

duty bags to commercial and industrial users, a right the company had retained.

The success of Ziploc bags naturally attracted rival brands, which employed improvements on the basic design to secure separate patents. As with the evolution of all artifacts, arguments for these new patents rested upon finding fault with existing patents. Ironically after reclosable bags became commonplace in the kitchen and workshop, it was not opening them but closing them properly that became the focus of manufacturers and users alike.

But not all potential competitors looked for new patents as a means of entering the market. Manufacturers in Taiwan and other Far East countries, in particular, totally disregarded the patents that Ausnit and Minigrip had so systematically acquired in order to protect their investment. Plastic bags from Taiwan, for example, produced with inexpensive labor and not having to recover the research and development or patent licensing costs normally associated with a new product, could be sold for a fraction of the cost of the Minigrip product. In such cases of unfair trade, a company can appeal to the International Trade Council Court, which Minigrip did. Such appeals are seldom upheld, but in this case an Exclusion Order was issued by the Court which essentially banned bags of foreign competitors that infringed on the patents held by Minigrip.

The stories of the original zipper, Velcro, the plastic zipper, and the resealable plastic bag derived from it each span many years and show how long and arduous the development of a conceptual design or a patent idea can be. These case studies also demonstrate how the success of one product leads to the conception and development of many derivative ideas, which in turn lead to others.

5

ALUMINUM CANS AND FAILURE

An idea that unifies all of engineering is the concept of failure. From the simplest paper clips to the finest pencil leads to the smoothest operating zippers, inventions are successful only to the extent that their creators properly anticipate how a device can fail to perform as intended. Virtually every calculation that an engineer performs in the development of computers and airplanes, or telescopes and fax machines, is a failure calculation. In analyzing the cantilever beam, even Galileo began by making assumptions about how it would break or fail. Today, in designing a cantilever bridge, the engineer must have an understanding of how much load the individual steel members can safely carry before they pull apart or buckle and how much deflection can be allowed in the center of the bridge.

Such considerations, made explicit at the outset, are known as failure criteria, and they provide limits that cannot be exceeded as the design develops, whether the artifact is a bridge, a building, or a beverage can. As the engineer calculates the forces and deflections of a trial design, each resulting numerical calculation takes on meaning and becomes acceptable only in comparison to failure criteria, which may have been determined by careful laboratory experiments on the materials and components in question. While most of our discussion up to this point has been couched in terms of the analysis of force and strength, form and function, similar remarks apply to problems involving other properties and criteria such as heat transfer calculations and the melting point of materials, or voltage and current calculations and their safe values in electrical conductors.

What distinguishes the engineer from the technician is largely the ability to formulate and carry out the detailed calculations of forces and deflections, concentrations and flows, voltages and currents, that are required to test a proposed design on paper with regard to failure criteria.

The ability to calculate is the ability to predict the performance of a design before it is built and tested. By understanding how and why a proposed design can fail, and by being able to calculate the quantities needed to assess whether failure conditions prevail, the engineer is able to test a design on the drawingboard or on the computer screen before any steel is erected, any valve is opened, or any switch is thrown. Calculations that indicate failure conditions in the design enable the engineer to modify and remodel the design until it is ready to be realized.

Failure manifests itself differently in different branches of engineering. In environmental engineering, for example, where limiting conditions may be expressed in parts of pollutant per billion parts of water, an environmental engineer needs to know how to calculate the amount of a contaminant that might seep from a proposed hazardous-waste disposal site into the soil near a source of groundwater, and then compare this result to the criteria set by federal regulations. Some problems of engineering design do not lend themselves so much to analytical calculations as to trial-and-error or to build-and-measure techniques.

Sometimes engineers test their ideas by simply imagining scenarios of use and behavior that might lead to the failure of a product and then trying out the product under those conditions. In the design of computer programs, for example, the software is first "alpha tested" by its designers and then "beta tested" by real users to uncover the bugs might have been inadvertently introduced during design or modification, and to discover how the program might fail to perform as intended. Whatever the method used to test a design, obviating failure is always the underlying principle.

Failure can take nontechnical forms. A design can be considered a failure if it is environmentally unsound or aesthetically unsatisfying. Such criteria ought to be taken into account from the beginning of the design phase, just as the strength of materials is. Often, however, technical details dominate the early stages of a design, when an engineer is trying to establish whether a particular idea is physically feasible.

In order to explore in more detail the role of failure in successful engineering design, let us consider something a bit more complicated than a paper clip or a pencil but still less massive than a bridge or a water supply system, and more tangible than the flow of electrons through a wire or a computer chip. All of us are likely to have held an aluminum beverage can in our hand at one time or another, and so we all may be assumed to have at least a passing familiarity with this now- ubiquitous artifact. The aluminum can may be described as a pressure vessel when it contains a

carbonated beverage (and even more so when it has been dropped or shaken up), and in this regard the lowly can has to be designed as carefully against accidental failure by explosion as does a steam boiler or a scuba diving tank. The successful design of an aluminum can depends on understanding how it can fail to contain its contents and on obviating the possibility that it will fail before it is supposed to. Carbonated beverage cans are made safe and reliable by using enough material in the proper configuration to keep the intensity of force within bounds of strength and to keep the cans from bulging out in the wrong places. But engineering also has to a lot to do with economics, and the object in designing and manufacturing something made by the billions, like beverage cans, is to make them extremely safe and reliable while at the same time costing as little as possible. A too-expensive beverage can will fail to survive the competition. While this may be considered a nontechnical failure mode, it is a failure mode nonetheless.

THE ALUMINUM BEVERAGE CAN

The earliest food and beverage cans were made of iron and were often as heavy as the food they contained. Moreover, their robust construction made opening them a major effort—some of the first iron cans even had instructions for opening that involved the use of a hammer and chisel. With the development of stronger steel, cans could be made thinner and thus lighter, but still they were difficult to open, and therefore specialized can openers were invented to make the task easier. Aluminum—because it was more expensive than steel—could not compete as a material for food cans, which had to be strong enough to resist being dented too easily. But with beverage containers it was a different story. Because soft drinks and beer pressurize a can, they provide some of its stiffness and make a thinner (and cheaper) can wall possible. On the other hand, the contents under pressure in turn requires the can wall to be strong enough to resist being split open just by the force of its contents.

Since aluminum is generally a much more ductile material than steel, it can be formed into containers in more direct and effective ways. Steel cans were long made by bending a flat sheet into a hollow cylinder, joining it along its seam, and adding top and bottom, a multistep, multipart process. By contrast, the entire seamless bottom and sides of an aluminum can could be formed from a single disk of metal (see Fig. 5.1), with only a top to be added after the can was filled with its contents. This formability of aluminum gave it a clear advantage in making cans by the billions.

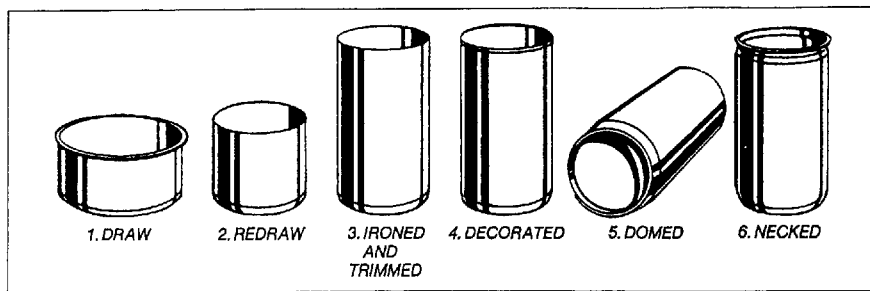


FIGURE 5.1 Steps in forming an aluminum can body

It is relatively easy to calculate how thick the aluminum must be to contain the pressure of the beverage and to take advantage of the pressure as it works to stiffen the thin-walled can against being crushed or dented. But the pressure would also tend to balloon out the flat bottom of an aluminum can, preventing it from sitting flat on a shelf or table. Thus, the characteristic inwardly dished bottom was developed, to act somewhat like an arch dam against the pressure while allowing the can to sit flat and stable on its rim. Were it not for this and other of its various structural features, the aluminum can would fail to be a very useful innovation.

The first aluminum cans were opened in conventional ways, which usually meant with a pointed can opener known as a church key. When this once-indispensable implement was first introduced, steel beer cans came with illustrated directions for its use printed on their labels. By the time aluminum cans were introduced, there was no need for such directions, and using the common opener was not considered especially inconvenient, since people had long become accustomed to the two-step process: First, a triangular-shaped hole was punched with the lever-opener in the can top, and then the whole can was rotated 180° about its cylindrical axis so that a second hole could be punched diametrically opposite the first. The contents of the can could then be poured or drunk easily from one hole, while the other allowed air to enter the can and displace the liquid, thus providing a more steady flow without spilling any of the contents. The two-step process soon had become such a familiar one to can users that they hardly gave it a second thought, and few probably realized it could be improved upon.

However, the necessity of using a church key did present a problem to at least one thirsty individual when a can opener was nowhere to be found, and little annoyances and predicaments such as this are what catch the

attention of inventors and clever engineers. One evening, while Ernal Frazee, of Dayton, Ohio, was reflecting on having found himself earlier that day without a can opener while on a picnic, he set out to devise a self-opening can. Though many may have realized how convenient it would be to do away with can openers, Frazee was in a position to do something definitive about the problem because of his knowledge of metal forming and scoring. He came up with the idea for the now-familiar aluminum tab-top or pop-top can in an evening and perfected it shortly thereafter (see Fig. 5.2).

Although much of engineering has to do with avoiding failure at almost any cost, the development of a self-opening aluminum can top presents an interesting example of balancing the competing aims of preventing and encouraging failure. Clearly, we would not want a beverage can to pop open spontaneously or too easily, and so the pop-top must be a relatively robust design. On the other hand, we do not want to have to exert undue force to open the can when we are thirsty. Scoring the can top just the right amount leaves enough strength to contain the pressure while at the same time providing a preferred site for the metal to fail (that is, tear open) when desired. The tab attached to the top of a pop-top can effectively serves as a small lever (somewhat akin to a little church key) to magnify the force of the fingers and cause the top to fail in a controlled way. However, because the contents are under pressure, the process is complicated.

In Frazee's early designs, the tab was riveted to the can top, and the rivet served as the lever's fulcrum. In some early designs, the rivet was a source of leaks. In others, the rivet was too easily pulled out of the top, thus leaving the thirsty consumer scurrying to find a church key to open the can in the conventional way. In other cases, when the lever was pushed into the can top to break the pressure seal, the rush of pressure was liable to make the top fly off and threaten the well-being of the would-be drinker. Such failures of the device to work properly led inventors and engineers like Frazee to improve incrementally the pop-top until it was so reliable and operated with so few surprises that it began to be taken for granted.

One engineering professor uses the aluminum beverage can in a very dramatic experiment to demonstrate the complexity of failure modes that engineers often face in their pursuit of fool-proof designs. He places an unopened can inside a large plastic Ziploc bag and, to be doubly sure, for reasons that will be apparent, encloses the can and bag in a second Ziploc bag. He then places the can between heavy rings on the platform

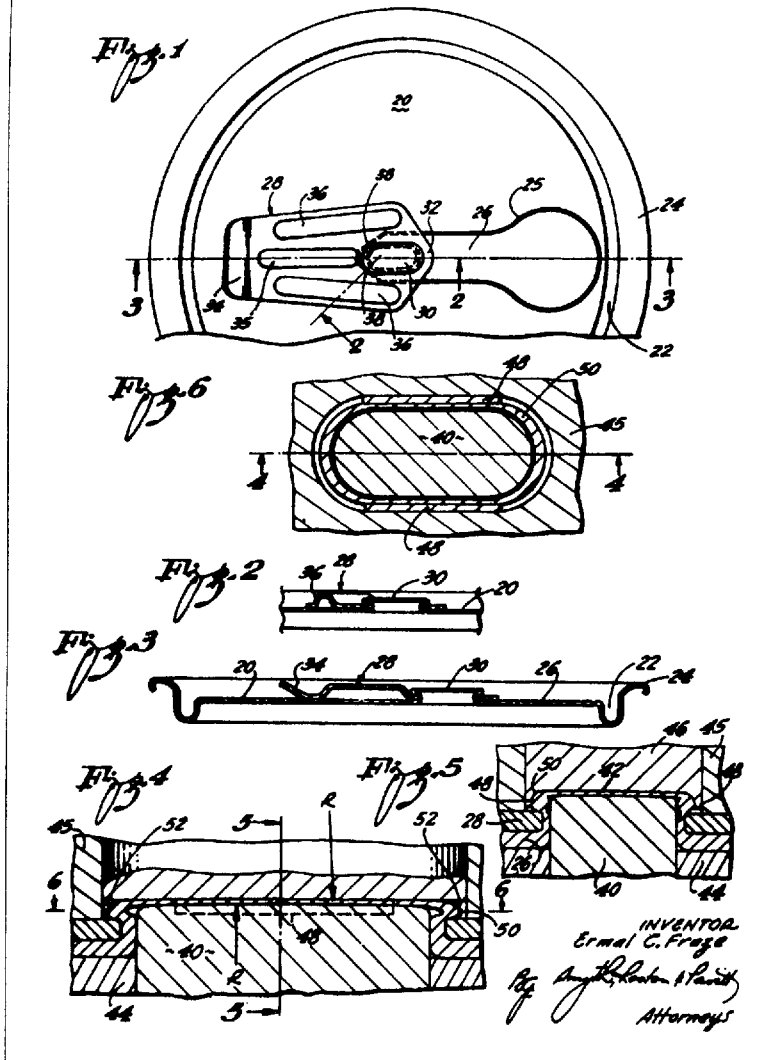


FIGURE 5.2 Patent for an early design of an easy opening can with removable tab top

and moveable head of the kind of testing machine usually employed to crush concrete samples to determine their (failure) strength, and the kind that David Letterman used on his old *Late Night* show to crush everything from light bulbs to watermelons.

In the aluminum-can engineering experiment, the rings bear on the rims of the can so that the machine's force does not bear directly on the center of either the top or bottom of the can, which can be taken out of the machine at various stages during the test to be inspected for damage. Before turning the machine on to begin the slow but deliberate crushing of the can between the powerful faces of the machine, the students are asked how they think the can is going to behave. In other words, how is the can going to fail? The variety of answers that result demonstrates how much more complicated a structure the aluminum can is than a cantilever beam. Whereas Galileo was faced with the relatively easy but, in his time, far from trivial problem of figuring out how the cantilever failed at the wall, there was no doubt about where it would fail.

In the case of the aluminum can in the testing machine, however, there are many conceivable ways in which failure can occur, and students usually have little trouble coming up with a goodly list. Furthermore, different failure modes can develop as the test progresses. Among the more obvious possibilities are: (1) the pressure of the compressed liquid splits the can's sides open, (2) the compression of the top causes the stepped neck to be pushed down into the can, (3) the can's sides wrinkle the way they do in an empty can, (4) the can's bottom pops out to accommodate the increased pressure, (5) the can's bottom splits open, (6) the can's top arches to accommodate the pressure, (7) the rivet in the pop-top is ejected or split open, acting like a pressure relief valve, (8) the top cracks open where it is scored, (9) the can begins to leak around the rim where the top joins the sides. Different styles of can are likely to exhibit different failure modes in different sequences and at different load levels, and the plastic bags themselves may fail in their own way, giving the onlookers a sticky shower. (To avoid such surprises, it is best also to surround the can and bags with a heavy plexiglass cylindrical shell.)

Whatever happens to a can in a testing machine, it is clear that the possibilities of failure are multifarious and generally beyond deterministic calculation. That is not to say that aluminum beverage can manufacturers and others do not consider such things. Among the losers as aluminum cans have become widely accepted has been the steel beverage can (see Fig. 5.3), and the steel can industry has long been trying to regain its

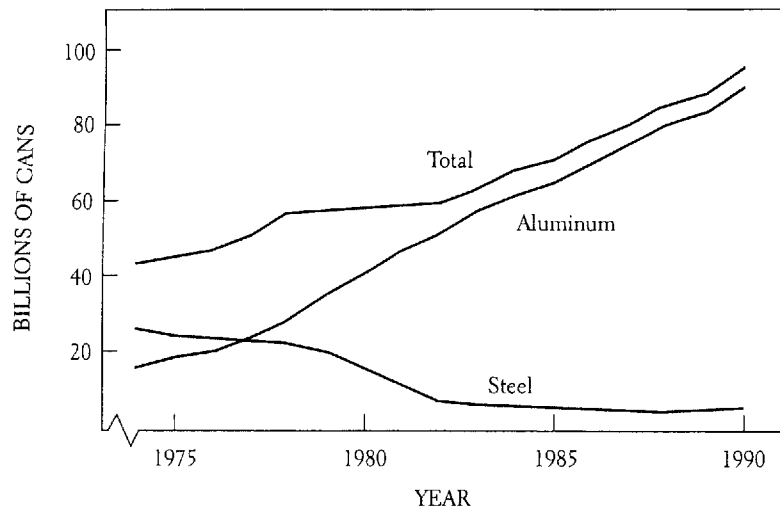


FIGURE 5.3 Growth of aluminum beverage cans at the expense of steel cans

once-dominant position. For years, research and development has been conducted to come up with a competitive steel can, and among the most vexing of problems has been how to design a steel pop-top that does not leave a sharp or jagged edge to cut the drinker's lips. For a while, steel can bodies were fitted with aluminum pop-tops, but this complicated recycling efforts.

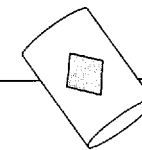
By 1993 steel cans were being made, like aluminum ones, in a drawing process that produced walls as thin as 0.0025 inches, which is less than the thickness of a piece of copier paper. Even with such thin walls, the "column load strength," or the force it would take to crush a full can by standing on it, was maintained at 340 pounds, and the steel can's "dome reversal strength," or the pressure it would take to pop out the bottom, was held at 100 pounds per square inch (psi). Even with such advances, the approximately 3 billion steel beverage cans shipped annually amounted to only a small percentage of the 100 billion total beverage cans, about 97 percent of which were aluminum, made in the United States.

Calculations employed in the design of beverage cans, or of engineering systems even more complicated, provide quantitative starting points for assessing if failure criteria are met, and guidance for changes in response to unacceptable behavior. For example, knowing the highest

THIS, BUD, 'S FOR YOU

Some years ago, in a popular commercial on television, a fellow smashed a beer can against his forehead. Did it hurt? Was the can closed or open, and would that make a difference? (This question requires only a theoretical answer. Do not attempt to investigate through experimental means.)

Although aluminum beverage cans must be designed primarily to withstand the internal pressure of their contents, most are designed to be strong enough (before being opened) to support a good-sized person standing on them. Is this behavior something that happens frequently in fraternity houses and such places, or are there other reasons for this design criterion?



pressure the contents are likely ever to be under, one could calculate the thinnest aluminum wall that could contain such pressure. To make a can thinner would not be a very likely place to start. But the thinnest possible can that could contain the pressure might not be acceptable, for it might not support enough vertical load to allow cases of cans to be stacked for shipment or storage. Further, there are other failure modes (such as those in the above list) and other considerations that relate to the use of the can when it has been opened and the pressure has been released.

Because an opened (and thus unpressurized) aluminum can must be sufficiently rigid to stand up on a table and not be crushed in the hand that lifts it to the lips, there is a limit to how thin it can be. We all know that cans are already almost at their practical limits of thinness because we must be careful not to hold them too tightly lest their sides buckle in and the can becomes unstable in our grasp. While such a consideration might not be strictly a question of strength or safety, it is clearly a limiting condition for the can to function comfortably in use, and it certainly constitutes another failure criterion that must be taken into account in the design.

An analogy can be found in building design. Much taller and more slender skyscrapers than presently exist could easily be built economically without any danger of collapsing, but with height and slenderness come flexibility, and this becomes the limiting factor on what can be practically achieved. The top floors of too flexible a skyscraper could sway several feet in just a gentle wind, and this can cause coffee to slosh around in mugs, elevators to bang and bind in shafts, and office workers to feel queasy at their desks. While no dramatic or catastrophic failure is occurring in such a situation, the structure has clearly failed to provide psychologically or physiologically effective office space for its users. From the total engineering perspective, and the economic or use value of the structure, this could be as much a failure as if the building had to be abandoned for structural reasons.

ENVIRONMENTAL FAILURE

By the early 1970s it became evident that the removable tab-tops of beverage cans were creating an environmental crisis. The small, sharp, ringed tabs of aluminum were being disposed of by the billions on roadsides, in parks, and on beaches. Besides creating a litter problem, they were presenting physical dangers where recreation seekers went barefoot

and where small children swallowed things not intended to be ingested. Especially on beaches, where the tab-tops were often too small to be caught in the standard beachcomber's rake, there was many a foot cut on an unseen tab lying just below the surface of the sand. Conscientious drinkers began to drop the tab into the can from which they were drinking, only to swallow it with a mouthful of beverage. In short, what began as a technological godsend for drinkers without church keys ended up as a devil of a problem.

This was a clear failure of the pop-top can to be a benign beverage container, and it sent inventors and engineers back to the drawingboard. A plethora of solutions resulted, including a can developed by the Adolph Coors Company in which a small aluminum button was first pushed into the top to break the pressure seal and then a second, larger button was pushed in to provide a drinking hole. Both buttons remained hinged to the can top and so created neither a litter problem nor a hazard. However, in order for the can top to function properly (actually, to fail in the proper mode at the proper time), the little button had to be small enough so that the total force of the pressure acting on it did not require too great a push to break the seal. But the smaller the button, the sharper it felt to the finger pushing it, and so opening a can could be an uncomfortable process. Such annoying details, coupled with the fact that two separate buttons had to be pressed to get at the beverage, as if one were using a church key again, led other inventors to look for alternatives. What evolved is the now familiar pop-top, in which the manipulation of a lever breaks the pressure seal, opens an orifice, and folds back (but does not break off) a flap of aluminum.

The stay-on tab was the invention of Daniel F. Cudzik, of Richmond, Virginia, who worked for the Reynolds Metals Company. In 1976 he was awarded a United States Patent (Fig. 5.4) for his invention of an easy-open aluminum can top with a tab that stayed attached. This development was instrumental in keeping the aluminum can from being outlawed altogether on environmental grounds. The new top was variously called an "ecology" top and an "environmental can end," the former term being especially popular in the 1970s. Reynolds Aluminum Company promoted its new stay-on-tab can end the way most new technologies are introduced—by comparing it with what it improved upon. However, also like most novel technologies, the way the new can top worked was not necessarily obvious to the potential customer, and so early promotional cans

