Prescription safety eyewear:
Impact studies of lens and frame failure

Paul F. Vinger, M.D.
Vision Performance and Safety Service
Tufts University School of Medicine
Medford, MA

Thomas A. Woods, B.A.
Ophthalmic Dispensing Department
New York City Technical College of the City University of New York
New York, NY

Presenting author:

Paul F. Vinger, M.D.
297 Heath's Bridge Road,
Concord, MA, 01742

Office 978-369-1310
FAX 978-371-9891
vingven@tiac.net

Abstract

Objectives. To determine if a plano lens could be the test lens for all prescription (Rx) lenses and to investigate why Rx lenses pop out of safety eyewear.

Design. Plano and Rx polycarbonate lenses (n=641) with varying thickness and edge geometry, mounted on steel lens holders, and Rx safety eyewear (n=128) placed on headforms, were impacted with test objects of varying diameter and hardness. Impacts were studied with 500 to 2000 frames-per-second motion analysis.

Results. Plano lenses were at least, or more, prone to failure (dislodgment, perforation, shatter, or crack) than –3.00 or +3.00 lenses of the same minimum thickness. Over 40% of safety frames with removable lenses broke or had lenses pop out when impacted with energies expected in industry and sports.

Conclusions. Plano lenses can be used as the test lenses for all Rx lenses made of the same material with the same minimal thickness. The ANSI Z87.1-1989 industrial standard for Rx eyewear is inadequate for sports or other activities with high impact potential. The best lens retention system has, as a component, a frame with a bevel perpendicular to a frontal impact force.

Introduction

Eye injuries, a major cause of disability, [1-3] can be reduced with protective eyewear. [4,5] Over the past three decades, a great deal of progress has been made designing and producing plano (zero power) protective eyewear for sports and industry, developing and revising standards for protective eyewear, and implementing safety regulations and guidelines. [6-14] Since approximately 50% of the population is ametropic, [15] it is essential that basic research be done to further define safety criteria for prescription eyewear. Prior to the development of polycarbonate, lenses shattered before safety frames failed. Now that polycarbonate lenses are the standard-of-care for safety eyewear, [16] frame failure is becoming more of a factor in eye injuries to people wearing eyeglasses with removable lenses; the lens remains intact but is not retained in the frame. Relatively low-energy impacts have caused lenses to pop out of safety frames. [17] A systematic evaluation of lens retention in frames must begin with the lenses themselves and the geometry of the interface between the lens edge and the frame.

Military personnel, workers, athletes, and other spectacle wearers—especially children and the functionally one-eyed—who require protection from impact, should expect that safety eyewear actually protects. The lenses should not shatter, should be retained in the frame, and should protect the eye from impact by the lens, the frame, or objects in the environment that can be reasonably expected to impact the eye. The requirements of ANSI Z87-1989 (Z87) [6] do not meet this reasonable expectation for those who wear Rx eyewear. The current Z87 industrial standard is "two-tier" in that there is a more stringent requirement for the impact testing of plano eyewear with non-removable lenses than there is for protective eyewear with removable lenses. Z87 requires that a frame designed for removable lenses be tested with a test lens. Since glass and allyl resin lenses shatter with the frame tests, the test lenses are polycarbonate. The combined test-lens/frame system must remain intact when impacted with a pointed 500g steel mass dropped from a height of 130cm (51.2"), but eye contact by the lens or frame is permitted. Eye contact is not permitted with the high-velocity impact tests using 6.35mm (1/4") diameter steel balls at a velocity of 45.7 m/s (150 ft/s) from various angles.

After the frame passes with the polycarbonate test lenses, other Rx lenses, which only must pass the impact of a 1" steel ball dropped from 51.2", but are permitted to fail with the high-mass and high-velocity tests, may be substituted for the test lenses. Since glass lenses cannot withstand the needle test, only plastic lenses are subjected to the penetration test with a needle in a 44.2g holder. Z87 minimal lens thickness requirements vary: plano lenses which pass the high velocity test 2.0mm; plano lenses which fail the high velocity test 3.0mm; lenses +3.00 in the most plus meridian 2.5mm; all other Rx lenses 3mm. Thus, until the standard is revised, prescription lenses made of glass or allyl-resin-plastic that are known to shatter with relative little impact energy may be used for industrial, educational, sports or military safety eyewear. At this time, there is no provision for a mechanism by which the consumer may be assured that Rx lenses will not shatter under the same conditions in which protection is expected from plano protective eyewear with non-removable lenses. There is also no provision to warn the user that the test lens was replaced with a lens more prone to shatter.

A difficulty in gaining consensus on tests for the certification of Rx lenses to a high impact standard is the belief by some that it is impossible to do a statistically significant number of high-impact tests on the large variety of possible Rx lenses. We believe that it is not only possible, but also essential to differentiate among Rx lenses and lens coatings as to their basic impact resistance. Needed is a reliable, inexpensive method of testing a small quantity of lenses which will predict the performance, with high impact energy, of all prescription lenses made of the same material, by the same manufacturing process, with the same coatings, and with the same minimum lens thickness.

This study concerns three aspects of polycarbonate prescription safety eyewear: (1) the use of plano lenses to predict the performance of prescription lenses, (2) lens thickness as a factor for polycarbonate lens penetration resistance, and (3) polycarbonate lens thickness and edge bevel design as a factor for retention in the frame.

Frame Failure Case Reports

1. A 46-year-old man was using a band saw to cut stainless steel rings off the end of a furnace roll. A ring piece broke off and struck the left lens of safety glasses that conformed to the Z87 requirements of for spectacles with removable lenses. The 2.0-mm-plano polycarbonate lens remained intact, but was driven through the frame from the impact at the lower left corner of the lens. The result was a corneal laceration, commotio retinae, hyphema, iritis, and cataract with dislocated lens. Final best-corrected vision is 20/200 because of a macula scar.

2. A 43-year-old oil rig worker slipped and struck the left lens of his safety glasses with a screwdriver. The glasses conformed to the Z87 requirements for spectacles with removable lenses. The 3-mm plano polycarbonate lens remained intact but popped through the frame. The screwdriver perforated the globe. Final vision after four surgical procedures is no light perception.

3. A 44-year-old man was struck on glasses that were advertised as sports goggles and which the manufacturer claimed passed ASTM F803 for racquet sports and ANSI Z87.1 for industry. A basketball struck the eyewear frame and cracked it, leaving two sharp edges. The 3-mm-center-thick, -

6.00-diopter polycarbonate lens remained intact. The man replaced the frame with an identical model. One month later, he collided with another basketball player, whose head struck the eyewear. The frame broke. Sharp frame edges, in combination with the back of the lens, which was left quite sharp by the optician, caused a significant lid laceration. The player wrote to the FDA stating "Based on these two situations, 1 believe that these frames are a serious safety risk and should not be sold for any use where blows to the frames could occur." There was no response. A similar letter was sent to the manufacturer with the addendum "I also believe that any current users should be informed immediately of the potential serious safety factors." The frame is still sold as a sports eye protector with removable lenses and claims that "All of our [manufacturer and model] safety products have a specially designed safety groove. That means the frontal edge of the groove is shorter than the back edge (see sketch). Therefore, the lens can only be inserted, or pop out towards the front, away from the eye."

Materials and Methods

Prior data. These studies are a continuation of: studies published in JAMA [16] concerning lens impact resistance; studies by Johnson and Good [17]concerning retention of lenses in metal and plastic safety frames; and studies on baseball eye protection. [18]

Test lenses. Three manufacturers supplied single-vision polycarbonate stock lenses of varying thickness in lens powers of +3.00 sphere, plano, and -3.00 sphere. The lenses were fabricated with the optical center coinciding with the mechanical center and edged round to 55mm. For tests to reflect the Z87 requirements, manufacturers used standard lens edging machinery for the processing of polycarbonate lenses and standard hand beveling to provide a one-millimeter rear bevel slope for Z87 safety frames. The lens bevel angles were 110^{0} and 121^{0} and complied with the 110^{0} to 130^{0} lens bevel range requirement of ANSI Z80.5-1997. [19] Other lens bevel designs were cut with specifically designed edge cutters for polycarbonate lenses. The manufacturers supplied 688 edged lenses which were weighed (± 0.01g), and measured (diameter, center thickness (ct), edge thickness (et) (± 0.1 mm). 641 of the lenses were impact tested and 47 kept in reserve.

Test lens holders. Test lens holders were made of 6.35mm (1 /4 ") tool-steel (Exhibit 1) and ground as depicted for each test setup (Exhibit 2), representing different relationships of the test lens edges to the lens holders. Test lens holders were mounted on a 17kg steel frame (Exhibit 3).

Impact test objects. Impact test objects were chosen with a wide variety of mass, diameter, and hardness to reflect the unpredictable nature of impacts to safety eyewear (Table 1). The dynamic hardness of each sports ball was determined by measuring the percent that the ball compressed on impact with a 17kg flat steel plate. Sports ball liveliness was determined by measuring the coefficient of restitution (COR),[20] which is the ratio of rebound to inbound speed when the latter is 60 mph. Z87 test objects were rated as hardness = 1.00, and COR = 0.55. 21 Energy and momentum were calculated for each impact.

Impact velocities. Impact velocities were chosen to correspond to existing standard specifications or velocities known to occur with the test object as ordinarily used (Table2).

Test methods and data analysis. Impact sequences were randomized with computer software (Microsoft Excel). The 500g Z87 pointed test mass, with a diameter of 25.2mm, was propelled

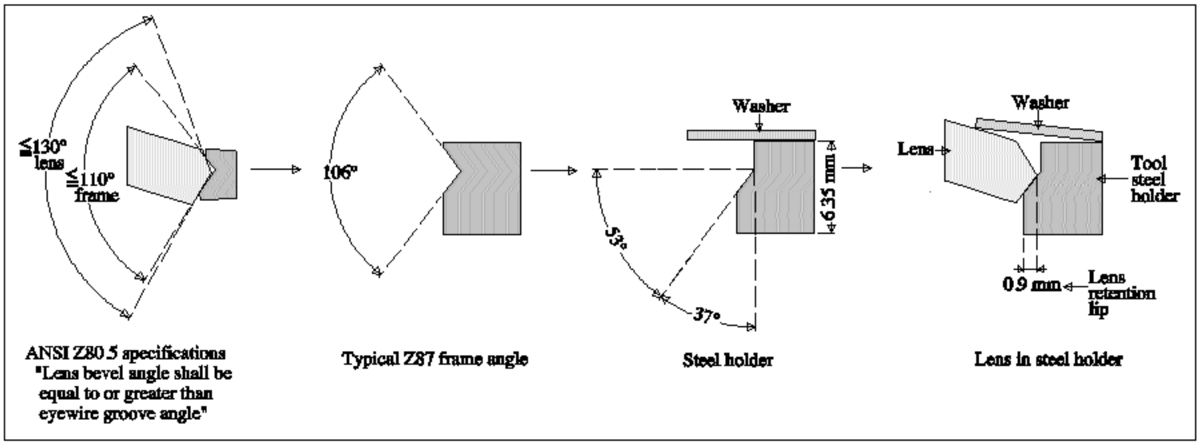


Exhibit 1. The progression from the actual lens requirements of ANSI Z80.5 to the construction and lens mounting of a standard bevel industrial safety lens with an 0.9 posterior lens retention lip in an "infinitely strong" frame with a standard Z87 posterior bevel.

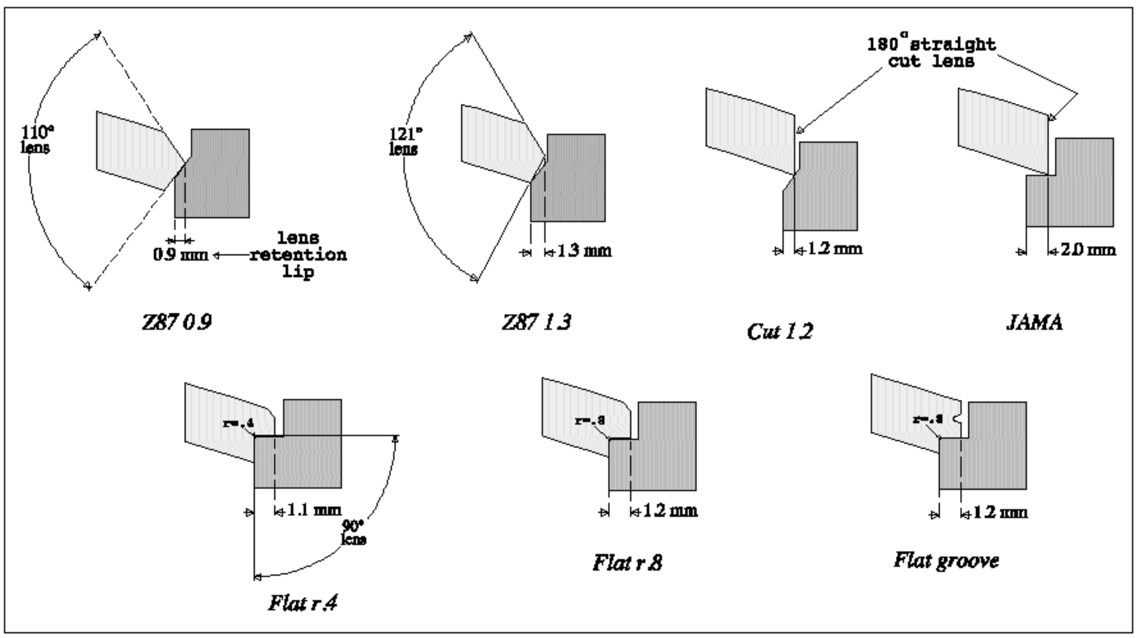


Exhibit 2. . Lens/frame geometry for test setups: lenses on steel holders. The Z87 setups reflect the angles of lens and frame bevel used for industrial safety eyewear. The Cut lens has the same bevel as the JAMA lens, but on a holder that reflects the Z87 bevel. JAMA is the setup used for the JAMA series. [16] The flat lenses represent the edging required of Rx lenses if they are to be inserted into a real frame with a flat bevel. The overlap (lip) of the lens on the steel holder is indicated.

through a 28.2mm inside-diameter aluminum tube by gravity from 635mm (25"), 1270mm (50"), and 1905mm (75"). The 6.35mm ANSI Z87 steel balls were propelled with a nitrogen-powered air gun. All other test objects were propelled with an air cannon. [18] Impacts were imaged using a Red Lake high-speed imaging system at frame rates between 500 and 4000 frames per second. Motion analysis was done with software supplied by Red Lake. [22] Velocities were calculated with an OehIer chronograph and the Red Lake software. Data analysis and statistics were computed with Data Desk,

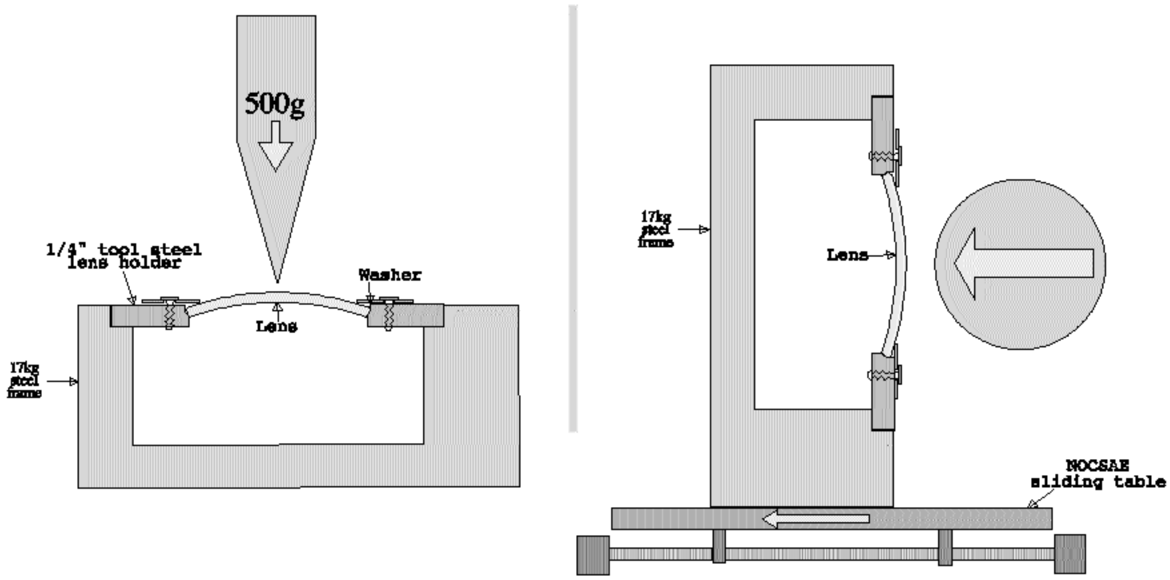


Exhibit 3. For the 500g high-mass Z87 drop test, the lens was parallel to the floor. For all other tests, the lens holder apparatus was affixed to a National Operating Committee on Standards for Athletic Equipment (NOCSAE) sliding table [19] with the lens plumb.

Table 1. Test objects used to impact lenses

Test object	Weight (g)	Diameter (mm)	COR* at 60mph	Dynamic hardness**	Energy Joules (SD) at test velocities	Momentum kgom/s (SD) at test velocities
Z87 6.35 mm steel ball	1.04	6.35	0.55	1.00	3.8 (2.1)	0.08 (0.03)
Z87 500g steel high mass	500.0	Conical tip Radius =1mm	0.55	1.00	6.3 (1.8)	2.48 (0.38)
Squash, hard	21.5	40.0	0.35	0.76	16.7 (3.3)	0.84 (0.09)
Squash, soft	23.4	39.5	0.26	0.53	20.8 (1.0)	1.01 (0.03)
Golf	45.8	42.7	0.84	1.00	21.0 (13.5)	1.31 (0.44)
Field hockey	175.9	71.2	0.47	0.92	25.2 (0.8)	2.98 (0.04)
Lacrosse	152.0	62.6	0.66	0.57	33.5 (14.8)	3.09 (0.71)
Tennis	57.1	64.5	0.44	0.50	45.2 (2.0)	2.27 (0.05)
Baseball	141.8	72.7	0.53	0.83	60.1 (22.3)	4.08 (0.73)

*Coefficient of restitution = the ratio of the rebound speed to the pre-impact inbound speed (60 mph) for all sports balls 19, and from 20 for Z87 test objects..
**Determined in sports balls by percent of flattening on impact with flat 17 kg steel plate on a NOCSAE sliding table at 60 mph. Red Lake motion analysis hard and software. 1.00 = no flattening
Energy and momentum are the mean and SD of all the impacts.

Version 6 [23] on a Power Macintosh G3/300 computer.

The lens retention geometries used in the Johnson and Good experiments were calculated using measurements of a lens bevel supplied by Drs. Johnson and Good, [17] and the frame eyewire lens retention bevel angles, depths, and geometry from drawings supplied by the manufacturer of the frames used in the Johnson and Good study.

The standard eyewire bevel for safety frames was determined by polling manufacturers and

Table 2. Typical test object velocities

Z87 500 g steel mass	25" 50" 75"
Z87 6.35 mm steel ball	150 to 300 ft/s
Squash ball	90mph
Golf ball	90 mph
Tennis ball	90 mph
Lacrosse ball	45 mph
Field hockey ball	40 mph
Baseball	70 mph

obtaining manufacturing specifications. Commonly used safety eyewear frames for removable lenses had eyewire grooves that were from 0.8 to 1.0mm deep and bevel angles that ranged from 104^{0} to 109^{0}, complying with the maximum 110^{0} requirement of ANSI Z80.5-1997. [19]

Results

The high correlation between weight and minimal lens thickness* of the *Z87 0.9* lenses could be expressed by regression formulas:

-3.00 weight (grams) = 2.66+2.73 *ct
plano weight (grams) = 0.19+2.70*ct
+3.00 weight (grams) = 2.18+2.82*et

*center thickness (ct) for -3.00 and plano; edge thickness (et) for +3.00

For any practical minimal lens thickness, the -3.00 lenses were heavier than the +3.00 lenses, which were heavier than the plano lenses.

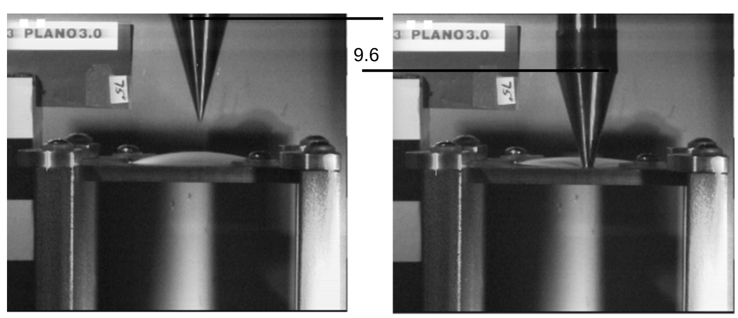
Results of tests with ANSI Z87.1-1989 test objects on lenses mounted in steel holders.

The energy in these tests is low compared to impacts from sports balls (Table 1). Analysis of the data revealed that difference in performance was independent of the manufacturer and the lens edge geometry.

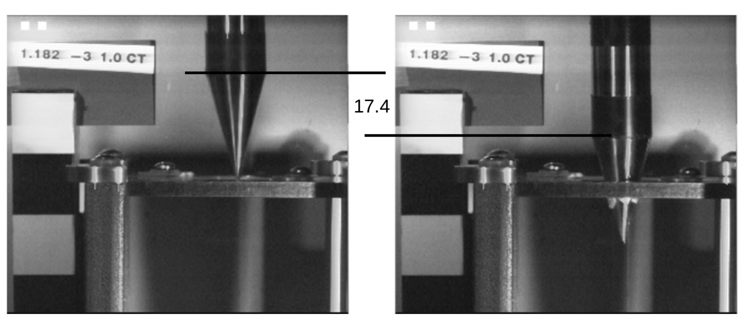
ANSI Z87 500 gram high mass (n=87). There was no significant difference in the results of this test using test setups Z87 0.9, Z87 1.3, and Cut 1.2, and the data were therefore pooled. No lenses cracked or shattered. Only one lens (Z87 0.9 2mm-ct-plano, 50" drop height) dislodged from the frame. The main lens failure was perforation (38 perforated /87 tested) (Exhibit 4), which was related to center thickness, but not to edge geometry or the posterior retention lip of the lenses. Lenses with a center thickness of less than 2.2mm had a significantly higher perforation rate. Exhibit 5

Exhibit 4. Z87 high mass, low velocity tests.

3.2mm ct plano lens, 9.6mm tip displacement at drop height of 75”, no perforation.



1.1mm ct -3.00 lens, 17.4mm tip displacement at drop height of 50”, significant perforation.



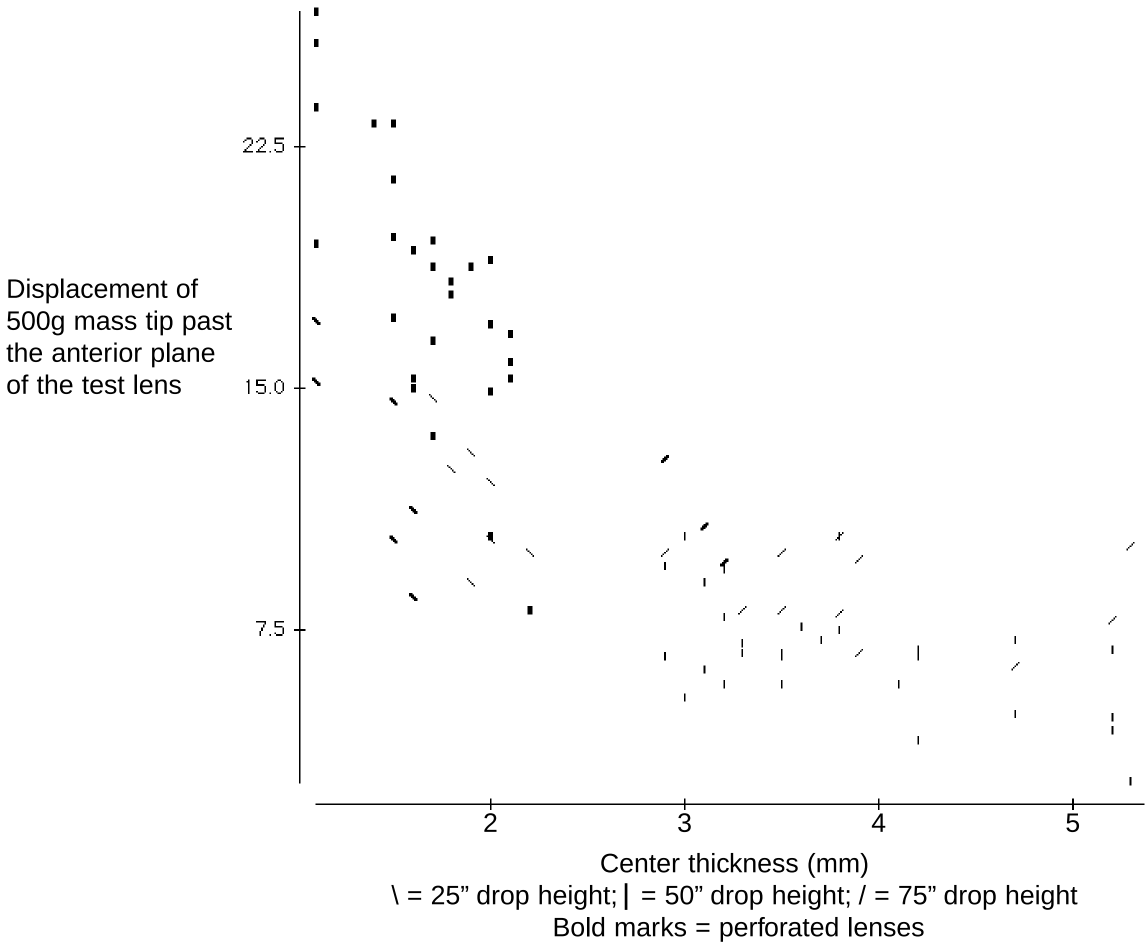


Exhibit 5. . Relationship among displacement (the maximum distance in mm by which the tip of the 500g mass passed the anterior plane of the lens) lens center thickness, lens perforation, and drop heights.

shows the correlation among displacement (the maximum distance in mm by which the tip of the 500g mass passed the anterior plane of the lens) lens center thickness, lens perforation, and drop heights.

<u>ANSI Z87 1/4" steel ball</u> (n=116). Again there was no significant difference in the results of this test using test setups Z87 0.9, Z87 1.3, and Cut 1.2, so the data were combined. No lens was perforated, displaced, or dislodged from the frame. Each of the 5 lenses that shattered had a center thickness of 1.8mm or less. One lens (plano, 1.8mm-ct) shattered at 150 ft/s, two lenses (-3.00, 1.1 and 1.5mm-ct) at 250 ft/s, 1 lens (plano, 1.7mm-ct), at 300 ft/s, and 1 lens (-3.00, 1.6mm-ct) at 375 ft/s. None of the 12 lenses that cracked (1 lens –3.00, 5 lenses plano, and 6 lenses +3.00) had any displaced pieces. Most of the lenses that cracked had a center thickness exceeding 2.2mm at impact velocities exceeding 300 ft/s.

Results of test setup impacts including sports balls and Z87.

Z87 0.9 (n=190). This test setup most closely reflects the industrial and sports safety frames for removable lenses that are currently available. There was adequate lens retention for the Z87 industrial test objects and for the tested racket sports (tennis and squash) for all thickness of tested +3.00 lenses, for -3.00 lenses with center thickness 1.5mm or greater, and for plano lenses with 3mm thickness. Lenses with 3mm minimum thickness retained the lacrosse ball, but not the golf, field hockey or baseball. Lens displacement was correlated with the energy, not the momentum of the impacting object. Harder objects with higher COR were more efficient at displacing lenses from the frame.

Z87 1.3 (n=190) This test setup reflects the effect of increasing the groove depth of a standard bevel eyewire frame to approximately 1.5mm. Increasing the lens retention lip resulted in adequate lens retention by –3.00 and +3.00 3mm minimum thickness lenses for all test objects. Some plano 3mm lenses dislodged with the baseball (66.8 mph) and golf ball (95.5mph).

JAMA (n=158) The JAMA test series 16 with straight cut (lens bevel = 180^{0}) -3.00 lenses on a flat lens holder and a 2mm posterior retention lip reflects the strength of the lenses themselves. Lenses in this test series were extremely difficult to dislodge. Lenses remained in the frames with baseballs up to 135 mph; lacrosse balls up to 107 mph; and tennis balls up to 170 mph. No 3.0mm-ct lenses were dislodged by golf balls up to 191 mph. Five 1.5mm-ct lenses were dislodged by golf balls at speeds ranging from 166 to 188 mph. A total of 18 lenses shattered: golf ball (1.5mm ct, 98-191 mph, 3 lenses; 3.0mm ct, 116 to 183 mph, 9 lenses), lacrosse ball (1.5mm-ct, 59 mph, 1 lens; 3.0mm-ct 76 to 80 mph, 3 lenses), and 0.51g lead air-rifle pellet (1.5mm-ct 456 and 460 mph, 2 lenses).

Cut 1.2 (n= 171) This setup compares a straight cut lens on a beveled frame (test lens holder bevel angle = 53^{0}) with the polycarbonate lens data from the JAMA series. Decreasing the lens retention lip and adding the bevel to the frame increased the tendency for the -3.00 lenses to be dislodged when compared to the JAMA series. However, all lenses with 3.0mm minimum thickness, except for 2 plano lens which dislodged with a baseball at 75.7 mph and a golf ball at 96.1 mph, were retained with all test object impacts.

Flat r.4 (n=54) This setup reflected the principles of the JAMA series, which had the lens flat against the lens holder with the holder bevel perpendicular to the force transmitted from the front of the lens. Minimum thickness 1.5mm and 3.0mm –3.00 and +3.00 lenses were adequately retained when impacted with squash, tennis and lacrosse balls. The 3mm plano lenses were retained with the lacrosse ball, but the 1.5mm thick plano lenses were not. Shearing of the anterior lens retention lip was the major problem with the high impacts of baseballs and golf balls. Ten of twelve baseball impacts and five of twelve golf impacts dislodged the lenses because the anterior lens retention lip sheared.

Flat r.8 (n=18) This test setup tested the effect of increasing the radius of the fillet to relieve the 90^{0} notch stresses of the right angle bevel cut in the lens. The increased radius eliminated shearing. When -3.00 (1.5mm, 3.0mm ct) and plano (3mm ct) lenses were impacted with baseballs, there was no shearing of the anterior lens lip. All of the -3.00 1.5mm ct lenses were dislodged at velocities between 44.3 and 52.5 mph. The -3.00, 3-mm ct lenses were retained below velocities of 77.7 mph, but dislodged at 88 mph. 3mm ct plano lenses were retained at velocities below 59.4 mph, but dislodged at 66.1 and 68.2 mph.

Flat groove (n=18) This test setup was used to see if there was a difference when the anterior 55^0 retaining bevel was replaced with a retention groove in the 0.8 fillet lens. There was no shearing. When impacted with a baseball, -3.00 (1.5mm-ct) lenses were retained at velocities up to 45 mph but dislodged at velocities above 49.8 mph. -3.00 (3mm ct) lenses were retained at velocities up to 74.3 mph, but the lenses were dislodged at velocities above 85.9 mph. Plano (3mm-ct) lenses were retained at to 55.2 and 66.1 mph, but dislodged at velocities ranging from 60 to 70.9 mph.

Z87 and sports plano eyewear with removable lenses on headforms, (n=128). With the 1/4" steel ball (n=10) the Z87 lenses remained intact and were retained in the frame at the specified Z87 test speed (150 ft/s). When the speed was increased to that required by Z87 of industrial goggles (250 ft/s) or face shields (300 ft/s) the lenses remained intact but three of the six frames tested cracked (237, 246, 300 ft/s) with resultant lens displacement and eye contact by the intact polycarbonate lens. When impacted with the 500g steel mass (n=4), there was eye contact with each of two impacts at 50" drop height. The lenses remained intact, but one lens was displaced 3mm posterior to the frame nasally. Side shields were penetrated when impacted from the side with the 500g mass from 50" and 75," but there was no eye contact and the lenses were retained. The protectors passed the tests with the Z87 weighted needle (n=4).

Impacts with the soft squash ball at 99 mph (n=3) broke all of the protectors at the hinge. When impacted from 45^0 the frame cracked upper nasally and the lens popped through. Approximately 50% of sports safety frames with removable lenses broke or had lenses pop out when impacted with baseballs and lacrosse balls at typical velocities in these sports.

Discussion

The study attempts to answer several questions and proposes further studies.

1. Are polycarbonate prescription lenses strong enough to give eye protection for sports and industry? Yes. The JAMA series, supported by this test data, show that polycarbonate is the most impact resistant lens material currently available for prescription eyewear and that, in practical thickness, the lenses are capable of withstanding likely impacts in sports and industry. This study, which used a rigidly fixed frame, is the "worst case scenario" for the lens itself, in that the lens absorbs all of the energy. The frame was tool steel and mounted to a high mass holder. Motion analysis showed that, even though the holder was mounted on a sliding table, the holder moved only after the test object bounced off, dislocated, displaced, shattered, oilcanned, or cracked the lens. The sliding table helped preserve the test apparatus, but did not help the lens absorb the impact energy.

2. Should there be a minimum thickness requirement for Rx polycarbonate lenses? This depends on the total protection system and the results of testing on the total system. Perforation with the Z87 500-g mass was directly related to center thickness, with lenses less than 2.2mm ct having a significantly greater tendency to perforation than thicker lenses. Shattering by the Z87 1/4" steel ball occurred in lenses with center thickness of 1.8mm or less. With all test objects, thinner lenses were more flexible and prone to "oil can" out of the frame than 3mm minimal thickness lenses. These data seem to point to a minimum thickness requirement for safety eyewear in which impact with sharp objects or high energy may be expected.

However, the optimal minimal thickness for any given protector system (the lens, the frame, the means of attaching the frame to the head) remains to be determined. The Johnson and Good study showed that a plano polycarbonate beveled lenses, ranging in thickness up to 3mm, placed in typical industrial beveled safety frames dislodged quite easily. However, a plano goggle which has a flat 5mm retention lip and soft sides, is quite resistant to dislodgment of a 2mm plano polycarbonate lens, since the lens is well-supported and the frame of the goggle has a good deal of room to deflect, is flexible, and is efficient as an energy absorber. When impacted with a golf ball at 60 mph, a properly engineered plano motorcycle goggle that has a flat 5mm retention groove and soft sides with foam padding retains, without eye contact, a plano polycarbonate lens that is only 0.78mm thick. The same goggle remains intact when impacted with a 6.35mm steel ball at 400 ft/s.

Because of the need for a closer vertex distance in Rx eyewear (13-15mm), compared to goggles (4-5cm), there will be less room for the Rx frame to absorb energy. Since it is also impractical, because of visual field and cosmetic compromises, to have the same retention lip length on a Rx frame as on a goggle, Rx lenses will have to be thicker than goggle lenses to prevent oilcanning out of the frame or eye contact. 3mm minimum thickness lenses may be necessary for high-impact Rx eyewear, but thinner lenses may be adequate if the frame is designed to retain the lens and absorb some of the impact energy by controlled deflection that prevents eye contact by the impacting object, the lens, and the frame itself.

In light of the data presented in this study, the current Z87 requirement of 3mm for Rx lenses, while permitting 2mm plano, does not make sense for polycarbonate lenses because plano polycarbonate lenses are more prone to failure than Rx polycarbonate lenses of the same thickness.

3. Can the impact testing of plano lenses predict the performance of prescription lenses? Yes—provided that the lenses are all made by the same manufacturer with the same manufacturing processes, have the same minimal thickness, and have the same coatings. This study showed that:

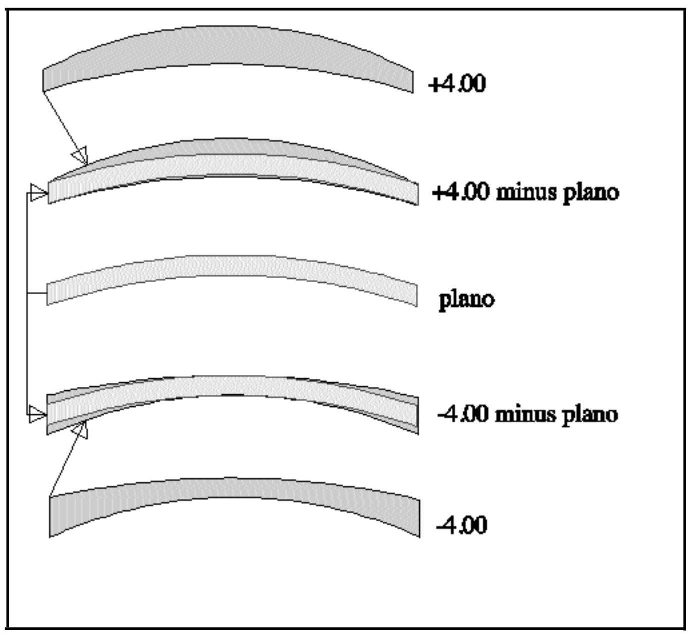


Exhibit 6. There is more material in any prescription lens than there is in a plano lens with the same minimum thickness.

a. The regression formulas of lens weights compared to lens power confirm the self-evident observation (Exhibit 6) that there is more material in a prescription lens of given minimal thickness than an equivalent plano lens.

b. Perforation with the Z87 pointed 500g mass was related to the center thickness but not the power of the lens or the interaction of the lens power and center thickness. -3.00 lenses were not more prone to perforation than plano lenses of the same center thickness. Because of greater center thickness, plus lenses with the same minimal lens thickness were more resistant to perforation.

c. There was no greater tendency for -3.00 or +3.00 lenses to shatter, oilcan, or crack than plano lenses of the same minimal thickness.

d. With all of the test objects, plano lenses were displaced from steel lens holders at lower energy levels than -3.00 or +3,00 lenses of the same minimal thickness.

It is commonly thought that minus lenses are weaker and more prone to shatter than other prescription lenses; -2.00 lenses are often used as test lenses to demonstrate lens material fragility. This study contradicts this tradition and demonstrates that the plano lens is at least, or more, prone to shatter, perforate, crack or displace as -3.00 and +3.00 lenses with the same minimal thickness. All lenses with prescriptions have the cross-sectional configuration of a bridge. The cross-sectional bridge configuration, combined with a greater quantity of polycarbonate, in all prescription lenses, when compared to plano lenses of the same minimal thickness, make it reasonable to assign the plano lens as the lens of choice to determine the resistance to perforation, shatter, crack, and dislodgment of all lenses made of the same material, by the same manufacturing process, with the same coatings, and edge configurations. For testing of lens materials, plano lenses in steel lens holders will give adequate information.

4. Why do safety lenses pop out of safety frames? Each of the individuals cited in the case presentations had the right to believe that he would be protected, yet they all sustained injury by failure of the frames to retain the lenses. The Johnson and Good experiments, which anchored the frame by the nosepiece and temples, had a high incidence of lens dislodgment. The 500-g mass dislodged 11 of 16 lenses at drop heights of 31 inches or less. A 6.35-mm steel ball (1.04g) at velocities between 230 and 357 ft/s dislodged 28 of 31 lenses. Metal frames retained lenses better than the zyl plastic frames, despite the fact that the zyl frames had deeper grooves and the posterior frame retention lip was longer then the anterior.

Our test setup of frames with removable lenses mounted on headforms affirms the tendency of lenses to pop through Z87 frames when the impact energy is raised slightly above the requirements of the Z87 standard.

There are at least four causes of lens dislodgment:

a. The posterior lens retention lip may be inadequate. ASNI Z80.5-1997 [19] specifies an eyewire angle that is more acute than the bevel angle on the lens (Exhibit 1). This has advantages, in that the frame will seat well on the anterior and posterior bearing surfaces of the lens bevel and not leave an unsightly gap. There also will not be stresses placed on the apex of the lens bevel, as would occur if the lens bevel angle were more acute than the frame eyewire angle, especially in metal frames. The differences in the angles allows for some error in frame and lens manufacture, assuring that the frame will bear on both sides of the lens bevel and not on the apex of the lens bevel. However, this geometry also assures that the lens does not insert all the way to the apex of the eyewire bevel and that the depth of the eyewire bevel is not equal to the posterior retention lip that actually holds the lens in place. Lens retention based on current lens and frame geometry is extremely optician-dependent. A typical sports or industrial frame for removable lenses only supports a 3-mm plano lens by 0.7 to 0.8 mm *if the lens is properly edged and inserted into the frame by the optician*. We have observed many instances of improper lens sizing and insertion of the lens into the frame causing stress on the lens (lens too large) or inadequate lens retention (lens too small).

b. The lens bevel causes a "wedge effect". When a lens with an ANSI Z80.5 bevel is impacted from the front, the lens bevel transmits forces perpendicular to the impact force—the "wedge effect". To calculate the wedge effect, we must determine the effective wedge angle (ø). We believe that the lateral forces generated by the wedge effect were a major component of the frame failure in Case 3, in which ø = 30^0. Exhibit 7, representative of the lens/frame geometry of the protector worn by Case 3, shows how ø can be extended back to a point about which there may be an axis of rotation which is parallel to the visual axis. The rotation results in a cone which, if placed in a circular spring and impacted (Exhibit 8), would cause a tension in the spring of 27.6% of the impacting force. This tension is due to the lateral forces, which are 173% of the impact force for ø = 30^0. Exhibit 9 illustrates

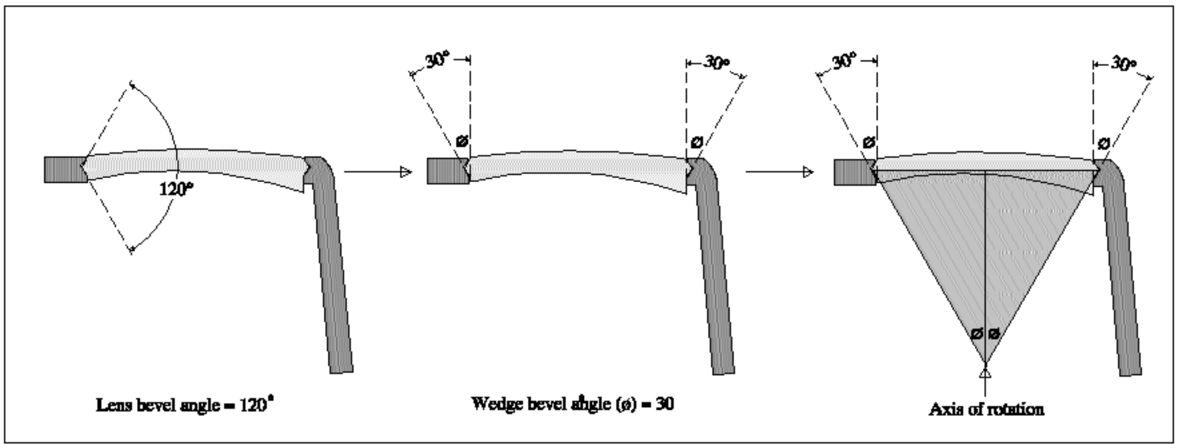
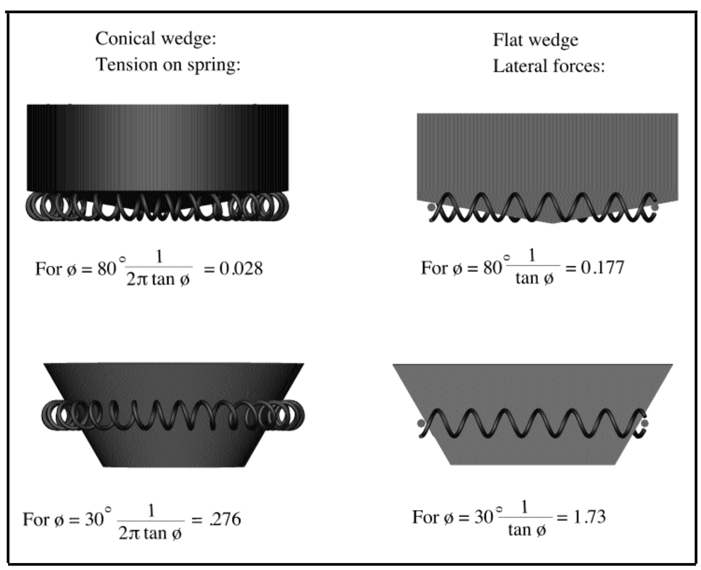


Exhibit 7. The eyewear worn by case 3. Ø can be extended back to a point about which there may be an axis of rotation, which is parallel to the visual axis. The rotation results in a cone.

Exhibit 8. A truncated cone for ø = 30^0,placed in a circular spring and impacted would cause a tension in the spring of 27.6% of the impacting force. This tension is due to the lateral forces, which are 173% of the impact force. If ø is increased to 80^0, the tension drops to 2.8% and the lateral forces to 17.7% of the impacting force. The tension to retain the lens goes to zero as the angle ø goes to =90^0 and the stresses in the frame become compressive only.



the tension required to retain the lens with varying lens bevel angles: the lateral forces decrease to zero as ø approaches 90^0. The ANSI Z80.5 posterior lens bevel angle requirements, ranging from ø =25^0 to ø = 35^0, are in the steep portion of the curve in which small decreases of ø result in far greater tension requirements for lens retention.

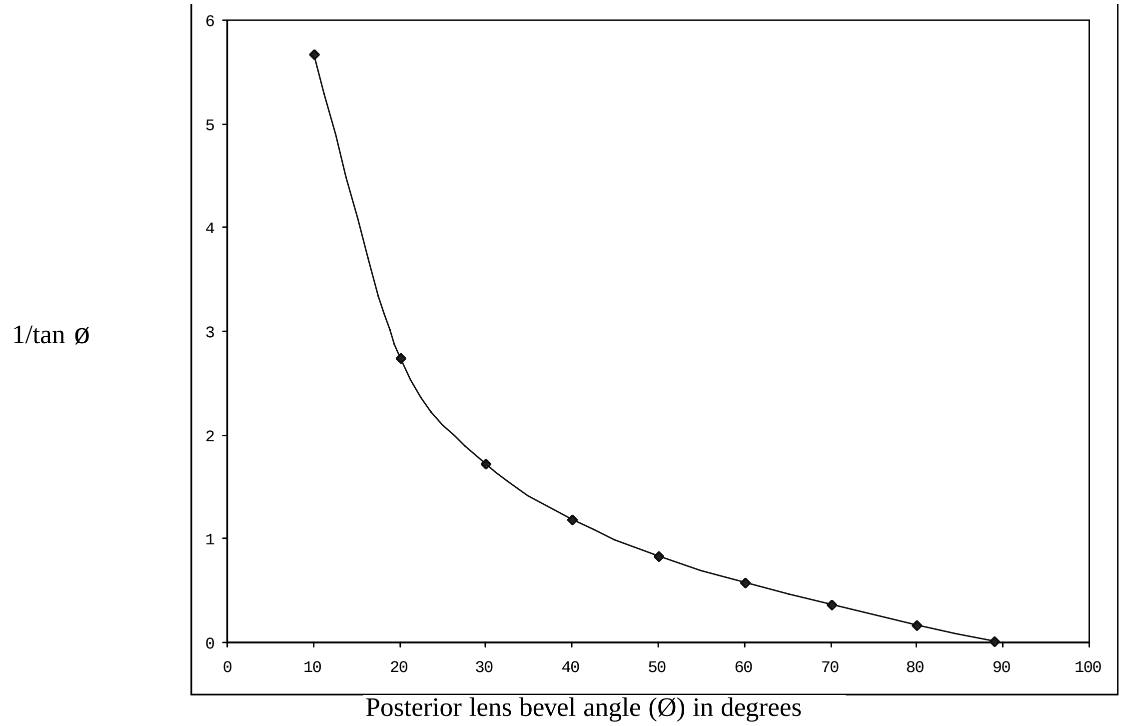


Exhibit 9. While this is not an analysis of the stresses in a real frame, it illustrates that the tension to retain the lens goes to zero as the angle goes to 90⁰ and the stresses in the frame become compressive only.

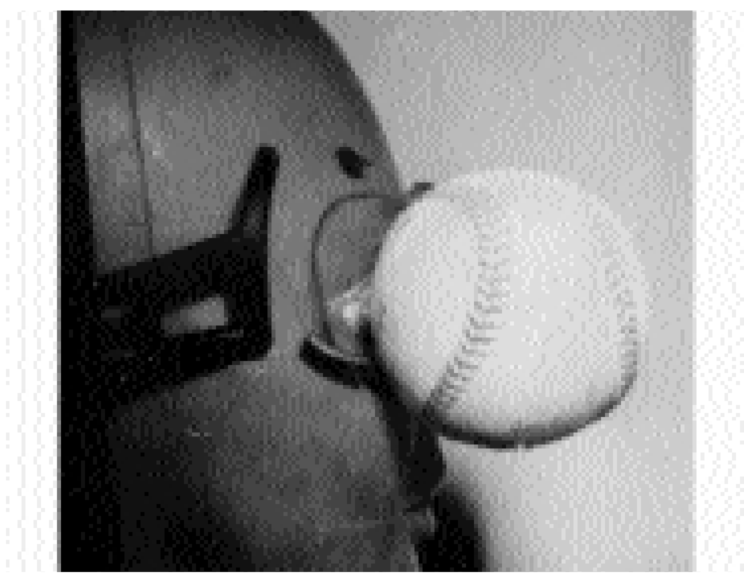


Exhibit 10. Baseball impact on sports frame. Note the effect of the lateral forces and eye contact by the displaced lens

We believe that these lateral forces transmitted to the frame by the wedge effect of the lens bevel may cause the frame to stretch or break (Exhibit 10), and that the metal frames retained lenses better than zyl plastic frames in the Johnson and Good study because the plastic frames required less energy to stretch (sufficiently to allow the lenses to pop through) than the metal frames.

Our study eliminated any stretching of the frame by using a test frame of "infinitely strong" tool steel. This "wedge effect" cause of frame failure was not addressed in our study and will require further study of lenses mounted in actual frames. Our test setup Z87 1.3 does show that, if a frame is made sufficiently strong, if the lens is stiff enough to resist bowing, and if the posterior lip is long enough, a lens can be retained with the current lens and frame specifications of Z80.5. We suspect, however, that it will be extremely difficult to construct a high-impact frame with a beveled lens, due to the lateral forces created by the wedge effect.

c. The lens oilcans. Thinner lenses were more prone to oilcanning (Exhibit 11) than thicker, stiffer lenses. This was the most common mechanism of thinner lens dislodgment. If the lens retention lip is long enough, the lens will remain in the frame, despite significant oilcanning.

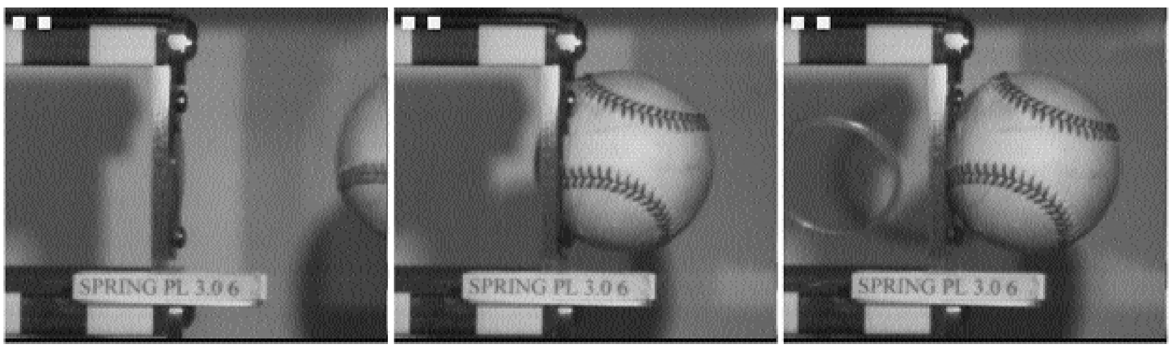


Exhibit 11. Lens dislodgment due to oilcanning.

d. The lens edge is forced through the frame by local deformations in the lens edge. Some of the thicker lenses dislodged with no apparent oilcanning, indicating that there were deformities in the lens edge that were hidden by the steel lens holder.

5. Is it true that a frame with a safety groove with the frontal edge shorter than the back will force the lens to pop out "away from the eye"? (See case 3) The zyl plastic frames tested by Johnson and Good had a safety groove with the frontal edge shorter than the back, yet the lenses popped through the back. In our study, which included safety frames that had a safety groove with the frontal edge shorter than the back, motion analysis revealed that every lens that was dislodged popped through the back of the frame towards the eye. Any manufacturer who makes a claim to the effect that lenses pop away from the eye should substantiate the claim with motion analysis and adequate test methodology to prove that the lens, in fact, pops away from the eye, and that there is no contact of the impacting object, the lens, or the frame with the eye of the headform.

6. If the JAMA straight cut lens edge with 2-mm posterior retention of a flat frame is the best, why not use that for all safety eyewear? The test object common to all of the test lenses was a baseball. If we look at baseball impacts onto -3.00 lenses, it is apparent that the JAMA design, with a 180^0 lens bevel and a 2mm retention lip on a flat lens holder, is the best lens retention system. In the JAMA tests, -3.00, 1.5mm-ct lenses were retained with baseball impacts at velocities up to 116 mph and -3.00, 3mm-ct lenses with baseball impacts up to 135 mph (the maximum capability of the test equipment).

Any single vision, non-astigmatic, straight cut lens with a 180^0 bevel will lie flat on a table if the lens is ground perfectly round with the optical and mechanical centers coincident, as were the lenses in our tests. However, lens edge thickness will vary greatly with the prescription, making it almost impossible to design a frame edge which will retain all powers of lenses cut straight with a 180^0 bevel. When lenses are ground out-of-round or have an astigmatic correction, the posterior geometries vary tremendously with lens power, diopters of astigmatism, and deviations from round. To practically fit prescription lenses in frames requires a posterior edge that is either ground parallel to the anterior lens edge —which varies with the usually spherical radius of the anterior lens surface (base curve)—or to a specific radius (base curve) which may or may not be parallel to the anterior lens surface. The 180^0 straight cut lens on a beveled frame was used in our test series to compare the lens on a beveled frame with a smaller retention lip to the JAMA series. The straight cut lens is not an option for any practical frame design.

7. Is the current lens/frame interface adequate? Possibly yes, if modified for sports and industrial situations with the possibility for high impact. The Johnson and Good study showed that the current lens/frame geometry is very susceptible to lens dislodgment if the frame is fixed at the nose bridge and temples. This study shows that the lenses are better retained when mounted on a headform, but there is significant eye contact with impact from the high-mass Z87 test and on impact with sports balls (Exhibit 12). This study also shows that if the frame is made "infinitely strong," a standard lens bevel, when tested with the Z87 500g mass and the 6.35mm steel ball, will retain the lens in a standard bevel safety frame with a 0.9mm posterior lens retention lip. However, when the energy is increased to that used in common sporting events, the lenses are poorly retained by the commonly used safety lens/frame geometry with 0.9 posterior retention lip, even if the frame is "infinitely strong."

Our Z87 1.3 test setup shows that if frames conforming to the requirements of ANSI Z80.5 are made with a deeper groove (approximately 1.5 mm), the lenses would be more resistant to displacement, provided that the frame is sufficiently strong to resist stretching or breaking from the lateral "wedge effect" forces, and the lens sufficiently stiff to resist oilcanning. However, because of the lens bevel wedge effect, the frame would have to be very resistant to stretching or cracking.

With sufficient energy, even straight cut 180^0 bevel lenses can pop through a rigidly fixed "infinitely strong" frame. In order to retain lenses subjected to high-energy impacts, with practical lens edge designs, the frame must be designed to absorb a portion of the energy, retain the lens in position, and prevent or minimize eye contact by the impacting object, the lens, or the frame itself.

There should also be the requirement of no eye contact. If we mount Z87 frames, fitted with 2.0mm polycarbonate lenses similar to those used by Johnson and Good, on a headform, the lenses are retained with the 500g low-velocity and 6.35mm high-velocity steel test objects at speeds specified in Z87, but there is contact with the eye of the headform on the high-mass test, and the protectors begin to fail with slight increase in the impact energy. It is apparent that the posterior displacement of the frame from the impact absorbs some of the energy and allows somewhat better lens retention when the frame is not fixed at the nosepiece and temples. However, the substantial contact to the eye of a headform by the lens or the frame may results in eye injury, even if the lens is retained. Lens retention alone is insufficient to measure the protectiveness of a frame mounted on a headform.

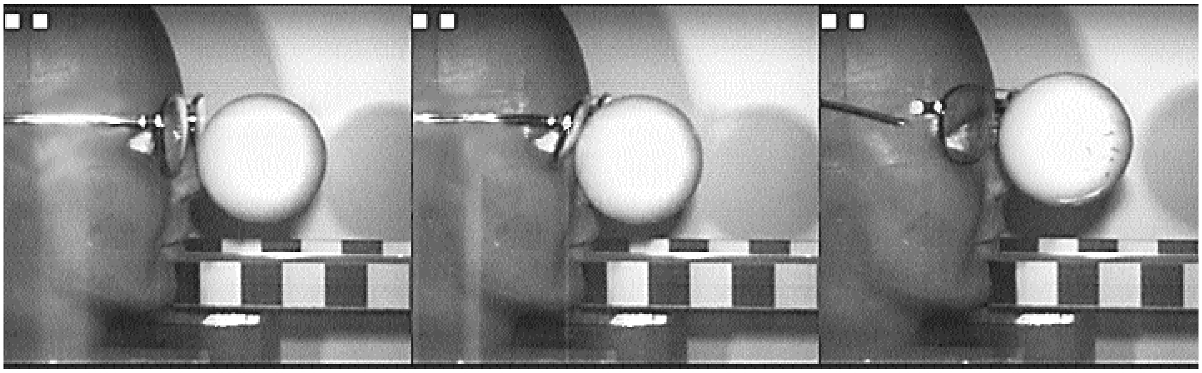


Exhibit 12. Significant eye contact because of frame failure. 3mm polycarbonate lens intact and retained in the frame. Field hockey ball at 40 mph.

8. Is there a better way to design a safety frame? Yes. We believe that a better frame/lens interface would be achieved with:

a. A 90^0 beveled lens on a flat frame for the frame/lens interface. The "gold standard" for lens retention was the JAMA test setup that had a 2mm retention lip on a flat frame. To apply this concept to a practical lens edge geometry requires a determination of the necessity for the full 2mm retention lip as well as a determination of the fillet radius needed to relieve the notch stresses caused by a 90^0 cut. This study shows that a 0.8mm fillet is sufficient to eliminate shear of the anterior lens lip. Further testing in frames on headforms may reveal that the 1.18mm retention lip may require lengthening mm to 1.5 or even 2mm—the comparison of Z87 0.9 with Z87 1.3 shows that lens retention is posterior lip dependent. Extension of the posterior lens retention 90^0 beveled lens lip

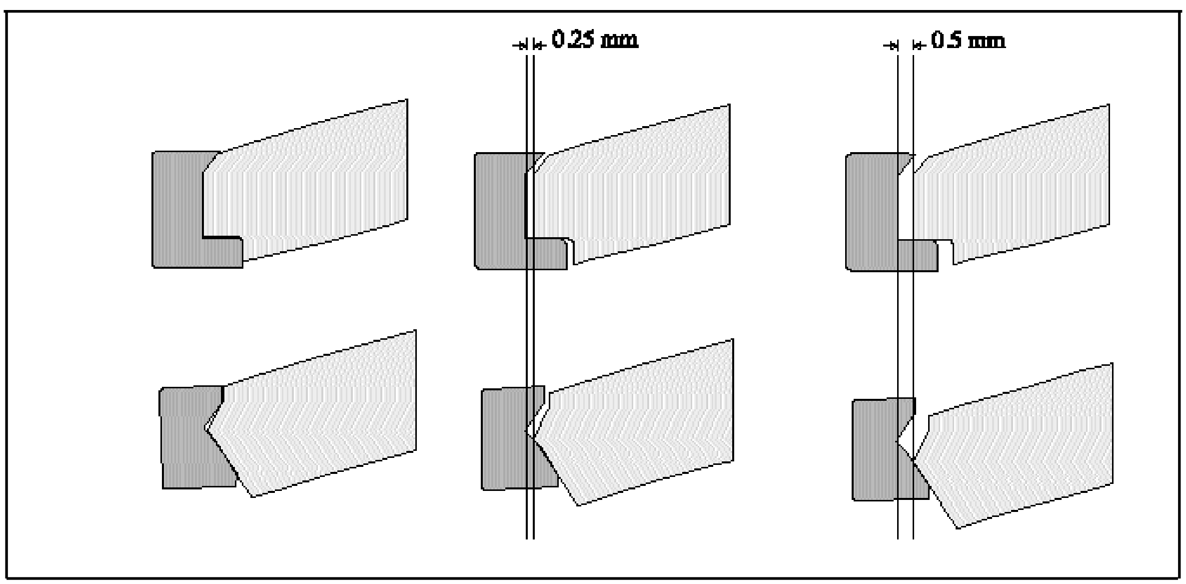


Exhibit 13. The effect of undersizing, by 0.25 and 0.5mm:
a typical Z87 industrial safety frame, 1mm groove depth, with a standard bevel, and a 90 degree lens bevel with a 1.2mm lens retention lip on a flat frame.

from the tested 1.18mm, combined with the energy absorption of a properly designed frame, should result in adequate retention.

The 90^0-beveled lens on a flat frame eliminates the lens "wedge effect." A 90^0-beveled lens on a flat frame with a longer posterior retention lip would be more "optician friendly" and forgiving of slightly undersizing the lens (Exhibit 13). We believe that a slightly undersized 90^0-beveled lens would not be as prone to dislodge as a slightly undersized beveled lens in a beveled frame.

b. The lens itself should be stiff enough to prevent eye contact as the frame "bottoms out" on the facial bones.

This puts a major responsibility for preventing eye contact on the lens, which should be sufficiently large to bridge over the orbital opening. A relatively stiff lens that bridges the orbit solves many problems, in that the frame need only hold the lens in position and have the lens itself transfer the energy to the supra and infra orbital bones. The frame should be sufficiently strong to hold the lens in position over the bones of the orbital rim, while retaining the lens. It is essential that the entire protective unit, mounted on appropriately sized headforms, with plano lenses of varying thickness, be tested to standards with impact requirements that reflect the actual impact hazard.

9. Where do we go from here? There are several potential ways to make safety eyewear that will give improved protection for spectacle wearers. An independent testing laboratory must test the protective unit with plano lenses of specified minimum thickness to an appropriate standard and must certify that all eyewear making a safety claim actually passes the standard. The mere claim by a manufacturer that eyewear is "approved for all sports" may only mean that the manufacturer has an internal unpublished standard and is worthless unless testing to an agreed-upon voluntary consensus standard by an independent laboratory substantiates the claim.

References

1. Schein OD, Hibberd PL, Shingleton BJ, Kunzweiler T, Frambach DA, Seddon JM, Fontan NL, Vinger PF. The spectrum and burden of ocular injury. Ophthalmology. 1988;95:300-305.
2. Katz J, Tielsch JM. Lifetime prevalence of ocular injuries from the Baltimore eye survey. Arch Ophthalmol. 1993;111:1564-1568.
3. Dannenberg AL, Parver LM, Brechner RJ, Khoo L. Penetrating eye injuries in the workplace. The National Eye Trauma System Registry. Arch Ophthalmol. 1992;110:843-848.
4. Fact sheeet No. OSHA-83-03. Eye protection in the workplace. U.S. Department of Labor. Program Highlights, Washington, DC. March, 1983.
5. Vinger PF. The eye and sportsmedicine. In: Duane TD, Jaeger EA, eds. Clinical ophthalmology. Philadelphia: J.B.Lippincott Company, 1994: v5, ch45,1-103.
6. American National Standard Practice for Occupational and Educational Eye and Face Protection: ANS1 Z87.1-1989. New York. American National Standards Institute, 1989.
7. Eye protectors for selected sports (racket sports, women’s lacrosse, baseball): ASTM F803-97. West Conshohocken, PA. American Society for Testing and Materials, 1997.
8. Eye and face protective equipment for hockey players: ASTM F513-95. West Conshohocken, PA. American Society for Testing and Materials, 1995.
9. High impact resistant eye protective devices for alpine skiing: ASTM F659-92. West Conshohocken, PA. American Society for Testing and Materials 1992.

10. Face guards for youth baseball ; ASTM F910-92. West Conshohocken, PA. American Society for Testing and Materials, 1992.
11. Eye protective devices for paintball sports: ASTM F1776-97. West Conshohocken, PA. American Society for Testing and Materials, 1997
12. Standard practice for paintball field operation. ASTM F1777-97. West Conshohocken, PA. American Society for Testing and Materials, 1997.
13. Head and face protective equipment for ice hockey goaltenders: ASTM F1587-96. West Conshohocken, PA. American Society for Testing and Materials, 1996.
14. Occupational Safety and health Administration, OSHA. Public law 91-596, 1970.
15. Keeney AH, Fintelmann E, Estlow B. Refractive correction and associated factors in spectacle glass injury. Arch Ophthalmol. 1972;88:2-8.
16. Vinger PF, Parver L, Alfaro DV, Woods T, Abrams BS. Shatter resistance of spectacle lenses. JAMA 1997; 277:142-144.
17. Johnson YM, Good GW. Ophthalmic lens retention in safety frames. Optometry & Vision Science 1996;78:104-108.
18. Vinger, P.F., "Baseball Eye Protection: The Effect of Impact by Major League and Reduced Injury Factor Baseball on Currently Available Eye Protectors," International Symposium on Safety in Baseball and Softball, ASTM STP 1313, Earl F. Hoerner and Francis A. Cosgrove, Eds., American Society for Testing and Materials, Philadelphia, 1996.
19. American National Standard for Ophthalmics: Requirements for ophthalmic frames: ANSI Z80.5-1997. New York, American National Standards Institute, 1997.
20. Standard method of impact test and performance requirements for baseball/softball batter's helmets, baseballs and softballs. National Operating Committee on Standards for Athletic Equipment (NOCSAE), Rhode Island, 1991.
21. Handbook of Engineering Fundamentals. OW Eshbach, ed. NY: J Wiley & Sons, 1990.
22. Red Lake Imaging. 16195 Monterey Street, Suite 108, Morgan Hill, CA 95037-5450.
23. Data Description, Inc. P.O. Box 4555, Ithaca, NY, 14852.

Acknowledgment

This work was funded, in part, by grants from: American Society of Safety Engineers Foundation, Massachusetts Lions Eye Research Fund, Essilor of America, Sporting Goods Manufacturers Association, Orcolite, Titmus, and Parmelee Foundation. Lenses were supplied and edged by Gentex, Vision Ease, and Orcolite.

We thank Eugene O'Connell, Peter Carellas, and Brian Anthony for assistance with high-speed video and motion analysis; Matt Hutcheson for statistical analysis; Martin Pernicka, Preston Fiske, Don Moodie, Stuart Morgan, and Norman Vallee, for technical assistance; and Robert Barrett for machining.

The authors, as stockholders in SprinGuard Technology Group, have a financial interest in safety lens edge geometry.