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ABSTRACT

Current windshield manufacturing processes produce residual tensile stresses near the edges of windshields. This residual tensile stress reduces the ability of the windshield to withstand suddenly applied external loading over a short time interval near the edge. Present manufacturing processes can reduce some of the residual tensile stress produced during the annealing process, but currently it is technically difficult to eliminate. However, an innovative and more cost-effective solution for the residual tensile stress problem has been proposed. Application of a thin film of polycarbonate around the perimeter of the windshield allows the energy generated during impact loading to be dissipated without the need to change the windshield's material properties. This paper presents the Knott Laboratory findings and conclusions generated from impact testing six different windshields, at nine perimeter impact locations protected by the polycarbonate film and nine unprotected perimeter control impact locations per windshield.

INTRODUCTION

Previous studies have shown that the stress-state at a point in the windshield is dependent on the residual stress as a result of the manufacturing and installation induced stresses. Edgeguard International™ has proposed a solution to the residual tensile stress problem by utilizing a thin layer of polycarbonate around the perimeter of the windshield, in order to reduce the number of edge fractures. To research the effectiveness of the polycarbonate, Knott Laboratory conducted a series of different impact tests. The purpose of this testing was to establish whether or not the film of polycarbonate was effective in the dissipation of kinetic energy, which would reduce the number of windshield fractures.

RESEARCH

Knott Laboratory engineers studied and tested a variety of methods to evaluate the speed, mass and energy of impact projectiles required to fracture windshields. These methods were qualitatively analyzed for their similarities to roadway debris impacts. Methods studies included the use of a pendulum, slingshot and spheres (bbs) fired by a pneumatic rifle.

PENDULUM METHOD

One of the testing strategies analyzed by Knott Laboratory engineers included the use of a pendulum. A test apparatus was constructed such that a vehicle could drive directly up to the pendulum and the entire apparatus could be adjusted in the x, y and z-axis to facilitate impacting different locations on the windshield.

A one-pound ball bearing was attached to a thin steel cable and the cable was mounted to a rolling element radial ball bearing to provide free rotation of the pendulum. The radial ball bearing was mounted on a linear ball bearing to provide axial translation along a steel shaft rigidly mounted in the test apparatus. The test apparatus allowed vertical and longitudinal adjustments to allow for the height and slope of the windshield while the linear bearing allowed lateral adjustment for the impact location.

The ball bearing was restricted to swing in a single plane and an accelerometer was attached to record the deceleration of the ball bearing normal to the windshield at impact. Based on a time history of the deceleration of the ball bearing and knowing the mass of the pendulum, the impact force or impulse could be calculated. The speed of the ball bearing at impact could also be found from the relationship between the potential energy of the ball bearing at its initial height and final kinetic energy.

Another pendulum method evaluated involved attaching a point-loading object to a rigid arm that swung from the steel shaft. In this testing, the accelerometer was attached to the opposite end of the point-loading object normal to the impact location and the point-loading object was restricted to swing in one plane.

Although the pendulum method was advantageous in terms of data acquisition opportunities and simple assessment of the impact speed of the impact object the method was not successful in producing damage consistent with roadway debris impacts. Observation of the ball bearing impacts revealed that the windshield could deform around the ball bearing and distribute the load to a greater surface area. Qualitative evaluation of typical windshield damage shows that the majority of damage originates from a single point load rather than a distributed force.

The point loading object was successful in creating a precise point load, but observation of the damage induced in testing indicated that the maximum pendulum length was not capable of producing a velocity sufficient to produce damage consistent with roadway debris. One possible explanation for the inability of the pendulum to produce consistent damage is that glass is an amorphous material and fractures when it is subjected to sudden changes is strain, or high strain rates. Therefore, production of impact damage consistent with roadway debris must be produced with high speed, low mass impact projectiles instead of low speed, high mass projectiles. Further testing methods evaluated concentrated of producing higher velocity projectiles with lower mass.

SLINGSHOT METHOD

The next testing strategy examined the use of a slingshot equipped with standardized sling shot (similar to 10 mm steel ball bearings) ammunition and pea size gravel. While testing with the standardized ammunition produced consistent fractures, the fracture pattern was not consistent with the majority of roadway debris impacts. Observation of roadway debris impacts shows that the majority of damaged windshields have a small, centralized impact location with cracks radiating from this location. The fractures typically produced by the slingshot were composed of a halo fracture pattern 1 - 2 cm from the impact location, as a result of a stress or strain wave propagating through the glass. In more severe impacts the halo pattern would be produced and the glass directly under the impact location would be crushed. Testing performed with gravel ammunition produced fractures similar to the steel ammunition.

One difficulty encountered during testing with the slingshot was controlling the impact velocity. The slingshot selected was a wrist-mounted model that imparted energy to the impact projectile by stretching and releasing an elastic band. Changing the amount the elastic band was stretched could control the velocity, but accurately controlling the amount of stretch proved difficult. Another difficulty encountered was accurately controlling the impact location. The physical design of the slingshot required that the elastic was stretched approximately ¾ of a meter to produce sufficient velocity to fracture the windshield. After stretching the elastic to this length the slingshot became difficult to aim accurately.

Due to the difference between damage observed from roadway debris impacts damage induced by the slingshot, and inconsistent impact locations that resulted from the use of the slingshot, Knott Laboratory engineers did not utilize this mode of testing and further research for a testing method was conducted.

PNEUMATIC RIFLE METHOD

Knott Laboratory engineers analyzed the use of a pneumatic rifle in the attempt to control the velocity of impact projectiles and produce damage consistent with roadway debris. Some models of pneumatic rifles are configured such that the number of pumps influences the velocity of the projectiles fired. The smaller the number of pumps, the lower the velocity of the projectile. For the testing described in this paper a Daisy Powerline 1880 model pneumatic rifle was selected. The maximum velocity the pneumatic rifle was capable of producing was approximately 208.8 meters per second (685 feet per second) after ten pumps of the pneumatic piston.

The pneumatic rifle was tested to correlate the number of pumps with the velocity of the projectile. Results from this study indicated that the magnitude of the initial velocity from one pump (approximately 80 m/s) was too great and the incremental increase in velocity from each additional pump was too large to accurately evaluate the point, or critical velocity, at which impending fracture occurred in the windshield. The pneumatic rifle required modification in order to decrease the initial speed from one pump and to decrease the change in velocity produced by additional pumps. Spacers of approximately 3, 6, 9, 16, and 19 mm were placed in the air compression chamber to modify the volume of air compressed with each pump. Larger spacers decreased the volume of air compressed and also decreased the stroke of the piston in the compression chamber. This modification enabled fine control of the velocity produced by the rifle and enables the determination of the critical velocity point at which the windshield would fracture.

To begin the rifle testing, Knott Laboratory tested the pneumatic rifle loaded with commercially available air gun pellets. Because of their lead composition and skirt design the pellets are more accurately aimed and have less deviation in their velocity. The pellets were fired at the windshield with a slow progression in the velocity in attempts to determine the lowest velocity required to fracture the windshield for a given kind of pellet. However, because of their soft lead material composition, the pellets were unable to produce fracture to windshields. Upon impact with the windshield, the pellets would experience a mushrooming effect and become compressed, thus absorbing the energy on impact, preventing the windshield from cracking.

Knott Laboratory then tested the pneumatic rifle with the use of small metal steel spheres, also known as bbs. The testing consisted of firing the small metal spheres of known mass at or near the windshield edge at a controlled velocity. The spherical impact projectiles of uniform weight and diameter are commercially available and make consistent impact speeds possible.

TESTING

In conducting this test, Knott Laboratory engineers tested two original equipment windshields installed at the factory and five windshields installed by certified technicians in 2001 Jeep Grand Cherokee Laredos. The first Grand Cherokee original equipment Safeguard windshield was used for test development and useful data was not collected. The first Grand Cherokee was also used for testing the PPG and Pilkington windshields and data regarding these tests is reported. The second Cherokee was used for testing the original equipment Safeguard windshield, an aftermarket installed Safeguard windshield, a Safelite windshield, and an FYG windshield.

First Grand Cherokee

- Factory Installed Safeguard windshield (no data collected)
- PPG windshield
- Pilkington windshield

Second Grand Cherokee

- Factory Installed Safeguard windshield
- Aftermarket Safeguard windshield
- Safelite windshield
- FYG windshield

In conducting this test, 18 perimeter impact locations were chosen for each windshield. The polycarbonate film was applied to one-half of the windshield perimeter such that 9 impact locations were protected with the polycarbonate and 9 mirror impact locations were unprotected. See Figure 1.

The impact test procedure included setting up a speed measuring device at a set distance from the impact location on the hood of the vehicle, and then firing impact projectiles at the impact location. The speed of the impact projectile would be incrementally increased until the projectile produced visible damage in the windshield. The speed required to fracture the windshield was recorded for each of the 18 windshield locations.

Collection of the impact speed required to fracture the windshield allowed comparison of the impact speed and kinetic energy of the impact projectile required to fracture the protected side of the windshield to the unprotected side.

Each impact location was documented by photograph prior to the impact testing and after testing. Damage observed during the testing typically included slight surface damage to the impact location and cracks in the windshields radiating from the impact location. Occasionally cracks would continue to propagate from the impact location to the edge of the windshield. Cracks would also generally propagate after moving the vehicle.

RESULTS

The reason for applying a polycarbonate to the perimeter of a windshield is to protect the areas of the windshield that are weakened by residual stress, and further weakened by installation induced stress. Therefore, the impact speed data required to produce fractures can be analyzed using two methods.

BRAND COMPARISON METHOD

The first method is the comparison of impact speeds across the windshield brands at a particular impact location. This method will determine whether or not a particular impact location is more susceptible to fracture due to the residual stress and installation stress. The comparison can be made with or without the polycarbonate because the polycarbonate does not increase of decrease the stress state within the glass underneath it, but simply dissipates the energy or speed of the impact projectile, and because the polycarbonate protected impact locations mirror the impact locations that are unprotected. One advantage to the first method is that the residual stress varies from manufacturer to manufacturer and therefore the stress induced by the installation or from the boundary conditions on the windshield becomes more apparent.

PROTECTED AND UNPROTECTED METHOD

The second method that can be used to evaluate the data is the comparison between the critical velocity or critical energy required to fracture the side of the windshield protected by the polycarbonate and the Critical velocity or critical energy required to fracture the unprotected side within one brand of the windshield. This comparison allows a qualitative evaluation on the resistance of a particular brand of windshield to impact resistance.

COMPARISON OF THE MANUFACTURERS

Impact testing across the six different brand windshields confirmed that different impact locations on the windshield required different impact speeds to produce fractures. Typically the impact locations on the bottom of the windshield fractured at the lowest speeds, the impact locations along the A-pillar fractured at slightly higher speeds, and the top of the windshield required the highest speeds (see Figure 2). Residual stress and installation stress varies in magnitude along the perimeter of the windshield due to difference in the geometry of the windshield (affecting the annealing process) and boundary conditions created by the frame of the windshield and external forces applied to the windshield. Previous studies have shown the stress state in the windshield can be the greatest in the lower corners of the windshield due to the weight distribution of the windshield (see Reference 3). Test results obtained by the authors from impact testing correlate with this finding. The critical velocity and energy increase from the lower impact locations of the windshield to the upper impact locations shows that the upper portions of the windshield contain less residual stress (see Figures 2 and 4).

COMPARISON WITHIN A SINGLE WINDSHIELD

The second method that can be used to analyze the impact data is the relative difference between the impact speeds for the 9 impact locations of a single windshield protected by the polycarbonate to the 9 impact locations on the mirror side of the windshield not protected by the polycarbonate. This comparison focuses on the relative difference in residual stress between windshield brands and the resistance against fracture of a particular windshield brand. Figure 6 presents the average impact velocity required to fracture each of the six windshields when they are protected by the polycarbonate and when the polycarbonate does not protect them. Figure 7 presents the percentage increase in the speed required to fracture a particular windshield when the polycarbonate is applied.

All of the six different brand windshields improved with the addition of the polycarbonate. The range of improvement with the addition of the polycarbonate in terms of critical velocity varied from 39% for the Safeguard windshield to 90% for the Safelite windshield.

Figure 8 presents the average critical kinetic energy required to fracture the 9 impact locations on each windshield protected by the polycarbonate and the 9 impact locations that were not protected by the polycarbonate film. Because of the relationship between kinetic energy and velocity the increases in the performance or resistance of the windshield to fracture in terms of energy is dependent on the difference between the squared velocities of the protected side and unprotected sides. Therefore, the Safeguard windshield increased its resistance to impact by 94% while the Safelite was able to dramatically improve 262% in terms of the kinetic energy of the impact projectile required to fracture the windshield. Figure 9 presents the energy increases required to fracture the windshields for the six different windshield manufacturers.

CENTER OF WINDSHIELD TESTING

Additional testing was also performed to compare the velocity and energy required to fracture impact locations in the interior of the windshield when the windshield was protected and not protected by the polycarbonate film. An impact location in the center of the region protected with was tested with the polycarbonate film applied and an impact location in the center of the side not protected by polycarbonate was also tested for each windshield. See Figure 10. Results from testing the center of the windshield were mixed. The impact speeds and energy were typically higher than the impact speeds and energy required to fracture the edges of the windshield and on two occasions the pneumatic rifle could not produce a velocity high enough (greater than 600 feet per second) to fracture the center (Pilkington and Safelite). Testing of the aftermarket Safeguard windshield indicated that the critical velocity required to fracture the windshield with the polycarbonate was lower than the velocity required to fracture the windshield without the polycarbonate. A qualitative conclusion that can be drawn from this testing is that the residual stress and installation stress is less in the center of the windshield than at the edges of the windshield.

LIGHT TRANSMITTANCE

Another aspect researched by Knott Laboratory engineers was a light transmittance study. Federal Motor Vehicle Safety Standard (FMVSS 205) requires that 70% of the normal light incident to the windshield is transmitted through the windshield[5]. On each of the seven windshields tested, Knott Laboratory engineers also tested the transmittance of normal light through the windshield with and without the application of the polycarbonate. The windshields were tested before and after placing a 2-inch by 2-inch square polycarbonate in five consistent areas on the windshield.

Results of the transmittance testing indicate that no measurable influence was made on the transmittance of visible light through the windshield with the application of the polycarbonate. Jeep Grand Cherokee windshields from the different manufactures were tinted to allow approximately 80% of visible light through the windshield and the polycarbonate did not measurably change the transmittance of light. See figure 11.

CONCLUSION

The test data was compiled and analyzed to evaluate the increase in the ability of the windshield to withstand impact damage. The results indicate that the application of the polycarbonate, patented by Edgeguard International™, increased the impact resistance of the windshield substantially, without reducing light transmittance. Results from testing six windshields, produced by various manufacturers, indicates that with the application of the polycarbonate protective film, the speed required to fracture the windshields increased approximately 69% and the energy required to fracture the windshield increased by approximately 188%. Furthermore, the most resilient windshield to impact loading was the FYG windshield with the application of the polycarbonate and the Safeguard without the polycarbonate.

ACKNOWLEDGMENTS

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Knott Laboratory would like to thank Aspen Auto Glass of Littleton, Colorado for their assistance during the testing.

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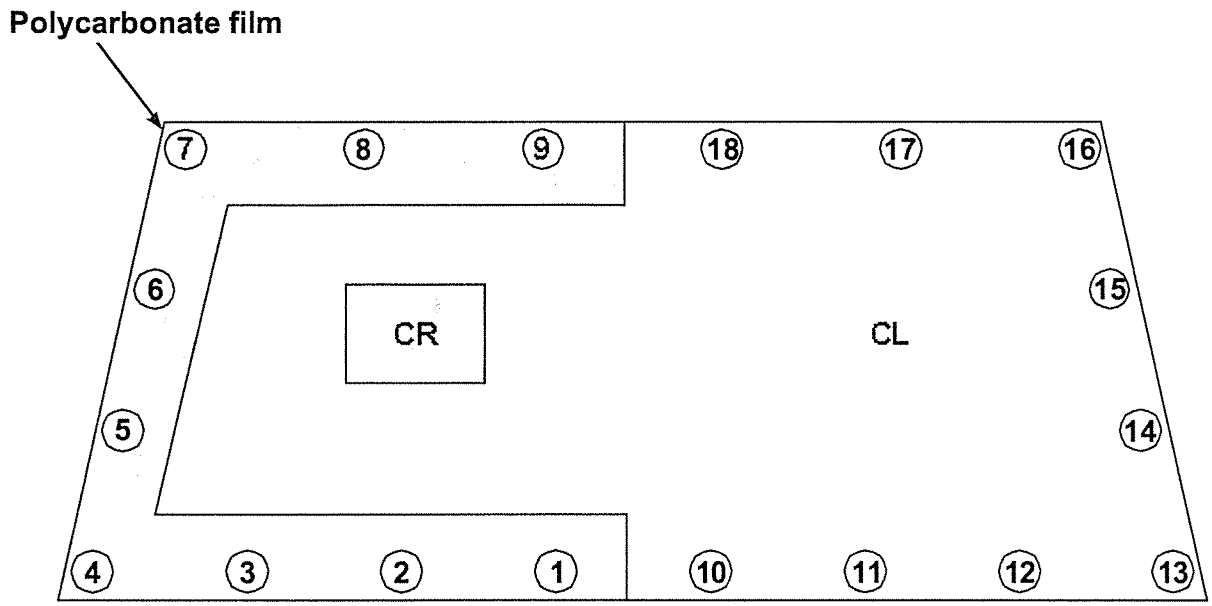


Impact Location Layout

Figure 1

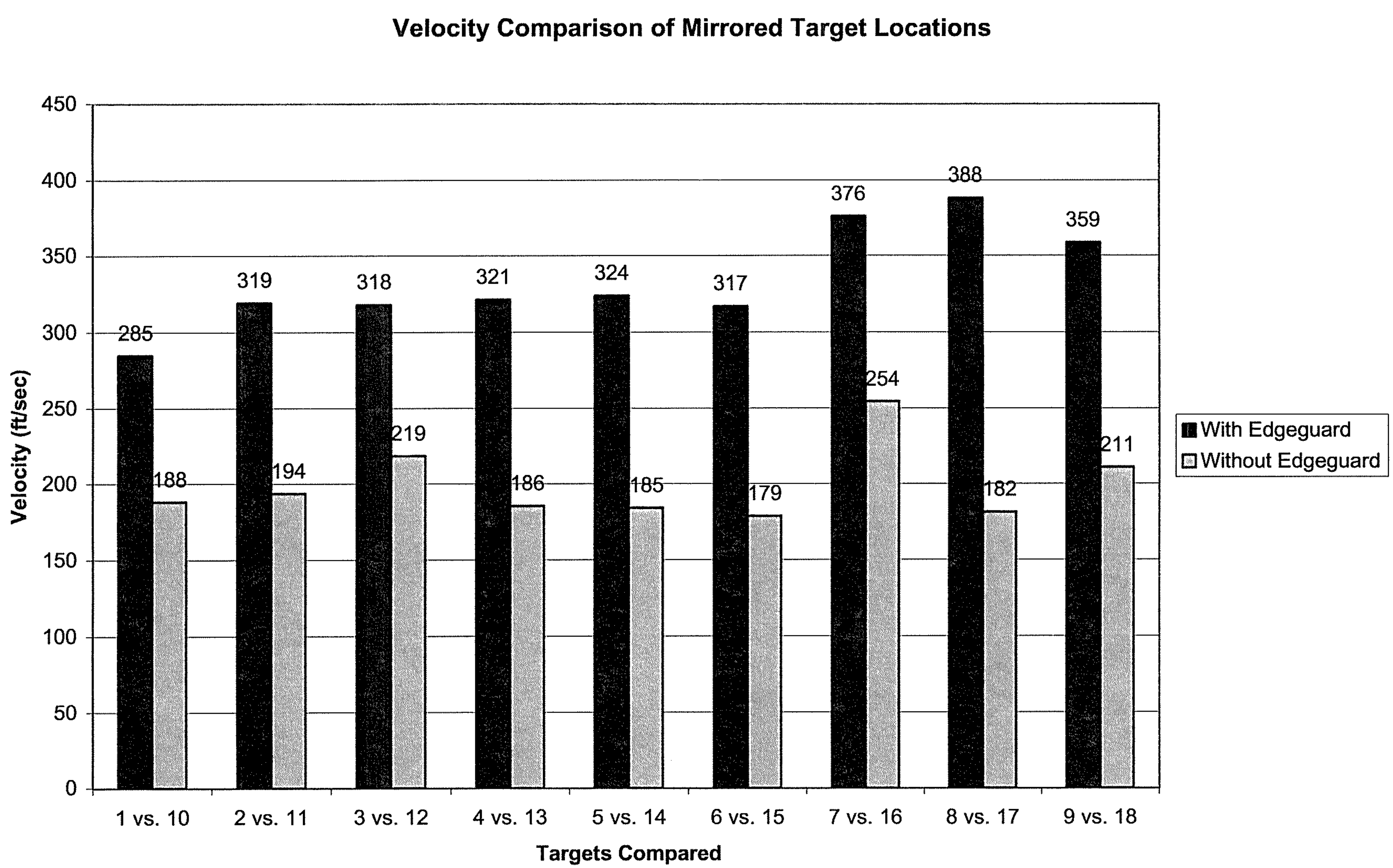
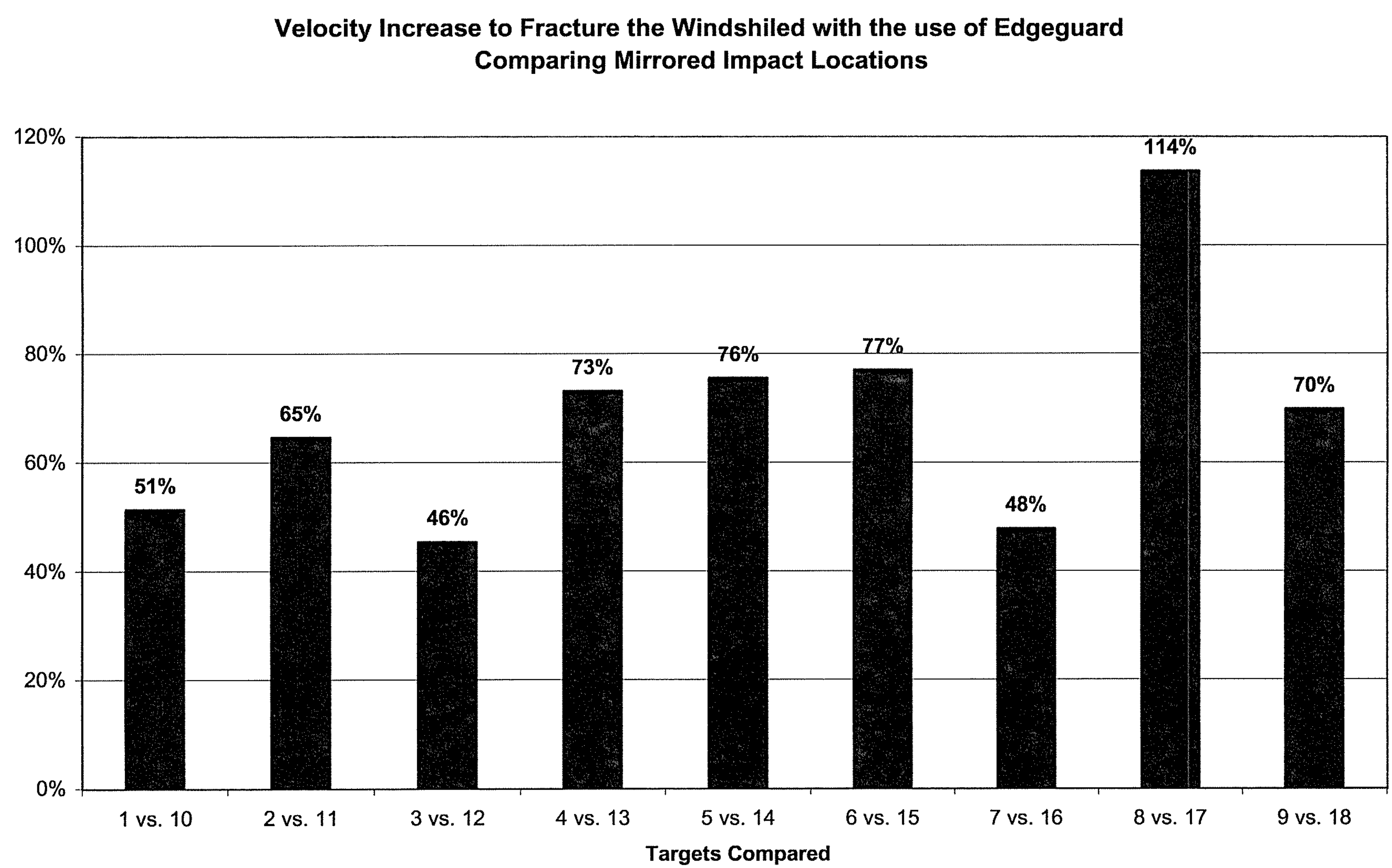
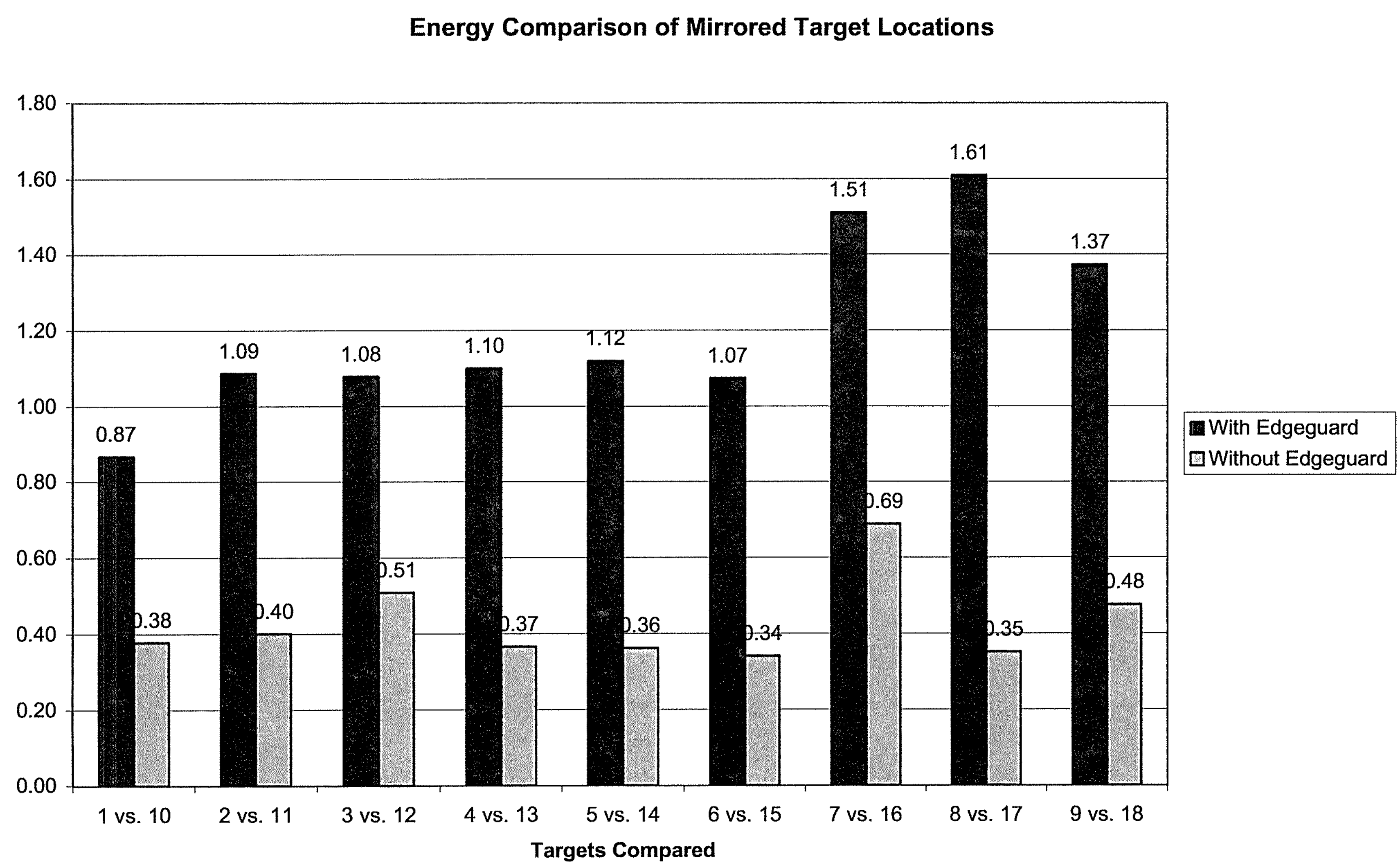

Velocity Comparison of Mirrored Target Locations
Velocity (ft/sec)
450
400
350
300
250
200
150
100
50
0
285
188
319
194
318
219
321
186
324
185
317
179
376
254
388
182
359
211
1 vs. 10
2 vs. 11
3 vs. 12
4 vs. 13
5 vs. 14
6 vs. 15
7 vs. 16
8 vs. 17
9 vs. 18
Targets Compared
With Edgeguard
Without Edgeguard

Figure 2



Velocity Increase to Fracture the Windshiled with the use of Edgeguard
Comparing Mirrored Impact Locations
120%
100%
80%
60%
40%
20%
0%
51%
65%
46%
73%
76%
77%
48%
114%
70%
1 vs. 10
2 vs. 11
3 vs. 12
4 vs. 13
5 vs. 14
6 vs. 15
7 vs. 16
8 vs. 17
9 vs. 18
Targets Compared

Figure 3



Energy Comparison of Mirrored Target Locations
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.87
0.38
1.09
0.40
1.08
0.51
1.10
0.37
1.12
0.36
1.07
0.34
1.51
0.69
1.61
0.35
1.37
0.48
1 vs. 10
2 vs. 11
3 vs. 12
4 vs. 13
5 vs. 14
6 vs. 15
7 vs. 16
8 vs. 17
9 vs. 18
Targets Compared
With Edgeguard
Without Edgeguard

Figure 4

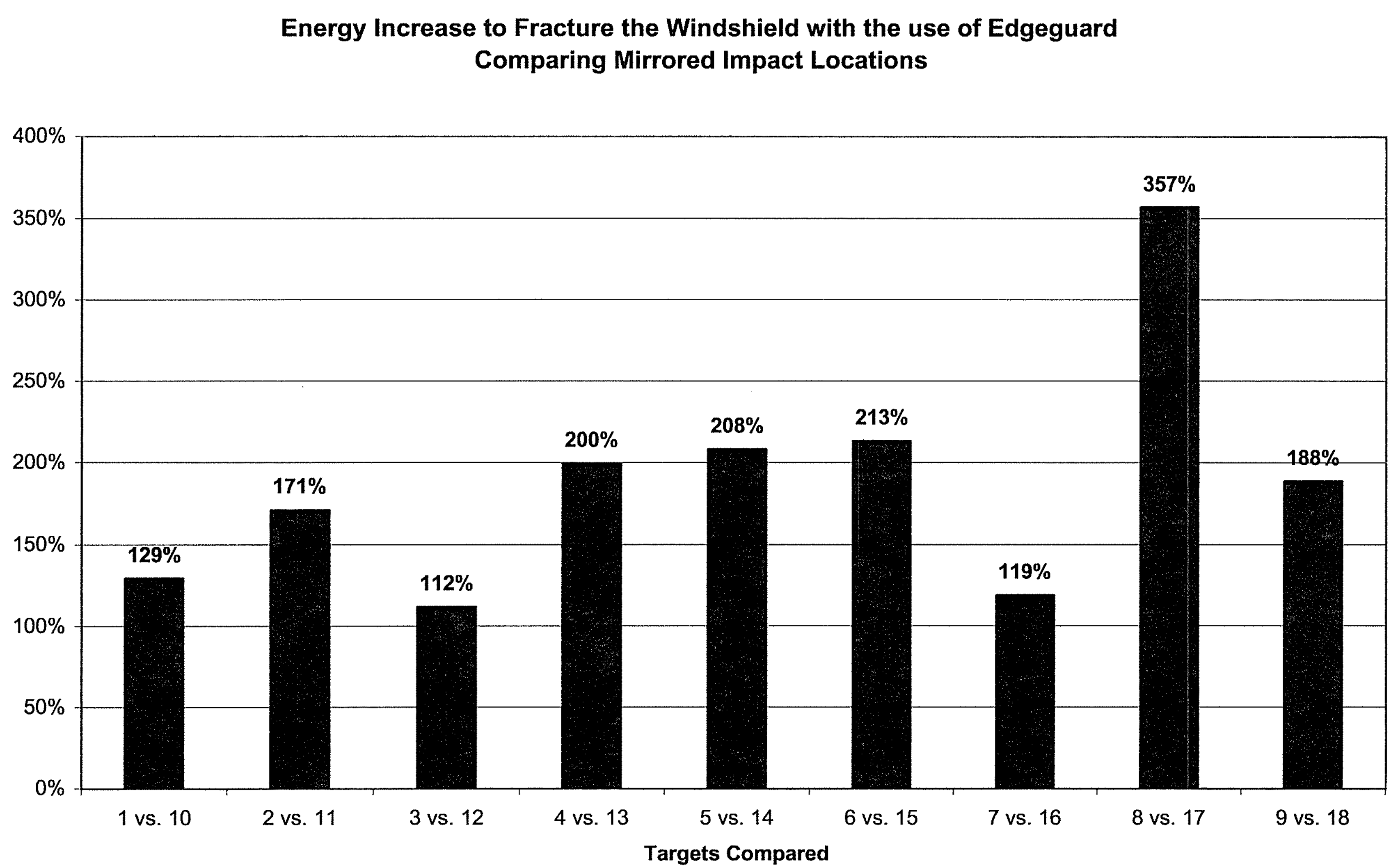

Energy Increase to Fracture the Windshield with the use of Edgeguard
Comparing Mirrored Impact Locations
400%
350%
300%
250%
200%
150%
100%
50%
0%
129%
171%
112%
200%
208%
213%
119%
357%
188%
1 vs. 10
2 vs. 11
3 vs. 12
4 vs. 13
5 vs. 14
6 vs. 15
7 vs. 16
8 vs. 17
9 vs. 18
Targets Compared

Figure 5

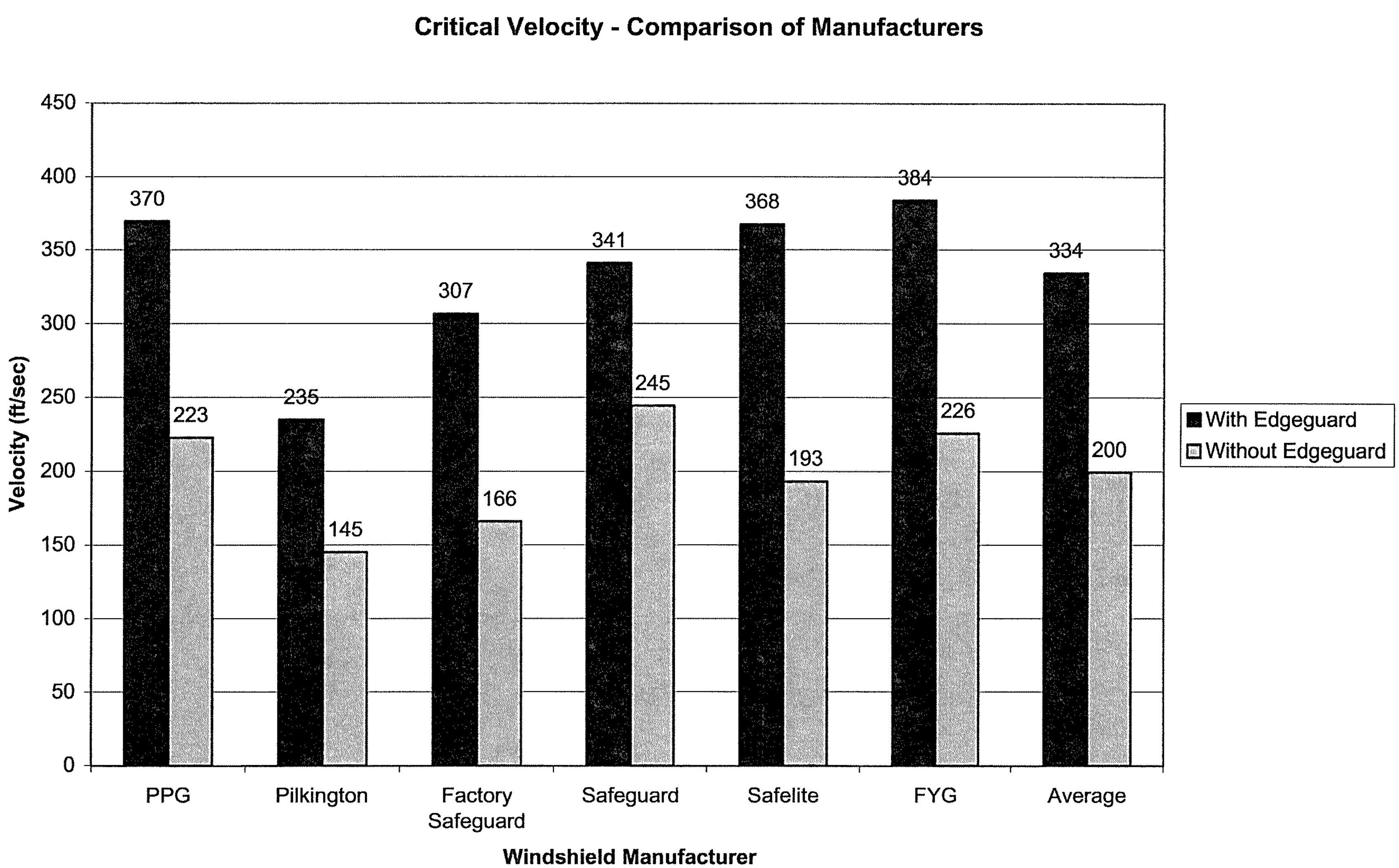

Critical Velocity - Comparison of Manufacturers
Velocity (ft/sec)
450
400
350
300
250
200
150
100
50
0
370
223
235
145
307
166
341
245
368
193
384
226
334
200
PPG
Pilkington
Factory Safeguard
Safeguard
Safelite
FYG
Average
Windshield Manufacturer
With Edgeguard
Without Edgeguard

Figure 6

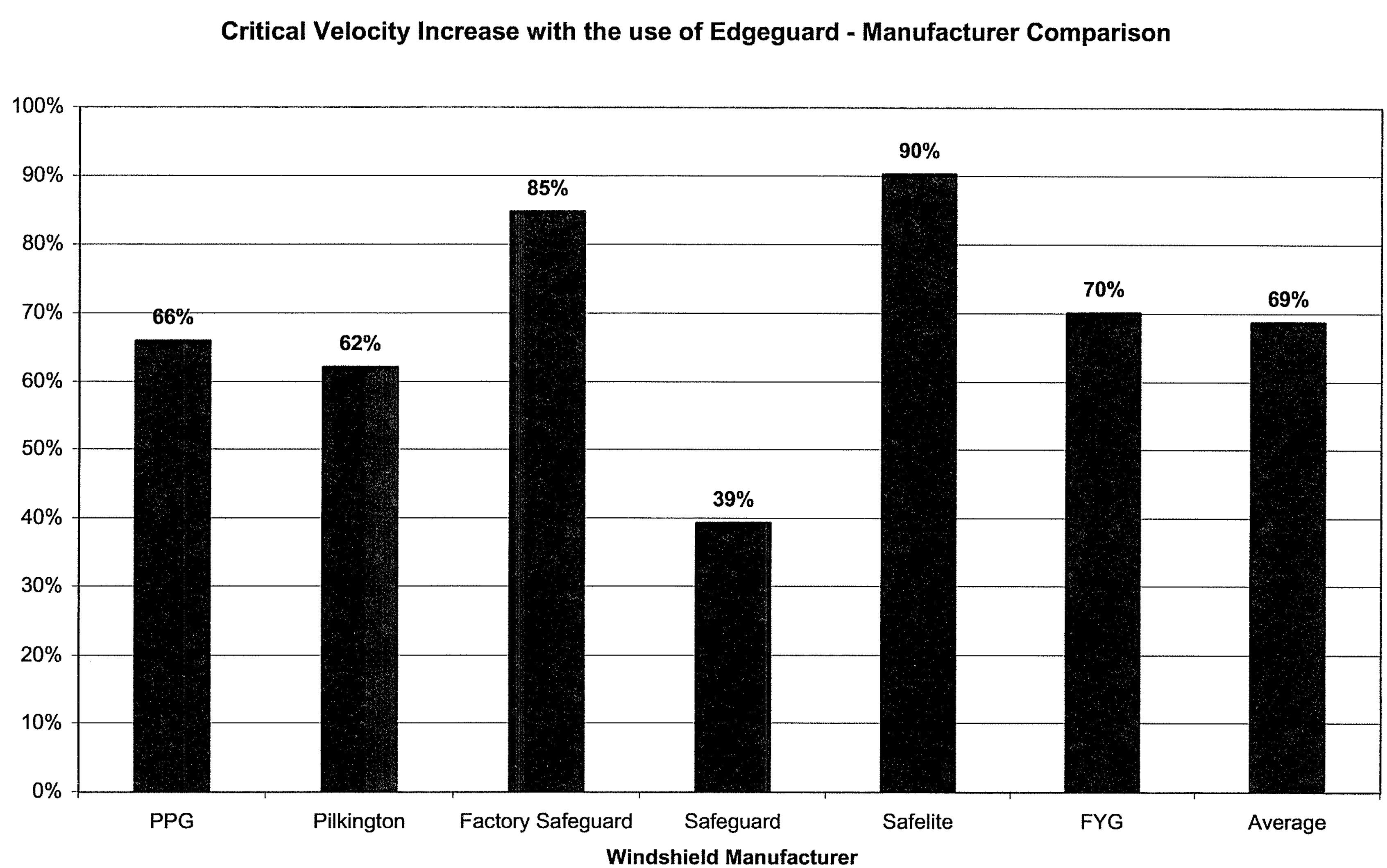

Critical Velocity Increase with the use of Edgeguard - Manufacturer Comparison
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
66%
62%
85%
39%
90%
70%
69%
PPG
Pilkington
Factory Safeguard
Safeguard
Safelite
FYG
Average
Windshield Manufacturer

Figure 7

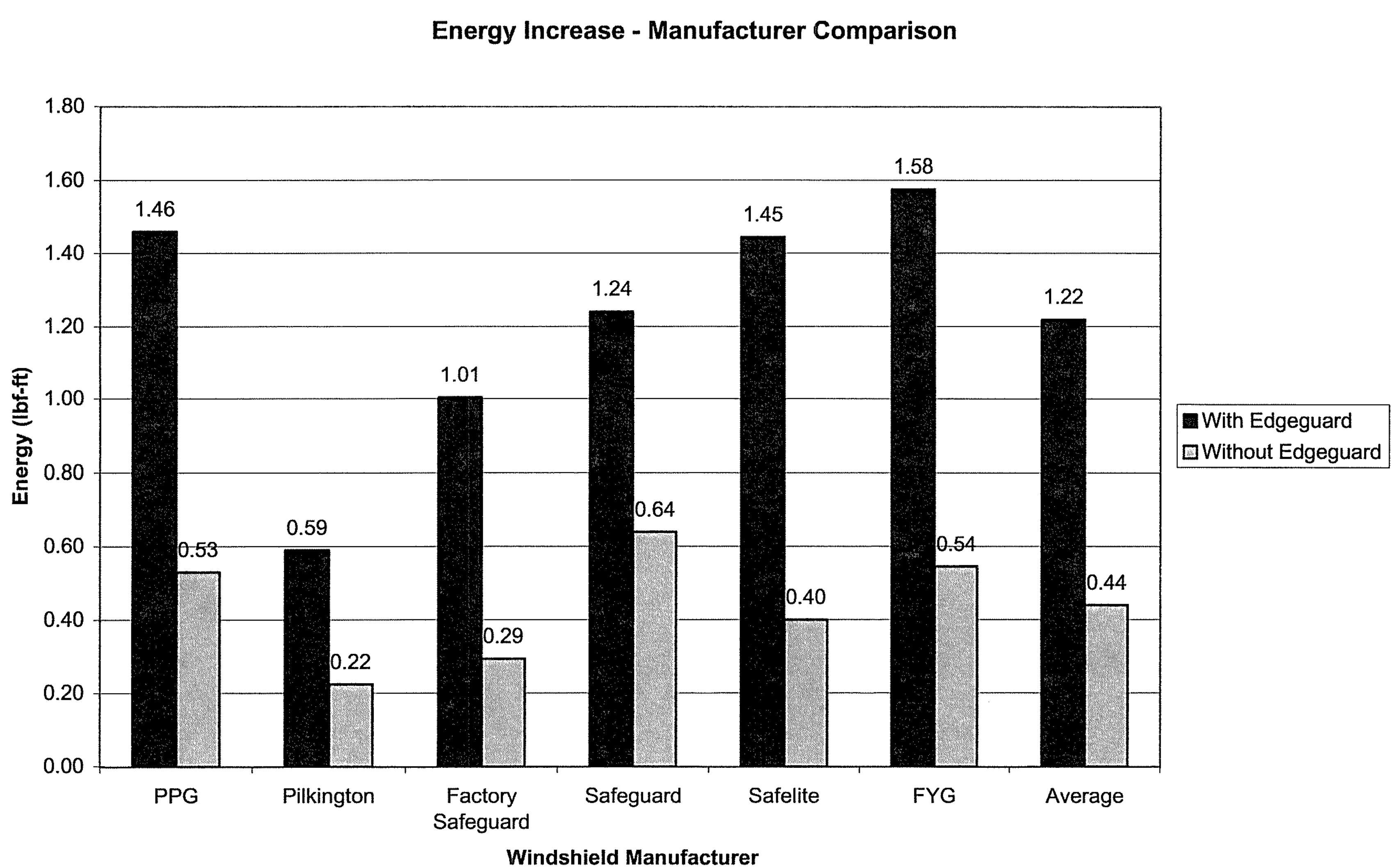

Energy Increase - Manufacturer Comparison
Energy (lbf-ft)
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1.46
0.53
0.59
0.22
1.01
0.29
1.24
0.64
1.45
0.40
1.58
0.54
1.22
0.44
PPG
Pilkington
Factory Safeguard
Safeguard
Safelite
FYG
Average
Windshield Manufacturer
With Edgeguard
Without Edgeguard

Figure 8

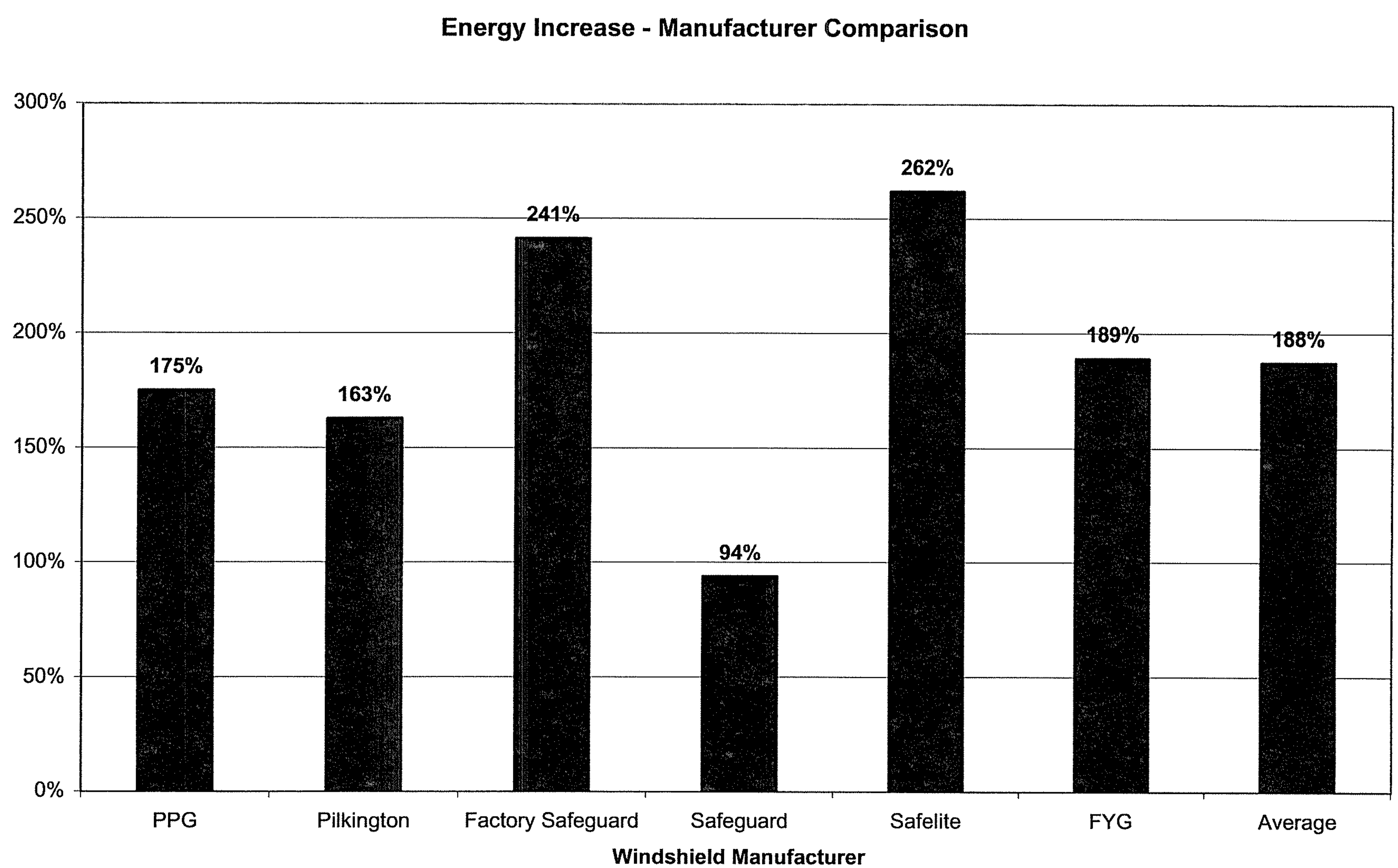
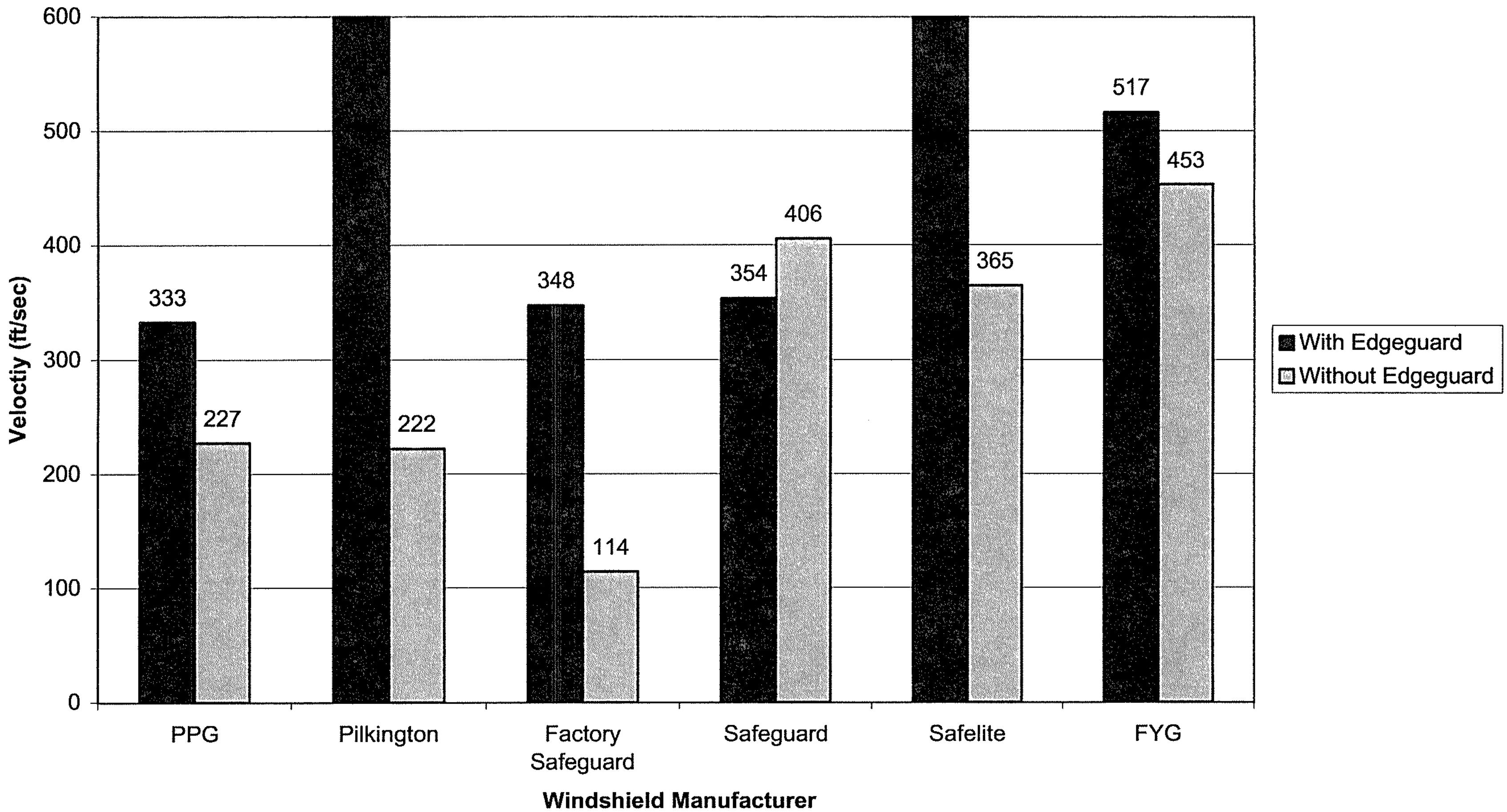

Energy Increase - Manufacturer Comparison
300%
250%
200%
150%
100%
50%
0%
175%
163%
241%
94%
262%
189%
188%
PPG
Pilkington
Factory Safeguard
Safeguard
Safelite
FYG
Average
Windshield Manufacturer

Figure 9

Critical Velocities to Break Center of Windshield - Manufacturer Comparison



NOTE: Unable to produce fracture with the use of Edgeguard on Safelite and Pilkington

Figure 10

Transmittance Data

Windshield	Location A			Location B		
	with	without	difference	with	without	difference
TEST #1-PPG	80%	80%	0%	80%	80%	0%
TEST #2-Pilkington	80%	80%	0%	80%	80%	0%
TEST #3- Factory Safeguard	79%	79%	0%	79%	79%	0%
TEST #4-Safeguard	80%	80%	0%	80%	80%	0%
TEST #5-Safelite	79%	79%	0%	79%	79%	0%
TEST #6-FYG	79%	79%	0%	79%	79%	0%

Windshield	Location C			Location D		
	with	without	difference	with	without	difference
TEST #1-PPG	80%	80%	0%	80%	80%	0%
TEST #2-Pilkington	80%	80%	0%	80%	80%	0%
TEST #3- Factory Safeguard	79%	79%	0%	79%	79%	0%
TEST #4-Safeguard	80%	80%	0%	80%	80%	0%
TEST #5-Safelite	79%	79%	0%	79%	79%	0%
TEST #6-FYG	78%	78%	0%	79%	78%	1%

Windshield	Location E		
	with	without	difference
TEST #1-PPG	81%	80%	1%
TEST #2-Pilkington	79%	79%	0%
TEST #3- Factory Safeguard	78%	78%	0%
TEST #4-Safeguard	80%	80%	0%
TEST #5-Safelite	79%	79%	0%
TEST #6-FYG	80%	80%	0%

Figure 11