 3 TEST RESULTS

| TEST NUMBER | C-01 | C-02 | C-03 | C-04 | B-08 | B-09 | B-10 | B-11 | B-13 | B-14 |
|---|---|---|---|---|---|---|---|---|---|---|
| DATE | 5/24/84 | 6/13/84 | 6/27/84 | 7/23/85 | 4/10/85 | 5/21/85 | 2/18/85 | 6/18/85 | 7/12/85 | 11/19/85 |
| MANUFACTURER | EAS | EAS | EAS | EAS | EAS | EAS | RSS | RSS | RSS | RSS |
| ATTENUATOR | GREAT | GREAT | GREAT | GREAT | EA III | EA III | FITCH | FITCH | FITCH | FITCH |
| FILL MATERIAL | HEXFOAM | HEXFOAM | HEXFOAM | HEXFOAM | FROZEN SAND | FROZEN SAND | FROZEN SAND | FROZEN SAND | FROZEN SAND | FROZEN SAND |
| VEHICLE WEIGHT (lbs) | 1794 | 1812 | 1795 | 4346 | 1798 | 4323 | 1792 | 4336 | 1795 | 1806 |
| IMPACT ANGLE (deg) | 0 | 15 | 20 | 0 | 0 | 0 | 7.5 | 0 | 0 | 0 |
| IMPACT SPEED (mi/h) | 59.9 | 59.5 | 59.7 | 58.4 | 60.4 | 60.9 | 59.4 | 58.8 | 54.6 | 60.8 |
| IMPACT LOCATION | CENTER | NOSE RIGHT CORNER | MIDSPAN | CENTER | CENTER | CENTER | 2.5FT RIGHT CENTER | CENTER | CENTER | CENTER |
| NUMBER OF DUMMIES | 1 | 1 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 1 |
| DUMMY WEIGHT (lbs) | 155 | 160 | 155 | 374 | 146 | 326 | 158 | 334 | 154 | 167 |
| TOTAL WEIGHT (lbs) | 1949 | 1972 | 1950 | 4720 | 1944 | 4649 | 1950 | 4670 | 1949 | 1973 |
| TOTAL KINETIC ENERGY (kip-ft) | 234 | 233 | 232 | 538 | 237 | 576 | 230 | 539 | 194 | 244 |
| ATTEN CRUSH ENERGY (kip-ft) | 195.9 | 199.7 | --- | 465.9 | 223.1 | 494.1 | --- | 517.4 | 180.7 | 228.8 |
| VEHICLE CRUSH ENERGY (kip-ft) | 20.1 | 16.4 | --- | 61.7 | 9.9 | 71.5 | --- | 45.1 | 5.8 | 4.6 |
| REBOUND DISTANCE (ft) | 40.8 | 37.5 | --- | 11.7 | 0.5 | 0.3 | --- | 0.5 | 0.8 | 0.8 |
| TOTAL SPEED CHANGE (ft/s) | 98.0 | 96.7 | 16.1 | 105.2 | 91.4 | 89.8 | 101.0 | 92.1 | 78.2 | 95.1 |
| STOPPING DISTANCE (ft) | 14.7 | 11.8 | --- | 18.4 | 17.2 | 22.5 | 25.0 | 22.3 | 16.2 | 16.2 |
| AVG ACCEL OVER STOP (g's) | -8.2 | -10.0 | --- | -6.2 | -7.1 | -5.5 | -4.7 | -5.2 | -6.1 | -7.6 |
| 50 MSEC PEAK (g's) | -12.3 | -13.0 | --- | -24.1 | -16.0 | -14.8 | -11.7 | -12.1 | -9.7 | -14.0 |
| DELTA V @2 FT FLAIL (ft/s) | 34.7 | 38.5 | 19.7 | 27.0 | 28.3 | 27.7 | 25.8 | 31.1 | 27.9 | 34.8 |
| TIME (msec) | 166 | 119 | 183 | 155 | 130 | 160 | 143 | 162 | 145 | 125 |
| ACTUAL FLAIL SPACE (ft) | 1.35 | 1.92 | 2.05 | 2.08 | 1.75 | 1.75 | 2.0 | 1.83 | 1.58 | 1.67 |
| DELTA V @ ACTUAL FLAIL (ft/s) | 31.2 | 37.9 | 19.8 | 27.3 | 26.1 | 25.6 | 25.8 | 29.7 | 23.6 | 30.3 |
| RIDEDOWN ACCEL (g's) | -12.7 | -11.0 | -0.8 | -42.3 | -22.3 | -25.9 | -16.7 | -16.3 | -12.1 | -18.7 |
| CLASS 60 DATA | | | | | | | | | | |
| LONGITUDINAL (g's) | -18.3 | -17.5 | -9.5 | -51.2 | -24.0 | -25.2 | -17.4 | -19.6 | -15.8 | -19.5 |
| TIME (msec) | 62 | 70 | 144 | 319 | 180 | 183 | 269 | 124 | 18 | 220 |
| LATERAL (g's) | -4.4 | -7.0 | -17.1 | 17.7 | -7.4 | 4.3 | -9.3 | -21.3 | -7.2 | -8.9 |
| TIME (msec) | 79 | 70 | 74 | 321 | 169 | 215 | 28 | 242 | 109 | 100 |
| VERTICAL (g's) | -14.6 | -4.6 | -9.4 | -25.8 | -17.2 | 11.1 | -14.7 | 18.5 | 20.6 | -20.6 |
| TIME (msec) | 70 | 23 | 149 | 311 | 19 | 210 | 247 | 126 | 105 | 85 |
| ROLL RATE (deg/s) | --- | -142.5 | -132.0 | -496.6 | 206.9 | 122.3 | 261.4 | -283.8 | 236.0 | -334.3 |
| TIME (msec) | --- | 145 | 187 | 65 | 87 | 173 | 149 | 143 | 118 | 120 |
| YAW RATE (deg/s) | --- | -82.8 | -301.0 | -255.0 | 88.4 | 59.8 | --- | 258.5 | 179.4 | -204.5 |
| TIME (msec) | --- | 182 | 148 | 323 | 228 | 168 | --- | 242 | 113 | 96 |
| CLASS 180 DATA | | | | | | | | | | |
| LONGITUDINAL (g's) | -21.6 | -22.5 | -12.0 | -84.7 | -25.9 | -27.3 | -17.9 | -25.8 | -23.0 | -22.7 |
| TIME (msec) | 53 | 70 | 135 | 321 | 180 | 181 | 269 | 125 | 18 | 17 |
| LATERAL (g's) | -10.3 | -10.0 | -25.5 | 25.8 | -14.0 | -9.5 | -15.8 | -40.9 | -11.0 | 15.7 |
| TIME (msec) | 35 | 68 | 74 | 321 | 25 | 171 | 26 | 242 | 109 | 56 |
| VERTICAL (g's) | -20.1 | -10.5 | -12.4 | -29.5 | -26.6 | 17.2 | -17.7 | -28.3 | -24.6 | -29.2 |
| TIME (msec) | 28 | 84 | 157 | 313 | 21 | 184 | 246 | 241 | 15 | 85 |
| DRIVER R or U? | U | U | U | U | U | U | U | U | U | U |
| HIC | 404 | 482 | 500 | 293 | 225 | 89 | 110 | 214 | 129 | 240 |
| CSI | 277 | 224 | 164 | 286 | 300 | 83 | 81 | 164 | 82 | 297 |
| MAX CHEST (g's) | 43.9 | 41.9 | 53.2 | 35.7 | 39.0 | 20.7 | 18.7 | 24.3 | 22.8 | 37.1 |
| RIGHT FEMUR (lbs) | 987 | 712 | 534 | 795 | 1365 | 141 | 1040 | 863 | 832 | 2650 |
| LEFT FEMUR (lbs) | --- | --- | --- | 957 | 692 | 199 | 1635 | 537 | 524 | 404 |
| PASSENGER R or U? | | | | R | | R | | R | | |
| HIC | | | | 260 | | --- | | 95 | | |
| CSI | | | | 174 | | --- | | 88 | | |
| MAX CHEST (g's) | | | | 30.0 | | --- | | 18.4 | | |
| RIGHT FEMUR (lbs) | | | | 280 | | --- | | 889 | | |
| LEFT FEMUR (lbs) | | | | 100 | | --- | | 317 | | |

TABLE 3 *continued*

| TEST NUMBER | B-01 | B-02 | B-03 | B-04 | B-05 | B-06 | B-07 | B-12 | E-01 | E-02 |
|---|---|---|---|---|---|---|---|---|---|---|
| DATE | 9/21/84 | 10/9/84 | 10/15/84 | 1/10/85 | 11/29/84 | 11/8/84 | 4/16/85 | 5/9/85 | 5/23/86 | 5/5/86 |
| MANUFACTURER | EAS | EAS | EAS | EAS | RSS | RSS | RSS | RSS | EAS | EAS |
| ATTENUATOR | EA III | EA III | EA III | EA III | FITCH | FITCH | FITCH | FITCH | EA III | EA III |
| FILL MATERIAL | PEA GRAVEL | SAND | SAND | SAND | SAND | SAND | SAND | SAND | BAGGED SAND | BAGGED SAND |
| VEHICLE WEIGHT (lbs) | 4312 | 1807 | 4306 | 1806 | 1823 | 1797 | 4317 | 1806 | 4302 | 1799 |
| IMPACT ANGLE (deg) | 0 | 0 | 0 | 15 | 15 | 0 | 0 | 0 | 0 | 0 |
| IMPACT SPEED (mi/h) | 58.8 | 58.0 | 58.6 | 59.4 | 60.0 | 58.4 | 60.6 | 60.1 | 57.7 | 61.1 |
| IMPACT LOCATION | CENTER | CENTER | CENTER | CORNER OF GORE | CORNER OF GORE | 5.7FT RIGHT CENTER | CENTER | CENTER | CENTER | CENTER |
| NUMBER OF DUMMIES | 2 | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 2 | 1 |
| DUMMY WEIGHT (lbs) | 309 | 168 | 326 | 150 | 154 | 166 | 352 | 164 | 322 | 169 |
| TOTAL WEIGHT (lbs) | 4621 | 1975 | 4632 | 1956 | 1977 | 1963 | 4669 | 1970 | 4624 | 1968 |
| TOTAL KINETIC ENERGY (kip-ft) | 534 | 222 | 531 | 231 | 238 | 224 | 573 | 238 | 514 | 245 |
| ATTEN CRUSH ENERGY (kip-ft) | 508.7 | 217.4 | 530.0 | --- | --- | --- | 525.6 | 221.7 | 475.0 | 225.8 |
| VEHICLE CRUSH ENERGY (kip-ft) | 11.3 | 5.6 | 12.0 | --- | --- | --- | 34.5 | 5.9 | 21.1 | 9.1 |
| REBOUND DISTANCE (ft) | 2.0 | 0.5 | 1.0 | 14.0 | 14.0 | --- | 1.0 | 1.1 | 2.4 | 0.2 |
| TOTAL SPEED CHANGE (ft/s) | 89.6 | 84.8 | 91.9 | 85.9 | 87.5 | 44.0 | 96.0 | 91.3 | 89.8 | 87.0 |
| STOPPING DISTANCE (ft) | 23.5 | 22.0 | 24.5 | 11.4 | 11.4 | 72.0 | 24.0 | 19.3 | 22.9 | 19.0 |
| AVG ACCEL OVER STOP (g's) | -4.9 | -5.1 | -4.7 | -10.3 | -10.5 | -1.6 | -5.1 | -6.3 | -4.9 | -6.6 |
| 50 MSEC PEAK (g's) | -11.2 | -10.1 | -11.2 | -15.3 | -14.3 | -9.3 | -9.8 | -9.3 | -10.9 | -15.7 |
| DELTA V @2 FT FLAIL (ft/s) | 24.5 | 26.8 | 26.3 | 38.0 | 37.4 | 29.2 | 26.6 | 29.3 | 27.9 | 29.7 |
| TIME (msec) | 183 | 139 | 171 | 104 | 111 | 130 | 170 | 132 | 178 | 144 |
| ACTUAL FLAIL SPACE (ft) | 1.71 | 1.5 | 1.33 | 1.63 | 1.92 | 1.5 | 1.58 | 1.94 | 1.58 | 1.71 |
| DELTA V @ ACTUAL FLAIL (ft/s) | 22.1 | 24.6 | 24.5 | 37.2 | 36.0 | 25.8 | 24.2 | 29.0 | 22.4 | 26.4 |
| RIDEDOWN ACCEL (g's) | -15.4 | -18.4 | -13.7 | -19.2 | -18.5 | -15.4 | -10.7 | -10.2 | -14.9 | -22.3 |
| CLASS 60 DATA | | | | | | | | | | |
| LONGITUDINAL (g's) | -17.1 | -21.4 | -16.4 | -19.9 | -19.3 | -20.8 | -11.2 | -18.5 | -18.3 | -24.7 |
| TIME (msec) | 243 | 173 | 242 | 127 | 112 | 139 | 214 | 28 | 263 | 157 |
| LATERAL (g's) | -4.9 | -2.6 | -5.2 | -10.0 | -7.6 | -8.6 | 3.8 | 4.3 | -5.2 | -5.2 |
| TIME (msec) | 212 | 183 | 226 | 28 | 27 | 31 | 151 | 3 | 265 | 165 |
| VERTICAL (g's) | 18.7 | -13.0 | 11.7 | -12.6 | -10.1 | 9.2 | 6.1 | -12.0 | 17.7 | -12.5 |
| TIME (msec) | 256 | 37 | 244 | 49 | 27 | 89 | 219 | 23 | 279 | 24 |
| ROLL RATE (deg/s) | 118.4 | 68.9 | -115.5 | -143.0 | 154.7 | --- | 77.2 | -126.2 | -260.0 | 110.2 |
| TIME (msec) | 252 | 141 | 362 | 130 | 94 | --- | 138 | 80 | 265 | 190 |
| YAW RATE (deg/s) | 58.6 | -28.6 | 44.3 | --- | 282.5 | --- | 41.8 | 50.8 | -121.6 | -73.9 |
| TIME (msec) | 259 | 265 | 128 | --- | 334 | --- | 134 | 61 | 263 | 185 |
| CLASS 180 DATA | | | | | | | | | | |
| LONGITUDINAL (g's) | -26.0 | -25.3 | -17.8 | -21.0 | -21.4 | -28.2 | -12.4 | -25.2 | -27 | -26.6 |
| TIME (msec) | 255 | 173 | 242 | 70 | 112 | 139 | 201 | 18 | 263 | 157 |
| LATERAL (g's) | -12.1 | -5.9 | -9.4 | -13.9 | -12.4 | -11.0 | 8.6 | 11.5 | -16.9 | -7.7 |
| TIME (msec) | 254 | 173 | 109 | 29 | 20 | 173 | 151 | 3 | 265 | 165 |
| VERTICAL (g's) | 27.7 | -16.2 | 14.6 | -17.9 | -12.9 | 13.7 | -7.4 | 22.8 | -30.8 | -18.5 |
| TIME (msec) | 255 | 37 | 251 | 49 | 29 | 140 | 206 | 28 | 260 | 24 |
| DRIVER R or U? | U | U | U | U | U | U | U | U | U | U |
| HIC | 265 | 117 | 159 | 517 | 457 | 679 | 144 | 389 | 78 | 758 |
| CSI | 329 | --- | 190 | 391 | 392 | 137 | 156 | 153 | 98 | 226 |
| MAX CHEST (g's) | 81.9 | --- | 28.0 | 44.2 | 39.8 | 40.8 | 26.9 | 31.9 | 24.9 | 42.0 |
| RIGHT FEMUR (lbs) | 620 | 1200 | 959 | 1969 | 874 | 930 | --- | 1813 | 650 | 841 |
| LEFT FEMUR (lbs) | 625 | 406 | 551 | --- | 1173 | 800 | 343 | 351 | 540 | 500 |
| PASSENGER R or U? | U | | U | | | | U | | U | |
| HIC | 314 | | 424 | | | | 274 | | 299 | |
| CSI | 218 | | 154 | | | | 153 | | 156 | |
| MAX CHEST (g's) | 47.7 | | 28.0 | | | | 32.0 | | 27.4 | |
| RIGHT FEMUR (lbs) | 738 | | 904 | | | | 1101 | | 720 | |
| LEFT FEMUR (lbs) | 525 | | 544 | | | | 449 | | 500 | |

TABLE 4 TEST RESULTS COMPARISONS

| Comparisons | Conditions | Results/Observations |
|---|---|---|
| Pea Gravel vs. Sand Fill | Energite/4500S/0° | No differences were observed using vehicle data. Some differences were observed in the dummy parameters. |
| Fitch vs. Energite | 4500S/0° | Similar results |
| Fitch vs. Energite | 1800S/15° | Similar results |
| Fitch vs. Energite | 1800S/0° | Delta-V higher for Fitch, ridedown higher for Energite. Results were similar for dummy parameters. Energite failed ridedown. |
| Frozen vs. Non-Frozen | Energite/1800S/0° | Frozen test more severe. Both tests failed ridedown criteria. |
| Frozen vs. Non-Frozen | Fitch/1800S/0° | Frozen test more severe. Frozen test failed delta-V and ridedown. |
| GREAT vs. Sand | 1800S/0°/Energite | GREAT test more severe for vehicle parameters. Dummy parameters show no significant difference. Stopping distance shows GREAT has a higher efficiency. GREAT failed delta-V and Energite III failed ridedown. |
| Head-on vs. 15° | GREAT/1800S | Similar results. Both tests failed delta-V. |
| Head-on vs. 20° (Redirectional) | GREAT/1800S | High maximum chest values for both; otherwise results were similar. Head-on failed delta-V. |

TABLE 4 *continued*

| Comparisons | Conditions | Results/Observations |
|---|---|---|
| 4500S vs. 1800S | GREAT/0° | Delta-V larger for small car, higher decelerations for 4500S, maximum chest for small car higher. Small car failed delta-V and large car failed ridedown. |
| 4500S vs. 1800S | Energite/0° | Similar results. Small car failed ridedown |
| 4500S vs. 1800S | Fitch/0° | Similar results. |
| Head-on vs. 15° | Energite/1800S | 15° test more severe. 15° test failed delta-V in addition to ridedown. |
| Head-on vs. 15° | Fitch/1800S | 15° test more severe. 15° test failed delta-V in addition to ridedown. |
| 4500S vs. 1800S | Frozen Fitch/0° | Similar results, both tests failed delta-V and ridedown. |
| 4500S vs. 1800S | Frozen Energite/0° | Similar results, both tests failed ridedown. |
| Fitch vs. Energite | Frozen/4500S/0° | Similar results, both tests failed ridedown. |
| Fitch vs. Energite | Frozen/1800S/0° | Similar results, Energite III failed ridedown. |
| Frozen vs. Non-Frozen | Energite/4500S/0° | Vehicle parameters show frozen test more severe. Dummy parameters show non-frozen test more severe. Frozen test failed ridedown. |
| Frozen vs. Non-Frozen | Fitch/4500S/0° | Vehicle parameters show frozen test more severe. Results were similar for dummy parameters. Frozen test failed ridedown and delta-V |

TABLE 4 *continued*

| Comparisons | Conditions | Results/Observations |
|---|---|---|
| Bagged vs. Non-Bagged | Energite/1800S/0° | Bagged sand test more severe both tests failed ridedown. Occupant compartment intrusion occurred with Bagged Sand. |
| Bagged vs. Non Bagged | Energite/4500S/0° | Similar results. |

hard point closer to the vehicle and reduces the effective stroke of the system.

### Barrel Attenuators (Bagged Sand)

These two tests demonstrated that barrel attenuators filled with bagged sand increase occupant risk as measured by occupant compartment intrusion. During the small vehicle test, the hood, windshield, and numerous bags of sand penetrated the occupant compartment. Also, bagged sand debris resulted in potential for subsequent accidents of oncoming vehicles.

### Barrel Attenuators (Pea Gravel)

This test was within specified values for dummy-based and vehicle-borne injury descriptors. However, the pea gravel provided potential for subsequent accidents because of the "ballbearing-like" gravel on the roadway.

### Great System

The six-bay GREAT configuration showed good performance for an 1,800-pound (818 kg) vehicle for both redirectional and arresting tests. For the 4,500-pound (2,045 kg) head-on test, the system did not have sufficient stroke. The system completely collapsed while the car was still traveling at 20 miles per hour (8.9 m/s). This resulted in a large deceleration level at the end of the impact. Thus, with a 4,500-pound (2,045 kg) vehicle impacting a six-bay GREAT at 60 miles per hour (26.8 m/s), occupant risk is considered very high. However, the system did perform well up to the point of total collapse, indicating that additional stroke (more bays) could have produced acceptable results. It should be noted that since the completion of this test program, Energy Absorption Systems, Inc., has redesigned the GREAT system with new Hexfoam II cartridges that allow the system to pass the limit criteria given in NCHRP 230.

### Drainage Tests

Tests were conducted to observe the drainage characteristic of various sand barrel configurations. These tests indicated that drainage continues for a long period of time. Over a 60-day period, the average moisture content of the barrels decreased from 18 percent to levels of 7 to 12 percent. These levels of moisture content can lead to frozen sand in large blocks. Based on observations from series III tests, considerable force is required to break up these blocks. It was also found that the Energite II barrels drained much better than the Energite III or Fitch barrels.

### Safety Evaluation

The 20 impact attenuator tests of this contract provide an excellent opportunity to compare dummy-based and vehicle-borne occupant injury descriptors. In all cases except one, the dummy data were within prescribed limits. This was not true of the vehicle-borne descriptors. Thirteen of the 20 tests conducted provided results that exceeded NCHRP 230 design criteria, while only 4 of the 20 test results exceeded the NCHRP 230 limit criteria. Based on the results of this program, it appears that the design criteria may be too conservative and that a point closer to the limit values should be considered the pass/test criteria, rather than the design values.

Dummy data indicated that most injuries occur when the occupant first impacts the interior of the vehicle. This typically occurs 100 to 130 milliseconds after impact. The major exception to this is for femur loads which sometimes show peak values shortly after the initial impact.

### Model Program for Force-Displacement

Standard design equations (momentum transfer techniques) provide good estimates of delta-V and the 50 ms acceleration but not good predictive methodology for the 10 ms acceleration (ridedown) data. For the tests conducted, the 10 ms acceleration can be calculated with good accuracy from the 50 ms acceleration using the following equation:

$$\text{Acel}_{10\ \text{ms}} = 1.89\ \text{accel}_{50\ \text{ms}} - 6.62$$

Force-displacement characteristics were made for all frontal head-on impacts. From these data traces, many comparisons were made. Of special interest were comparisons of the two brands of sand barrels under similar conditions (1800S, 60 mi/h, head-on), which show no difference; frozen vs. nonfrozen for similar conditions, where differences were observed; and bagged sand versus loose sand under similar conditions (1800S, 60 mi/h, head-on), where differences were observed. These comparisons are shown in Figure 7.

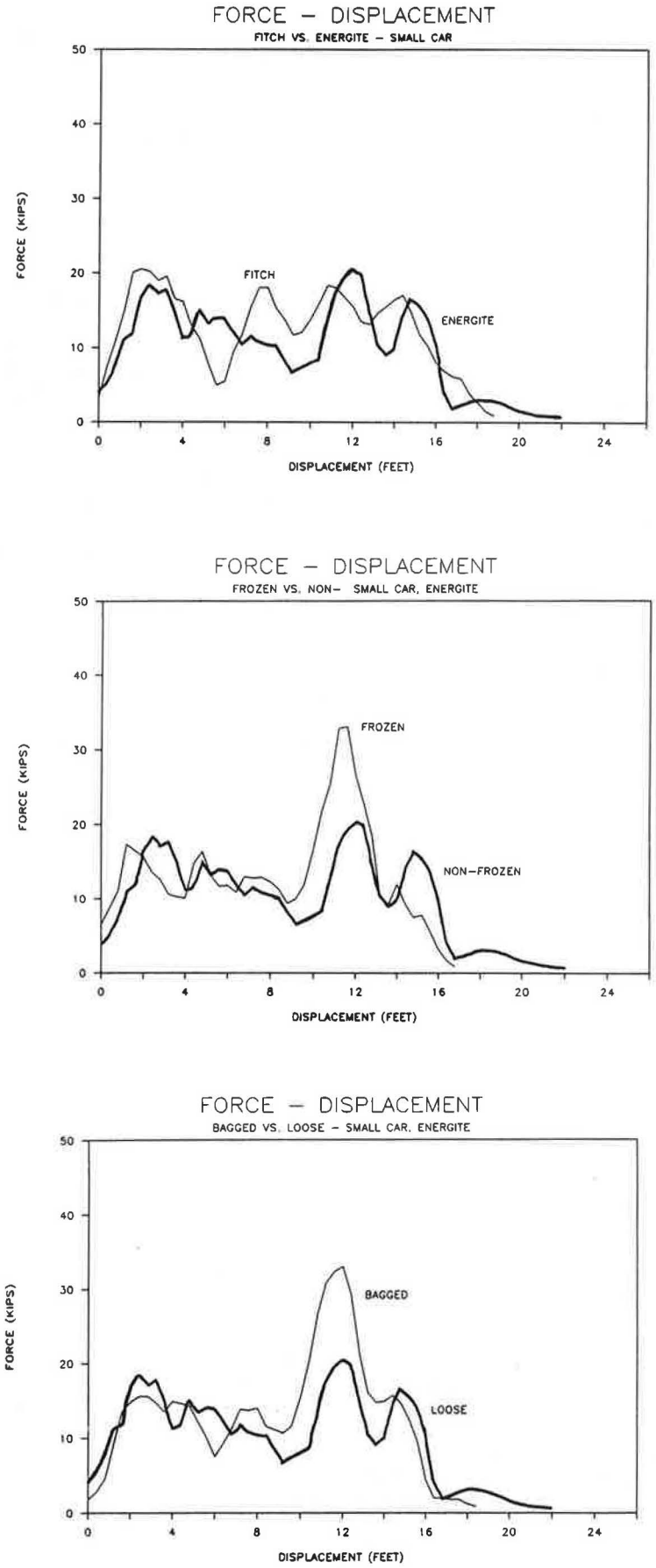


**FIGURE 7 Force-displacement comparisons.**

### Test Data Correlations

A set of relationships between various parameters of the test data was developed. These were developed using a "least square" approach between the sets of data.

These analyses showed very good correlations ($r$ greater than 0.8) between:

1. 50 ms and 10 ms (ridedown) accelerations, and
2. Delta-V based on 2-foot flail and delta-V based on actual flail.

Lower correlations were found between:

3. HIC and Delta-V based on 2-foot flail,
4. CSI and Delta-V based on 2-foot flail,
5. Maximum chest acceleration and delta-V based on 2-foot flail.

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## DISCUSSION

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The engineering evaluation of impact attenuators, as reported in this paper, was sponsored by the Federal Highway Administration and conducted by ENSCO, Inc. It was a well planned and comprehensive program. The authors of this paper are eminently qualified researchers in vehicle crash testing and performance evaluation of highway safety appurtenances. The quality of the conducted research and of this paper attests to their prominence in the field.

However, in their comments under Results/Observations in Table 4, the authors' use of "failed" conveys to the reader an impression that the three tested systems are unsafe and unacceptable for installation on highways. This is not the case. For approximately two decades, thousands of installations of

| Impact Direction[aa] and Appurtenance Type | Occupant/Compartment Impact Velocity[b]—(fps) | | | Occupant Ridedown Acceleration—(g's) | | |
|---|---|---|---|---|---|---|
| | Flail Space Recommendation | | TRC 191 | Flail Space Recommendation | | TRC 191[e] |
| | $(\Delta V)_{Limit}/F^{(c)}$ | $(\Delta V)_{Design}$ | | $(a)_{Limit}/F^{(c)}$ | $(a)_{Design}$ | |
| **Longitudinal (X) Direction** | | | | | | |
| Breakaway/Yielding Supports | | | | | | |
| • Signs and luminaire | 40/2.67 | 15 | 11-16[f] | 20/1.33 | 15 | |
| • Timber Utility Poles | 40/1.33 | 30 | — | 20/1.33 | 15 | |
| Vehicle Deceleration Devices | | | | | | |
| • Crash cushions and barrier terminals | 40/1.33 | 30 | 32-39[d] | 20/1.33 | 15 | |
| Redirectional Barriers | | | | | | |
| • Longitudinal, transitions and crash cushion side impacts | 40/1.33 | 30 | 25-36[d] | 20/1.33 | 15 | |
| **Lateral (Y) Direction** | | | | | | |
| Redirectional Barriers | | | | | | |
| • Longitudinal, transitions and crash cushion side impacts | 30/1.50 | 20 | 14-18[d] | 20/1.33 | 15 | |

Notes:

(aa) With respect to vehicle axis.
(b) Occupant to windshield, dash or door impact velocity with occupant propelled by vehicle deceleration pulse through 2-ft forward or 1 ft lateral flail space; multiply fps by 0.305 to convert to m/s.
(c) F is acceptance factor to be established by highway agency.
(d) Values calculated from TRC 191 criteria assuming that the highest 50-ms acceleration limits of TRC 191 are constant for the duration of the event and shown here for reference.
(e) Flail space accelerations are highest 10 ms averages beginning with occupant impact to completion of pulse; TRC 191 accelerations are less severe, highest 50 ms averages or those averaged over vehicle stopping distance. These values are not comparable.
(f) From TRC 191.

FIGURE 8 Recommended occupant risk values (*1*, Table 8).

these impact attenuators, approved by the Federal Highway Administration, the states, or local transportation agencies, have been most effective in saving lives and preventing serious injuries. These life-saving systems are in widespread use throughout this country and in some foreign countries.

In almost every case in the Results/Observations comments, the authors use "failed" to report a "derived" value for occupant impact velocity or ridedown acceleration when the value fell between the recommended design value and the limit value defined in NCHRP Report 230. While the lower design value is a more commendable value, highway safety appurtenances are nevertheless approved for federal aid and state construction projects when values obtained from full-scale crash tests do not exceed the limit value specified in NCHRP Report 230.

In light of the state of the art and current approval practices for highway safety appurtenances, it would have been more accurate and meaningful for the authors to have indicated where the derived occupant risk values fell with respect to the recommended design value and the limit value. The authors are to be commended for having done such an identification in their comprehensive publication, *Impact Attenuators—A Current Engineering Evaluation* (Report FHWA/RD-86-054, August 1986).

In light of the long-term experienced effectiveness of the FITCH, ENERGITE, and GREAT attenuator systems, the information in this paper is misleading.

To enhance the value of the paper to the reader, Table 8 (Recommended Occupant Risk Values) from NCHRP Report 230 (Figure 8) (*1*) is included in this discussion. This table should promote a better appreciation for the authors' work, not only for this paper but also for their final research report.

## REFERENCE

1. *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, TRB, National Research Council, Washington, D.C., 1981.