Glass Works: How Corning Created the Ultrathin, Ultrastrong Material of the Future

Source

Don Stookey knew he had botched the experiment.

One day in 1952, the Corning Glass Works chemist placed a sample of photosensitive glass inside a furnace and set the temperature to 600 degrees Celsius.

At some point during the run, a faulty controller let the temperature climb to 900 degrees C.

Expecting a melted blob of glass and a ruined furnace, Stookey opened the door to discover that, weirdly, his lithium silicate had transformed into a milky white plate.

When he tried to remove it, the sample slipped from the tongs and crashed to the floor.

Instead of shattering, it bounced. ...

The future National Inventors Hall of Fame inductee didn't know it, but he had just invented the first synthetic glass-ceramic, a material Corning would later dub Pyroceram.

Lighter than aluminum, harder than high-carbon steel, and many times stronger than regular soda-lime glass, Pyroceram eventually found its way into everything from missile nose cones to chemistry labs.

It could also be used in microwave ovens, and in 1959 Pyroceram debuted as a line of space-age serving dishes: Corningware. ...

The material was a boon to Corning's fortunes, and soon the company launched Project Muscle, a massive R&D effort to explore other ways of strengthening glass.

13 A breakthrough came when company scientists tweaked a recently developed method of reinforcing glass that involved dousing it in a bath of hot potassium salt.

14 They discovered that adding aluminum oxide to a given glass composition before the dip would result in remarkable strength and durability.

15 Scientists were soon hurling fortified tumblers off their nine-story facility and bombarding the glass, known internally as 0317, with frozen chickens.

16 It could be bent and twisted to an extraordinary degree before fracturing, and it could withstand 100,000 pounds of pressure per square inch.

17 (Normal glass can weather about 7,000.)

18 In 1962 Corning began marketing the glass as Chemcor and thought it could work for products like phone booths, prison windows, and eyeglasses. ...

19 Yet while there was plenty of initial interest, sales were slow.

20 Some companies did place small orders for products like safety eyeglasses.

21 But these were recalled for fear of the potentially explosive way the glass could break.

22 Chemcor seemed like it would make a good car windshield too, and while it did show up in a handful of Javelins, made by American Motors, most manufacturers weren't convinced that paying more for the new muscle glass was worth it – especially when the laminated stuff they'd been using since the '30s seemed to work fine. ...

23 Corning had invented an expensive upgrade nobody wanted.

24 It didn't help that crash tests found that "head deceleration was significantly higher" on the windshields

– the Chemcor might remain intact, but human skulls would not.

25 After pitches to Ford Motors and other automakers failed, Project Muscle was shut down and Chemcor was shelved in 1971.

26 It was a solution that would have to wait for the right problem to arise.

27 **From above,** Corning's headquarters in upstate New York looks like a *Space Invaders* alien: Designed by architect Kevin Roche in the early '90s, the structure fans out in staggered blocks.

28 From the ground, though, the tinted windows and extended eaves make the building look more like a glossy, futuristic Japanese palace.

29 The office of Wendell Weeks, Corning's CEO, is on the second floor, looking out onto the Chemung River.

30 It was here that Steve Jobs gave the 53-year-old Weeks a seemingly impossible task: Make millions of square feet of ultrathin, ultrastrong glass that didn't yet exist.

31 Oh, and do it in six months.

32 The story of their collaboration – including Jobs' attempt to lecture Weeks on the principles of glass and his insistence that such a feat could be accomplished – is well known.

33 How Corning actually pulled it off is not.

34 Weeks joined Corning in 1983; before assuming the top post in 2005, he oversaw both the company's television and specialty glass businesses.

35 Talk to him about glass and he describes it as something exotic and beautiful – a material whose potential is just starting to be unlocked by scientists.

36 He'll gush about its inherent touchability and authenticity, only to segue into a lecture about radio-frequency transparency.

37 "There's a sort of fundamental truth in the design value of glass," Weeks says, holding up a clear pebble of the stuff.

38 "It's like a found object; it's cool to the touch; it's smooth but has surface to it.

39 What you'd really want is for this to come alive.

40 That'd be a perfect product."

41 Weeks and Jobs shared an appreciation for design.

42 Both men obsessed over details.

43 And both gravitated toward big challenges and ideas.

44 But while Jobs was dictatorial in his management style, Weeks (like many of his predecessors at Corning) tends to encourage a degree of insubordination.

45 "The separation between myself and any of the bench scientists is nonexistent," he says.

46 "We can work in these small teams in a very relaxed way that's still hyperintense."

47 Indeed, even though it's a big company – 29,000 employees and revenue of $7.9 billion in 2011 – Corning still thinks and acts like a small one, something made easier by its relatively remote location, an annual attrition rate that hovers around 1 percent, and a vast institutional memory.

48 (Stookey, now 97, and other legends still roam the halls and labs of Sullivan Park, Corning's R&D facility.) "We're all lifers here," Weeks says, smiling.

49 "We've known each other for a long time and succeeded and failed together a number of times." ...

50 One of the first conversations between Weeks and Jobs actually had nothing to do with glass.

51 Corning scientists were toying around with microprojection technologies — specifically, better ways of using synthetic green lasers.

52 The thought was that people wouldn't want to stare at tiny cell phone screens to watch movies and TV shows, and projection seemed like a natural solution.

53 But when Weeks spoke to Jobs about it, Apple's chief called the idea dumb.

54 He did mention he was working on something better, though — a device whose entire surface was a display.

55 It was called the iPhone. ...

56 Jobs may have dismissed green lasers, but they represented the kind of innovation for innovation's sake that defines Corning.

57 So strong is this reverence for experimentation that the company regularly invests a healthy 10 percent of its revenue in R&D.

58 And that's in good times *and* in bad.

59 When the telecom bubble burst in 2000 and cratering fiber-optic prices sent Corning's stock from $100 to $1.50 per share by 2002, its CEO at the time reassured scientists that not only was Corning still about research but that R&D would be the path back to prosperity. ...

60 “They’re one of the very few technology-based firms that have been able to reinvent themselves on a regular basis,” says Rebecca Henderson, a professor at Harvard Business School who has studied Corning’s history of innovation.

61 “That’s so easy to say, and it is so hard to do.”

62 Part of that success lies in the company’s ability not only to develop new technologies but to figure out how to make them on a massive scale.

63 Still, even when Corning succeeds at both, it can often take the manufacturer decades to find a suitable – and profitable enough – market for its innovations.

64 As Henderson notes, innovation at Corning is largely about being willing and able to take failed ideas and apply them elsewhere. ...

65 The idea to dust off the Chemcor samples actually cropped up in 2005, before Apple had even entered the picture.

66 Motorola had recently released the Razr V3, a flip phone that featured a glass screen in lieu of the typical high-impact plastic.

67 Corning formed a small group to examine whether an 0317-like glass could be revived and applied to devices like cell phones and watches.

68 The old Chemcor samples were as thick as 4 millimeters.

69 But maybe they could be made thinner.

70 After some market research, executives believed the company could even earn a little money off this specialty product.

71 The project was codenamed Gorilla Glass. ...

72 By the time the call from Jobs came in February 2007, these initial forays hadn't gotten very far.

73 Apple was suddenly demanding massive amounts of a 1.3-mm, chemically strengthened glass — something that had never been created, much less manufactured, before.

74 Could Chemcor, which had never been mass-produced, be married to a process that would yield such scale?

75 Could a glass tailored for applications like car windshields be made ultrathin and still retain its strength?

76 Would the chemical strengthening process even work effectively on such a glass?

77 No one knew.

78 So Weeks did what any CEO with a penchant for risk-taking would do.

79 He said yes. ,,,

80 **For a material** that's so familiar as to be practically invisible, modern industrial glass is formidably complex.

81 Standard soda-lime glass works fine for bottles and lightbulbs but is terrible for other applications, because it can shatter into sharp pieces.

82 Borosilicate glass like Pyrex may be great at resisting thermal shock, but it takes a lot of energy to melt it.

83 At the same time, there are really only two ways to produce flat glass on a large scale, something called fusion draw and the float glass process, in which molten glass is poured onto a bed of molten tin.

84 One challenge a glass company faces is matching a composition, with all its desired traits, to the manufacturing process.

85 It's one thing to devise a formula.

86 It's another to manufacture a product out of it. ⁂

87 Regardless of composition, the main ingredient in almost all glass is silicon dioxide (aka sand).

88 Because it has such a high melting point (1,720 degrees C), other chemicals, like sodium oxide, are used to lower the melting temperature of the mixture, making it easier to work with and cheaper to produce.

89 Many of these chemicals also happen to imbue glass with specific properties, such as resistance to x-rays, tolerance for high temperatures, or the ability to refract light and disperse colors.

90 Problems arise, though, when the composition is changed; the slightest tweak can result in a drastically different material.

91 Throwing in a dense element like barium or lanthanum, for example, will decrease the melting temperature, but you risk not getting a homogeneous mixture.

92 And maxing out the overall strength of a glass means you're also making that glass more likely to fracture violently when it *does* fail.

93 Glass is a material ruled by trade-offs.

94 This is why compositions, particularly those that are fine-tuned for a specific manufacturing process, are fiercely guarded secrets. ⁂

95 One of the pivotal steps in glassmaking is the cooling.

96 In large-scale manufacturing of standard glass, it's essential for the material to cool gradually and uniformly in order to minimize the internal stresses that would otherwise make it easier to break.

97 This is called annealing.

98 The goal with tempered glass, however, is to *add* stress between the inner and outer layer of the material.

99 This, paradoxically, can make the glass stronger: Heat a sheet of glass until it softens, then rapidly cool, or quench, its outer surfaces.

100 This outside shell quickly contracts while the inside remains molten.

101 As the center of the glass cools, it tries to contract, pulling on the outer shell.

102 A zone of tension forms in the center, while the outer surfaces are even more tightly compressed.

103 Tempered glass will eventually break if you chip through this toughened outer compressive layer into the zone of tension.

104 But even thermal tempering has its limits.

105 The amount of strengthening you can achieve is dependent on how much the glass contracts upon cooling, and most compositions will shrink only modestly. ‟

106 The interplay between compression and tension is best demonstrated by something called a Prince Rupert's drop.

107 Formed by dripping globs of molten glass into ice water, the quickly cooled and compressed heads of these tadpole-shaped droplets can withstand massive amounts of punishment, including repeated hammer blows.

108 The thin glass at the end of the tail is more vulnerable, however, and if you break it the fracture will propagate through the drop at 2,000 miles per hour, releasing the inner tension.

109 Violently.

110 In some cases, a Prince Rupert's drop can explode with such force that it will actually emit a flash of light. ‟

111 Chemical strengthening, the method of fortifying glass developed in the '60s, creates a compressive layer too, through something called ion exchange.

112 Aluminosilicate compositions like Gorilla Glass contain silicon dioxide, aluminum, magnesium, and sodium.

113 When the glass is dipped in a hot bath of molten potassium salt, it heats up and expands.

114 Both sodium and potassium are in the same column on the periodic table of elements, which means they behave similarly.

115 The heat from the bath increases the migration of the sodium ions out of the glass, and the similar potassium ions easily float in and take their place.

116 But because potassium ions are larger than sodium, they get packed into the space more tightly.

117 (Imagine taking a garage full of Fiat 500s and replacing most of them with Chevy Suburbans.)

118 As the glass cools, they get squeezed together in this now-cramped space, and a layer of compressive stress on the surface of the glass is formed.

119 (Corning ensures an even ion exchange by regulating factors like heat and time.)

120 Compared with thermally strengthened glass, the "stuffing" or "crowding" effect in chemically strengthened glass results in higher surface compression (making it up to four times as strong), and it can be done to glass of any thickness or shape.

121 **By the end of March,** Corning was closing in on its formula.

122 But the company also needed to manufacture it.

123 Inventing a new manufacturing process was out of the question, as that could take years.

124 To meet Apple's deadline, two of Corning's compositional scientists, Adam Ellison and Matt Dejneka, were tasked with figuring out how to adapt and troubleshoot a process the company was already using.

125 They needed something capable of spitting out massive quantities of thin, pristine glass in a matter of weeks. ...

126 There was really only one choice: fusion draw.

127 In this technique, molten glass is poured from a tank into a trough called an isopipe.

128 The glass overflows on each side, then the two streams rejoin under the isopipe.

129 It's drawn down at a prescribed rate by rollers to form a continuous sheet.

130 The faster it's drawn, the thinner the glass. ...

131 Corning's one fusion-capable factory in the US is in Harrodsburg, Kentucky.

132 In early 2007, that plant's seven 15-foot-tall tanks were going full blast, each churning out more than 1,000 pounds per hour of sold-out LCD glass for TV panels.

133 One tank could meet Apple's initial request.

134 But first the old Chemcor compositions had to be reformulated.

135 The glass not only needed to be 1.3 mm now, it also had to have better visual characteristics than, say, a pane in a telephone booth.

136 Ellison and his team had six weeks to nail it.

137 To be compatible with the fusion process, the glass also needed to be extra stretchy, like chewing gum, at a fairly low temperature.

138 The problem was, anything you do to increase a glass's gooeyness also tends to make it substantially more difficult to melt.

139 By simultaneously altering seven individual parts of the composition — including changing the levels of several oxides and adding one new secret ingredient — the compositional scientists found they were able to ramp up the viscosity while also producing a finely tuned glass capable of higher compressive stress and faster ion exchange.

140 The tank started in May 2007.

141 By June, it had produced enough Gorilla Glass to cover seven football fields.

142 In just five years, Gorilla Glass has gone from a material to an aesthetic — a seamless partition that separates our physical selves from the digital incarnations we carry in our pockets.

143 We touch the outer layer and our body closes the circuit between an electrode beneath the screen and its neighbor, transforming motion into data.

144 It's now featured on more than 750 products and 33 brands worldwide, including notebooks, tablets, smartphones, and Tvs. If you regularly touch, swipe, or caress a gadget, chances are you've interacted with Gorilla.

145 Corning's revenue from the glass has skyrocketed, from $20 million in 2007 to $700 million in 2011.

146 And there are other uses beyond touchscreens.

147 At this year's London Design Festival, Eckersley O'Callaghan — the design firm responsible for some of Apple's most iconic stores — unveiled a serpentine-like glass sculpture made entirely from Gorilla Glass.

148 It may even end up on windshields again: The company is in talks to install it in future sports car models.

149 Today, two yellow robotic arms grab 5-foot-square panels of Gorilla Glass with special residue-limiting suction cups and place them in wooden crates.

150 From Harrodsburg, these crates are trucked to Louisville and loaded on a westbound train.

151 Once they hit the coast, the sheets get loaded onto freight ships for their eventual date at one of Corning's "finisher" facilities in China, where they get their molten potassium baths and are cut into touchable rectangles.

152 Of course, for all its magical properties, a quick scan of the Internet will reveal that Gorilla Glass does fail, sometimes spectacularly so.

153 It breaks when phones are dropped, it spiders if they bend, it cracks when they're sat on.

154 Gorilla Glass is, after all, glass.

155 Which is why a small team at Corning spends a good portion of the day smashing the hell out of the stuff.

156 "We call this a Norwegian hammer," says Jaymin Amin, pulling a metal cylinder out of a wooden box.

157 The tool is usually wielded by aircraft engineers to test the sturdiness of a plane's aluminum fuselage.

158 But Amin, who oversees all new glass development in the Gorilla family, pulls back the spring-loaded impact hammer and releases 2 joules of impact energy onto a 1-mm-thick piece of glass, enough to put a big dent in a block of wood.

159 Nothing happens.

160 The success of Gorilla Glass presents some unique challenges for Corning.

161 This is the first time the company has faced the demands of such rapid iteration: Each time a new version of the glass is released, the way it performs in the field has to be monitored for reliability and robustness.

162 To that end, Amin's team collects hundreds of shattered Gorilla Glass phones.

163 "Almost all breakage, whether it's big or small, begins at one spot," says senior research scientist Kevin Reiman, pointing to a nearly invisible chip on an HTC Wildfire, one of a handful of crunched phones on the table in front of him.

164 Once you actually locate that spot, you can start to measure the crack to get an idea of how the tension was applied to the glass; if you can reproduce a break, you can study how it propagated and attempt to prevent it, either compositionally or through chemical strengthening. ‟

165 Armed with this information, the rest of the group jumps in to re-create that precise kind of failure over and over.

166 They use lever presses; drop testers with granite, concrete, and asphalt surfaces; free gravity ball drops; and various industrial-looking torture devices armed with an arsenal of diamond tips.

167 There's even a high-speed camera capable of filming at 1 million frames per second to study flexure and flaw propagation. ‟

168 All this destruction and controlled mayhem has paid off.

169 Compared with the first version of the glass, Gorilla Glass 2 is 20 percent stronger (a third version is due out early next year).

170 The Corning composition scientists have accomplished this by pushing the compressive stress to its limit – they

were being conservative with the first version of Gorilla — while managing to avoid the explosive breakage that can come with that increase.

171 Still, glass is a brittle material.

172 And while brittle materials tend to be extremely strong under compression, they're also extremely weak under tension: If you bend them, they can break.

173 The key to Gorilla Glass is that the compression layer keeps cracks from propagating through the material and catastrophically letting tension take over.

174 Drop a phone once and the screen may not fracture, but you may cause enough damage (even a microscopic nick) to critically sap its subsequent strength.

175 The next drop, even if it isn't as severe, may be fatal.

176 It's one of the inevitable consequences of working with a material that is all about trade-offs, all about trying to create a perfectly imperceptible material. ,,,

177 **Back at the Harrodsburg** plant, a man wearing a black Gorilla Glass T-shirt is guiding a 100-micron-thick sheet of glass (about the thickness of aluminum foil) through a series of rollers.

178 The machine looks like a printing press, and appropriately, the glass that comes off it bends and flexes like a giant glimmering sheet of transparent paper.

179 This remarkably thin, rollable material is called Willow.

180 Unlike Gorilla Glass, which is meant to be used as armor, Willow is more like a raincoat.

181 It's durable and light, and it has a lot of potential.

182 Corning imagines it will facilitate flexible smartphone designs and uber-thin, roll-up OLED displays.

183 An energy company could also use Willow for flexible solar cells.

184 Corning even envisions ebooks with glass pages. ...

185 Eventually, Willow will ship out on huge spools, like movie reels, each holding up to 500 feet of glass.

186 That is, once someone places an order.

187 For now, rolls of glass sit on the Harrodsburg factory floor, a solution waiting for the right problem to arise.