



Potential hazards from carbonated drinks bottles

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BJ Norris, N Hopkinson, RC Cobb & JR Wilson
Product Safety and Testing Group
Institute for Occupational Ergonomics
Department of Manufacturing Engineering
and Operations Management
University of Nottingham
University Park
Nottingham
NG7 2RD

Summary

The study highlighted specific factors in the use and handling of carbonated drinks bottles which may lead to a risk of injury from closures missing or being propelled at high speeds from plastic (PET) carbonated drinks bottles.

It was shown that *under normal conditions*, closures on PET bottles are secure and unlikely to miss. However, although still likely to be rare, missing can occur under certain conditions. The combination of exposing bottles to increased temperatures (such that liquid temperature can reach up to 59°C), agitation *and* the use of tools such as nutcrackers or special openers and turning closures the wrong way during opening, can cause closures to miss at internal pressures as low as 50 pounds per square inch - a pressure that can be encountered inside bottles under these conditions. The use of tools or other methods such as teeth and door jams to open bottles is already established and people can get confused over which way to turn closures during opening. It was shown that closures are currently too difficult for children and the elderly to open and this may make these age groups more likely to use tools.

Recommendations are made regarding the risk of missing closures from PET bottles, and include printing arrows on caps to indicate opening direction and increased public information.

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1 Introduction

1.1 Aims

This report covers research into the potential hazards from Poly(ethylene)Terephthalate (PET) plastic carbonated drinks bottles. A small number of incidents involving ‘fizzy’ or carbonated drinks bottles had attracted media attention and concerns were being raised over their safety. These incidents involved bottle closures being propelled (or ‘missiled’) from PET bottles at high speeds causing facial or eye injuries. Accident scenarios had also implicated the use of tools to open stubborn closures (either grippers designed especially for the purpose or inappropriate tools such as nutcrackers, door frames, teeth), and also turning closures the wrong way. The remit of the study did not include a detailed examination of the aetiology of accidents. The purpose of the study was to estimate the extent of the risk from PET carbonated drinks bottles and to identify specific factors in their design and use which may contribute to that risk.

1.2 Objectives

The objectives of the study were to investigate:

- i the effect of temperature, head space and agitation on the level of internal pressure within PET carbonated drinks bottles
- ii the likelihood of ‘missiling’ of bottle closures, the conditions for this to occur and the velocity of missiling caps
- iii the contribution of opening behaviour to the likelihood of missiling
- iv what measures can be taken to reduce the risk of accidents

The study involved a combination of technical evaluations and a human factors investigation. In addition, industry tests and data were reviewed.

2 Background

2.1 Bottles

Approximately five million bottles of carbonated drinks are sold every day in the UK (Britvic, 1993). Over the last twelve years there has been a switch in the UK from glass to plastic or polymer bottles. Glass bottles with metal screw-caps are now used primarily for carbonated water, non-alcoholic wines etc. Unlike many European countries where most soft drinks bottles are returnable or recycled, the majority of carbonated drinks in the UK are now packaged in ‘one-trip’ PET bottles with screw-threaded closures. Closures are manufactured from either polypropylene or polyethylene. Bottle sizes include 0.25, 0.5, 1, 1.5, 2 and 3 litres. One and a half litre bottles are a standard shape across the industry whereas other sizes are becoming product-specific (Britvic, 1993).

All PET bottles have a standard neck and thread design, referred to as the British Plastics Federation (BPF) Standard (see Appendix 1). This standard bottle thread has four vertical slots to allow ‘venting’ of carbon dioxide from the bottle as the cap is unscrewed - the slots in the thread on the bottle line up with the breaks in the thread on the caps to allow a gradual release of pressure from the bottle as the cap is unscrewed. The standard thread was introduced in the late 1980s to prevent a phenomenon known as ‘tail end blow off’, or tailing. This is when pressure within the bottle caused caps to eject while being unscrewed as they reached the end of contact with the threads on the bottle.

2.2 Closures

Over recent years six designs of closures have been used. The two most commonly used are manufactured from polyethylene and polypropylene. All closures are attached to a tamper-evident band which is either retained on the bottle when opened or removed with the cap.

2.3 Literature

The main issue discussed in the technical literature regarding the risk of missiling from PET bottles was the level of headspace in a bottle. Headspace is the name given to the space at the top of the bottle above the fill level of the liquid. This is sometimes expressed as vacuity - the volume of headspace as a percentage of the volume of the liquid. The industry currently adopts a vacuity of 3.5 to 4.5% (Willhoft, 1992). It has been argued that reducing the headspace in a bottle is one route to reducing the potential injuries from a missiling cap (Willhoft, 1992). Willhoft argues that, based on a mathematical model, a reduction in headspace reduces the potential ballistic energy of a missiling cap and that the volume of headspace currently in use is excessive. The industry, however, argues that the currently adopted vacuity of 3.5 to 4.5% is needed for the expansion of the liquid which occurs with increased temperature. Also that a higher fill level would cause spillage during filling and the dried sugar solution on the threads would make closures difficult to open.

Mathematical analysis and experimental work confirm Willhoft's predictions that decreasing vacuity will reduce missiling velocity. However, at high temperatures (over 30°C, for instance a bottle left in the back of a car in direct sunlight), reducing vacuity leads to an increase in internal pressure which in turn can lead to an increased risk of missiling.

2.4 Industry tests and data

One of the purposes of the study was to establish what tests are carried out by industry, to review their data and, where necessary, develop new test methods to provide appropriate, independent performance data. A number of visits were made to bottle manufacturers, closure manufacturers and bottling plants and their tests relevant to the issue of missiling were reviewed.

2.4.1 Burst strength of PET bottles

PET bottles are tested by manufacturers regularly during production, as a quality control procedure. Production line samples are screwed into a test chamber and filled with pressurised water until failure. This normally occurs at around 150 pounds per square inch (psi) and failure usually involves bottles tearing around their base. Since the neck of the bottle is screwed into the test chamber this is a test of the burst strength of the bottle below the support ring only.

2.4.2 Burst strength of closures

Burst strength is tested by removing the neck portions from bottles and subjecting the closure to 100 psi for one minute and 175 psi for a further minute. The test is not a quality control procedure during production but a development test used to evaluate new designs and tests primarily for leakage. The majority of closures are said to resist these pressures and do not missile, although some leakage may occur.

2.4.3 Release of pressure during opening

Closures are located in a jig and unscrewed at a rate of two revolutions per second, which is faster than is possible by hand. The level of pressure in the bottle is recorded from a sealed hypodermic needle inserted into the bottle wall and a profile of internal pressure is recorded as closures are unscrewed. Again this is used as a developmental test and is used primarily to test new designs of closure.

3 Technical evaluation

The technical evaluation consisted of the following tests:

3.1 Measurement of internal pressure

including the effect of headspace, bottle size, product type, liquid temperature & agitation

3.2 Security of closures

3.2.1 The internal pressure required to 'missile' closures and the effect of temperature and opening behaviour

3.2.2 The missileing velocity of closures

3.2.3 The tensile force needed to remove closures

3.1 Measurement of internal pressure

Pressure inside a carbonated drinks bottle is caused by carbon dioxide being released from its liquid state within the beverage into the headspace at the top of the bottle. This internal pressure provides the potential energy within a bottle, and so the level of pressure inside bottles in their 'normal' off-the-shelf state and when exposed to various conditions is important. Measurements of internal pressure were made on a range of bottles, either bought locally from supermarkets or small retailers or delivered direct from a manufacturer. Differences due to bottle size, headspace and product were investigated in bottles in their normal 'off-the-shelf' state. In addition, the effects of external factors (ie temperature and agitation) on internal pressure were studied. Measurements were made on a total of one hundred and two PET bottles.

Apparatus

Internal pressure was measured using a sealed hypodermic needle inserted through the caps of unopened bottles. Pressure was recorded using a pressure transducer and digital display.

Procedure

A sample of sixty-two bottles was tested in their normal 'off-the-shelf' state (at air temperature with no agitation). Twenty-five different products in bottles varying from 0.25 to 3 litre in size were tested. The vacuity of each bottle was recorded by measuring the volume of liquid and the volume of each bottle after internal pressure had been measured. A further sample of forty bottles were tested after being exposed to a variety of conditions, as detailed below:

Temperature Bottles were placed in a kiln at a temperature of 70°C for up to three hours in order to raise liquid temperature. The temperatures quoted below refer to liquid temperatures and were measured with a digital thermometer inserted into the liquid after pressure testing.

Agitation Bottles were shaken vigorously by hand for between thirty seconds and two minutes immediately prior to measuring the internal pressure.

Temperature and agitation Bottles were heated as above and then agitated.

Opened and agitated Bottles were opened fully to allow the internal pressure to escape. The bottle caps were then replaced by hand and the bottles agitated for thirty seconds.

Results

The internal pressures recorded for normal conditions and for increased temperatures and/or agitation are shown in table 1.

Conditions	bottle size	n	mean	sd	min	max
'Normal/off-the-shelf'	0.25	8	38.1	1.5	37	41
	1	8	42.4	5.7	34	51
	1.5	8	45.4	9.4	35	57
	2	30	46.4	6.5	26	56
	3	8	46.4	1.8	44	49
Agitation (at room temperature)	2	10	48.3	6.4	35	56
Increased temperature (Liquid temperature 20-39°C)	2	10	55.2	6.7	46	66
(Liquid temperature 40-59°C)	2	10	58.4	7.5	46	69
Increased temperature and agitation (Liquid temperature 40-59°C)	2	10	86.2	15.6	69	118

Table 1 - The internal pressure (psi) recorded in PET bottles for different bottle sizes, temperatures and agitation

Internal pressure in 'off-the-shelf' bottles ranged between 26 and 57 psi (mean 44.7 psi) with the majority of bottles recording pressures between 40 and 50 psi. Bottle size and product type appeared to have little effect on internal pressure although no tests of statistical significance were performed. The vacuity of the sample of sixty-two bottles tested varied between 0.47 and 7.5% (defined as the volume of the headspace as a percentage of the volume of the bottle). Industry aims to produce a headspace of 3.5 to 4.5% (Willhoft, 1992).

Agitation seemed to have little effect, only marginally increasing the mean recorded internal pressure in 2 litre bottles from 46.4 to 48.3 psi and the maximum recorded internal pressure (56 psi) barely increased.

When bottles were opened and resealed, internal pressure was always lower after resealing, even when bottles were agitated.

Internal pressure increased with temperature. Liquid temperatures were raised up to 59°C and the maximum internal pressure measured in a two litre bottle went from 56 to 69 psi. There is some dispute over the maximum liquid temperature that can be reached in a PET bottle. Industry sources maintain that liquid temperature can reach 65°C, for instance when bottles have been left in the back of a car in sunlight: others suggest the maximum figure is likely to be 50°C (Packaging Week, 1988). Of the bottles tested in the 40-59°C range, half were under 50°C.

Increased temperature causes PET bottles to deform, beginning at a liquid temperature of approximately 45°C. Noticeable deformation of the PET occurs around the shoulders of the bottles and up to and just below the support ring. In a few cases, although not visibly detected, some deformation occurred in the threads of either the cap or bottle, since the cap either began to leak or could not be removed.

The combination of increased temperature and agitation caused the greatest increase in internal pressure. Mean internal pressure in two litre bottles rose from 46.4 to 86.2 psi (standard deviation 15.6) and the maximum internal pressure recorded in the study was 118 psi, in a two litre bottle agitated at 59°C.

3.2 Security of closures

This study investigated the conditions necessary for the missing of closures and the velocity with which closures may be propelled. Independent research carried out elsewhere prior to this study had suggested that under 'normal' conditions closures were secure and that missing was difficult to reproduce under laboratory conditions.

3.2.1 Internal pressure to missile closures

The security of closures is dependent on whether closures can be propelled from internal pressures encountered in realistic conditions. Bottle closures were therefore subjected to increasing levels of internal pressure to test whether missing would occur.

Apparatus

Figure 1 is a schematic representation of the test rig designed to hold the neck sections of plastic bottles, cut approximately 2.5 cm below their support ring. The rig consisted of two parts: a base with an inlet valve through which pressure was administered and a top section (not shown) which secured the neck over an 'O' ring on the bottom half of the rig to create a sealed system. The rig was supplied with pneumatic pressure up to 120 psi or hydraulic pressure up to 1000 psi. Since only the neck and thread sections of bottles were tested, which are standard on all bottles (see Appendix 1), the neck sections of 1.5 litre bottles only were used.

Procedure

Hydraulic pressure was applied into the system with a hand pump. Pneumatic pressure was used on some closures to compare methods. Pressure was recorded until the closure failed. The process was recorded on video in order to record the precise failure pressure. Failure was classified as either:

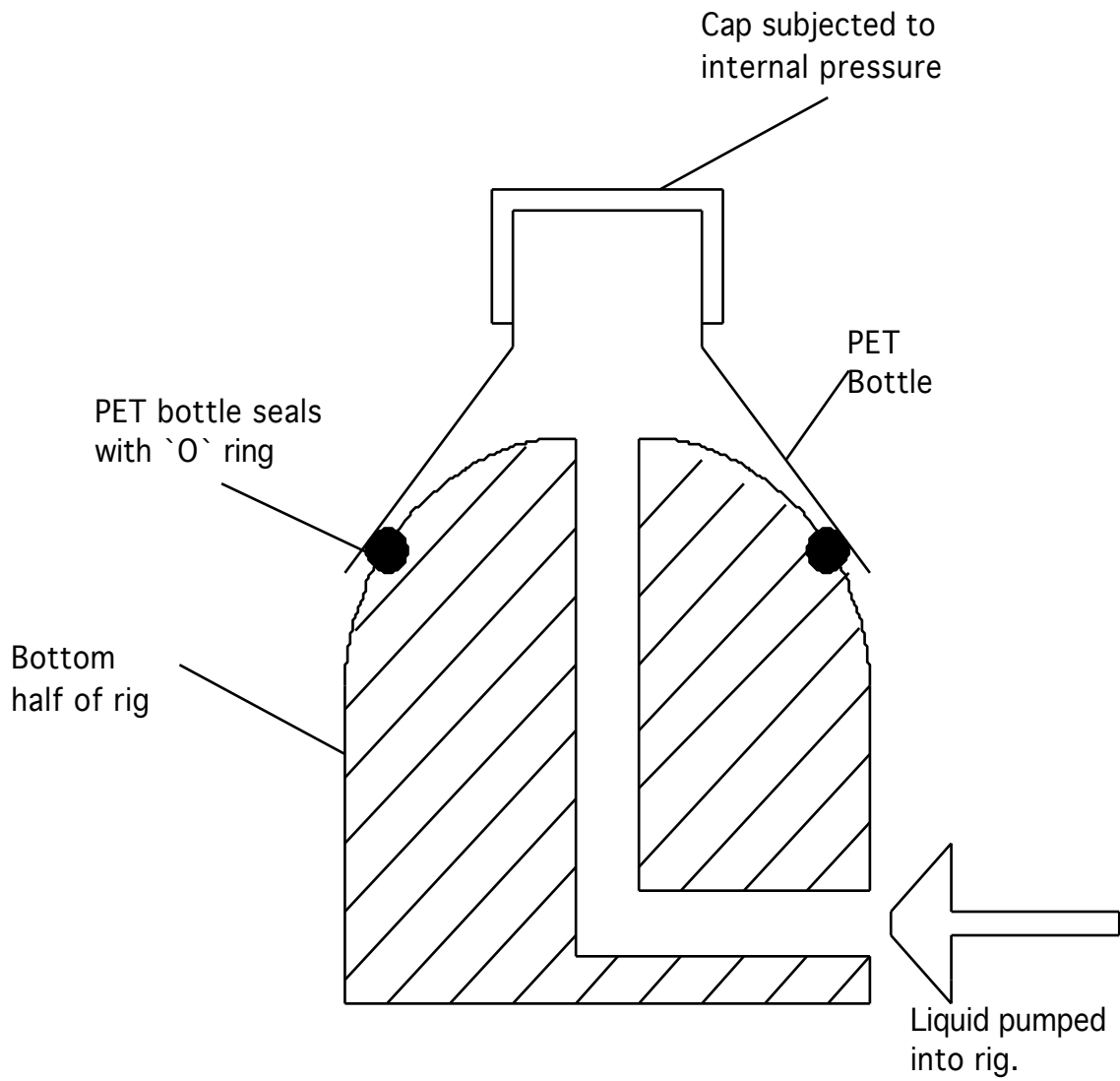


Figure 1: Schematic diagram of test apparatus for measurement of internal pressure to missile closures

Leakage Any increase in applied pressure was released through the cap without any change in the status of the cap

Missiling The cap was propelled from the bottle in one piece

Exploding The cap shattered and was propelled from the bottle in more than one piece

Closures were tested in their ‘off-the-shelf’ state. Closures were also tested after being subjected to a number of external conditions. These were:

Loosening Closures were opened (turned anticlockwise) through a specific Angle

Over-tightening by hand Closures were over-tightened (turned clockwise) to a torque of approximately 30 inch-pounds (3.39 Nm)

Over-tightening with tools Closures were over-tightened (turned clockwise) using grippers designed for opening bottles or jars, or nutcrackers, to a torque of 3.39 Nm. This left visible damage on the closures

Temperature The bottle necks and closures were heated in water at 40-50°C for ten minutes

Temperature and tightening with tools As above

Three types of commonly used caps were tested, referred to as type A (n=37), type B (n=75) and type C (n=12).

Results

Table 2 shows that of twelve closures tested in their ‘off-the-shelf’ state, five missiled or exploded and seven leaked. However, the lowest internal pressure at which a closure was propelled (exploded) from a bottle was 400 psi. Such high pressures are unlikely to be encountered inside carbonated drinks bottles, under any circumstances. It is therefore very unlikely that caps will missile in their normal ‘off-the-shelf’ state under ‘normal’ temperatures and with correct opening procedures.

Loosening the closures showed that even higher pressures were required to cause failure, and most of the caps leaked rather than missiled or exploded.

However, other external treatments caused the closures to fail at much lower internal pressures.

Over-tightening closures with the hand meant that closures were more likely to missile/explode than to leak but this occurred at a minimum pressure of 325 psi. Such a high pressure is also very unlikely ever to be reached inside a bottle.

Over-tightening closures with a tool dramatically reduced the pressure to missile, to a minimum of 125 psi. However, this is still higher than the maximum internal pressure of 57 psi measured inside a bottle for ‘off-the-shelf’ bottles at air temperature (see table 1).

An increase in temperature reduced the minimum pressure to missile/explode to 200 psi, but again this is higher than the maximum internal pressure of 118 psi previously recorded inside a bottle at increased temperature. Also, more caps leaked than were propelled from the bottle necks.

Over-tightening closures with a tool combined with an increase in temperature did, however, cause closures to fail at much lower pressures and which may be found in practice, as low as 50 psi. The maximum internal pressure recorded at increased temperature was 118 psi (see table 1) and in total four closures missed at pressures lower than this: at 50, 66, 76 and 100 psi. All had been over-tightened with grippers and had been heated to temperatures of 38-40°C.

A comparison of internal pressures at which closures missed/exploded under different conditions is shown in figure 2.

Conditions	n	Leak				Missile/explode				%
		n	mean	min	max	n	mean	min	max	
'off-the-shelf'	12	7	311	150	500	5	455	400	500	42
loosened	18	16	227	25	350	2	563	425	700	11
hand tightened	20	7	298	175	400	13	427	325	525	65
tool tightened	16	7	314	100	500	9	286	125	500	56
heated	12	8	206	100	375	4	306	200	350	33
heated & tool tightened	31	15	150	0	300	16	271	50	500	52

Table 2 - Range of pressures (psi) required to cause failure of PET bottle caps under various conditions and the percentage of the sample that missed or exploded

Cap	Conditions	n	Missile				Explode				%
			n	mean	min	max	n	mean	min	max	
A	hand tightened	4	2	350	325	375					50
	tool tightened	7	5	185	125	275					71
	heated & tool tightened	15	7	196	50	275					47
B	'off-the-shelf'	8					5	455	400	500	63
	hand tightened	11					9	453	400	525	82
	loosened	10					2	563	425	700	20
	heated	8					3	342	325	350	38
	tool tightened	8					4	413	325	500	50
C	heated & tool tightened	15					9	330	125	500	60
	hand tightened	5					2	375	375	400	40
	heated	2					1	200	200	200	50

Table 3 - Range of pressures (psi) required to cause closures to explode or missile according to cap type and the percentage of the sample that missed or exploded

Some differences were noted between different types of closures, as shown in table 3. When propelled from a bottle, all type A caps missed in one piece and none exploded. However, all other closures (types B and C) exploded into a number of pieces rather than missing. Also, type A closures were the only type to miss at pressures below the threshold value 118 psi, the maximum internal pressure recorded in a bottle in this study. One type B closure did explode at 125 psi which is only slightly above the threshold value of 118 psi.

3.2.2 The velocity of missing closures

The velocity and direction with which closures are propelled from bottles will determine the likely severity of any potential injury. The study therefore attempted to estimate the speed and behaviour of missing caps. A number of methods were used but difficulties were encountered due to the high speed of the closures. Also estimation of velocity could only be carried out on caps that missed in one piece and not on those that shattered.

Apparatus and procedure

Normal lighting and a video camera recording at 50 frames per second proved too slow to make any estimations of missing velocity. A high frequency (300 Hz) strobe light was used to illuminate the video and this gave a number of images per frame and velocity could thus be estimated by measuring the distance travelled by the cap between each image.

Results

Only four out of twenty missing caps filmed using this method provided images clear enough to allow estimations of velocity. These were all type A caps. The velocities and internal pressures and conditions which caused missing are shown in table 4.

Internal pressure (psi)	Velocity	Conditions
76	60	Tool tightened at 40°C using pneumatic pressure
66	51	Tool tightened at 40°C using pneumatic pressure
225	48	Tool tightened at 40°C using hydraulic pressure
100	16	Tool tightened at air temp using hydraulic pressure

Table 4 - Velocity (ms^{-1}) of missing caps

The maximum velocity recorded was 60 ms^{-1} (135 miles per hour). It has been suggested previously (Willhoft, 1992) that headspace dictates the potential energy in a missing cap and therefore its potential speed. Willhoft has produced an equation which suggests that missing velocities between 46 and 167 ms^{-1} are possible from a one and a half litre bottle with 34 psi internal pressure, with vacuities between one and fifteen percent respectively. All the tests carried out in this study were independent of headspace and with only a small sample it is not possible to make any correlation between missing speed and headspace.

3.2.3 The tensile force required to remove closures

At the outset of the study it was unknown whether closures would miss due to internal pressure. Also, accident reports had implicated the use of tools but the lack of accident scenarios did not clarify how the tools had been used. It was therefore of interest to identify whether closures could be 'pushed' off and at what force. This was done by measuring the tensile force required to push closures off the bottle-necks.

Apparatus

The rig described in section 3.2.1 was used to secure the top section of a bottle. Two grippers were clamped around the cap so that the tensile force was applied underneath the tamper-evident band of the cap in order to push the cap away from the bottle neck. The rig and grippers were secured in an Instron mechanical testing machine. The design of the rig meant that the majority of tests were carried out on type B closures only in their normal 'off-the-shelf' state.

Procedure

Tensile testing was carried out at a rate of either 25 mm per minute (on thirteen closures) or 50 mm per minute (four closures) until the closures were removed from the bottles. The force to remove the closures in kilo-Newtons was converted to pressure in psi (pounds per square inch) so that comparisons could be made with the internal pressure tests in section 3.2.1. Given the internal cap diameter of 25 mm and taking the acceleration of freefall to be 9.8 metres per second squared then pressure (psi) can be calculated using the equation:

$$P = 301.5 \times F \quad \text{where } F = \text{tensile force to remove the closure (kN)}$$
$$P = \text{equivalent pressure in (psi)}$$

Results

On a sample of seventeen closures the mean force to remove a cap in this way was equivalent to an internal pressure on the cap of 397 psi (standard deviation = 63). The minimum force was 272 psi and the maximum was 543 psi. These results are comparable to the internal pressure required to missile closures, but not to explode, recorded in section 3.2.1. The closures showed no signs of damage after being pulled off in this way, the threads of the cap having slipped over the threads on the bottle. The caps could easily be screwed back onto the bottle.

4 Human factors investigations

The human factors investigation consisted of two parts: user trials in which opening behaviour was observed and users' opening strength was measured, and an in-home study of the use of bottles. The results of both stages are presented jointly according to the relevant human factors issues.

4.1 User trials

Aim

The aim of the user trials was to establish whether the way in which people open bottles contributes to the likelihood of injury. For instance, do people have difficulty opening caps and do they use tools?

Qualitative data was gathered by observation and interviews. Quantitative data on whether consumers have difficulty in opening bottles was gathered by measuring opening strength with the hands and using tools.

Subjects

Sixty eight subjects ranging from four to eighty-six years completed the first stage of the user trials in which opening behaviour and opening strength with the hands was recorded. A second sample of ten adult subjects were used to collect strength data using tools. Subject numbers are shown in table 5 and full subject details are shown in Appendix 2.

	Ages	Males	Females	All
First stage	5-9	6	5	11
	10-14	6	7	13
	15-19	5	2	7
	20-39	5	7	12
	40-59	5	5	10
	60-69	3	3	6
	70-79	1	4	5
	80-86	-	4	4
Second stage	22-32	5	5	10
Total		36	42	78

Table 5 - Subjects taking part in the user trials

Procedure

Each subject in the first stage of the trials was observed opening four bottles (two x 3 litre and two x 1.5 litre). They then performed three maximum and three comfortable strength measurements, with a two minute rest period between each measurement. A balanced experimental design was used to evaluate any order effects.

Comfortable opening force was described as a force which did not hurt the subject's hand, and maximum force as the highest force one could possibly exert without injuring oneself (based on a method established by Berns, 1981). No restrictions were placed on subjects' posture or technique in performing any of the tasks: subjects were free to sit or to stand, to rest the bottle on a work surface or hold the bottle and in any orientation. Subjects were then interviewed as to whether they found bottles difficult to open and if they ever used tools. Those who admitted to using tools to open bottles were observed doing so.

In the second stage of the trials maximum torque was measured using hands, a rubber cone (a device specifically designed for the disabled), a rubber mat and a pair of nutcrackers, turning both anticlockwise (opening) and clockwise (over-tightening).

Apparatus

Each subject was observed opening four bottles: two with closures that had been factory fitted to a torque of approximately 18 inch pounds (2.034 Newton metres). This was verified by measuring the removal torque of a sample of twenty-six closures. The mean torque recorded was 17.15 inch pounds (standard deviation = 1.95, range = 14-20). The other two were fitted by hand to a torque of approximately 17 inch pounds. All bottles had the labels removed and were fitted with plain (no printing) caps.

Opening strength was measured on a replica aluminium bottle specially manufactured to the dimensions and weight of a one and half litre bottle. The cap on the bottle was fixed onto a central member which in turn was fixed to the bottom of the bottle and was instrumented with strain gauges. The cap was restrained so that a torque applied to the cap was measured against the external walls of the bottle. The bottle had a cable leading from its side so that it could be picked up and handled in a realistic manner. Output from the strain gauges was recorded in volts on an oscilloscope and converted to torque in Newton-metres.

Ethical considerations

Given that the reason for the study was to evaluate the risk from missing closures there were ethical considerations about exposing subjects to risk during user trials. After review it was decided that any bottles to be opened by children or using tools would be filled with water to remove any risk. Bottles containing carbonated drinks were used for the remainder of the study. Pilot trials revealed that bottles filled with water were less rigid than those filled with carbonated drinks due to the lack of pressure acting on the bottle walls. Results showed later that this had a negligible effect on the way bottles were handled during opening.

4.2 Home study

Aims

The aim of the study was to provide reliable data on the way in which people open carbonated drinks bottles and especially the extent to which people use tools. This would provide empirical data to corroborate information reported by subjects during interviews.

Sample

Leaflets were sent to a random sample of four hundred homes in the Nottingham area including urban and rural areas, and a further seven hundred and fifty to University employees. Fifty-one homes were used in the study. Two did not return any bottles giving a final sample of forty-nine homes.

Procedure

Under the guise of a study of recycling, households were asked to save their usual carbonated drinks bottles and closures over a period of three to five weeks. Labels were provided to be attached to each bottle in order to record who opened, used and disposed of each bottle and when. Each household was also given two bottles of lemonade with two of the three possible designs of caps under evaluation. Bottles and closures were collected and the closures examined for evidence of the use of tools or misuse - marks in the tops indicating the use of grippers, nutcrackers, teeth, door jambs etc. A postal questionnaire (see Appendix 3) was then sent to each household to establish information on bottle use. Respondents were asked explicitly whether they or other members of the household ever use nutcrackers, grippers, teeth door jambs or anything else to open bottles. Forty homes in the home study returned questionnaires.

4.3 Results

4.3.1 Opening strength

Review of literature

According to one manufacturer, bottle closures are presently applied to a target wet torque of 18 inch pounds (2.034 Newton-metres). This apparently drops to approximately 15 inch pounds when dry. However, in the sample of twenty-six closures tested in this study, the mean removal torque was 17.15 inch pounds/1.938 Nm, (standard deviation = 1.95, range = 14-20 inch pounds). These target torques are based on strength data measured on Spanish subjects opening metal closures. These data are inappropriate due to population differences and different coefficients of friction for metal and plastic caps. A literature search was therefore carried out to establish what other strength data were available. There are a considerable number of sources of strength data but few relate to bottle closures. It has been shown that diameter and grip characteristics directly affect exertable torque and so these data were inapplicable (Pheasant, 1975). A number of sources of torque strength measured on bottle closures were identified and reviewed.

Imrhan and Loo (1986)

Torque strength was measured in forty-two elderly USA subjects aged sixty to ninety-seven years (mean seventy-seven years), on a 31 mm diameter cap on a bottle held vertically in a 'Torque Tester' and placed on a work surface. Subjects were allowed to stabilise the bottle with their other hand. Mean torque was recorded as 1.62 Nm on a 'rough' (undefined) lid and 1.53 Nm on a 'smooth' lid.

Konz and Ravishankar (1989)

Torque strength was measured in eighteen students on six plastic pop bottle lids, all 28 mm with different designs of knurling. The lids were attached via a shaft to a torque meter which was clamped to a table. Torque was shown to increase with degree of knurling. Mean torque measured on the cap most similar to those currently used (13 knurls per cm) was 2.44 Nm.

Rohles, Moldrup and Laviana (1983)

Torque strength was measured in two hundred elderly subjects aged sixty-two to ninety-two years and two hundred children aged four years. Torque was measured on two pop bottle lids (27 and 29 mm diameter) attached via a shaft to a torque meter. Mean torque varied between 0.92 (elderly females) and 2.04 Nm (elderly males) and 0.58 (four year old girls) and 0.63 Nm (four year old boys). This study showed that direction of turn (opening versus tightening) did not significantly effect torque strength.

Nagashima and Konz (1986)

Torque strength was measured in ten female students on jar lids, the smallest diameter of which was 48 mm, attached via a shaft to a torque meter. The study found that use of a rubber gripper significantly increased torque on this size of lid and that the use of a cotton cloth significantly decreased torque.

Berns (1981)

Torque strength was measured in one hundred and forty-four "normal" women aged twenty to seventy-plus years and fifty-four "normal" men aged over sixty. Also measurements were made in eighty-seven "handicapped" subjects (with "handicap" considered to include rheumatic arthritis, cerebral palsy, multiple sclerosis, Parkinson's disease and one-hand function). Torque was measured on a 28 mm cap fixed to a replica bottle placed on a worktop; it is assumed that the bottle was not fixed to the worktop and could be moved. Measurements of 'comfortable' and 'maximum' torque were made. The comfortable force was described as a force during which one should feel no pain and the maximum force as the most force one could possibly exert without injuring oneself. The results were presented graphically for the whole "normal" sample and fiftieth percentile values have been estimated as 1.18 Nm for maximum torque and 0.94 Nm for the comfortable torque.

It was felt that none of the available sources provided adequate data since all except Berns had measured torque on either lids removed from bottles or on bottles fixed to a work surface. Strength is known to be dependent on posture and orientation of the joints and so it was felt that, for validity, opening torque should be measured on a replica bottle which could be moved and held as realistically as possible. Data from Berns was limited due to its presentation and restricted age groups. Maximum and comfortable torque strength was therefore collected as part of this study on children, adults and the elderly using a replica bottle which could be held in any orientation and is described above.

Results

The results of these measurements are presented in tables 6 and 7.

Ages (years)	male					female					all				
	n	mean	sd	min	max	n	mean	sd	min	max	n	mean	sd	min	max
MAX															
5-9	5	1.55	0.24	1.23	1.81	5	1.47	0.23	1.13	1.71	10	1.51	0.22	1.13	1.81
10-14	5	2.18	0.67	1.41	3.01	7	2.60	0.58	2.01	3.67	12	2.43	0.63	1.41	3.67
15-19	4	2.80	0.80	1.96	3.87	2	2.99	0.25	2.81	3.17	6	2.86	0.63	1.96	3.87
20-39	5	4.05	1.35	2.11	5.53	7	2.46	0.64	1.51	3.52	12	3.12	1.25	1.51	5.53
40-59	5	3.01	0.96	1.91	4.02	5	2.16	0.59	1.46	2.81	10	2.59	0.88	1.46	4.02
60+	3	2.33	0.73	1.81	3.17	11	1.71	0.61	1.00	2.51	14	1.84	0.67	1.00	3.17
COMF															
5-9	5	1.03	0.21	0.90	1.38	5	1.04	0.22	0.78	1.38	10	1.04	0.20	0.78	1.38
10-14	4	1.98	0.38	1.61	2.51	7	2.03	0.43	1.46	2.51	11	2.01	0.39	1.46	2.51
15-19	4	1.81	0.47	1.47	2.41	2	2.39	0.39	2.11	2.66	6	2.00	0.50	1.41	2.66
20-39	5	3.07	0.97	1.56	4.12	7	2.18	0.67	1.41	3.22	12	2.55	0.89	1.41	4.12
40-59	5	3.16	1.23	2.21	4.82	5	2.15	0.49	1.36	2.56	10	2.65	1.03	1.36	4.82
60+	3	1.94	0.34	1.56	2.21	11	1.07	0.28	0.73	1.61	14	1.26	0.46	0.73	2.21

Table 6 - Peak (of three) maximum and comfortable opening torque (Nm)

ages (years)	male					female					all				
	n	mean	sd	min	max	n	mean	sd	min	max	n	mean	sd	min	max
MAX															
5-9	5	1.35	0.23	1.08	1.71	5	1.23	0.16	1.03	1.39	10	1.29	0.20	1.03	1.71
10-14	5	1.87	0.65	1.27	2.73	7	2.29	0.58	1.67	3.35	12	2.12	0.62	1.27	3.35
15-19	4	2.42	0.73	1.59	3.28	2	2.42	0.03	2.39	2.45	6	2.42	0.57	1.59	3.28
20-39	5	3.71	1.78	1.98	4.78	7	2.12	0.40	1.46	2.61	12	2.78	1.12	1.46	4.77
40-59	5	2.69	0.35	1.79	3.72	5	1.94	0.54	1.32	2.51	10	2.31	0.75	1.32	3.71
60+	3	2.09	0.56	1.62	2.71	11	1.44	0.38	0.87	2.16	14	1.58	0.53	0.87	2.71
COMF															
5-9	5	1.11	0.37	0.79	1.71	5	0.97	0.18	0.77	1.25	10	1.04	0.29	0.77	1.71
10-14	5	1.59	0.67	0.55	2.31	7	1.78	0.40	1.21	2.12	12	1.70	0.51	0.55	2.31
15-19	4	1.61	0.42	1.27	2.14	2	2.00	0.18	1.88	2.13	6	1.74	0.39	1.27	2.14
20-39	5	2.70	0.73	1.44	3.21	7	1.97	0.51	1.29	2.68	12	2.27	0.69	1.29	3.22
40-59	5	2.56	0.65	1.91	3.38	5	1.96	0.47	1.14	2.29	10	2.26	0.62	1.14	3.38
60+	3	1.77	0.39	1.37	2.16	11	0.95	0.23	0.64	1.47	14	1.13	0.43	0.64	2.16

Table 7 - Mean (of three) maximum and comfortable opening torque (Nm)

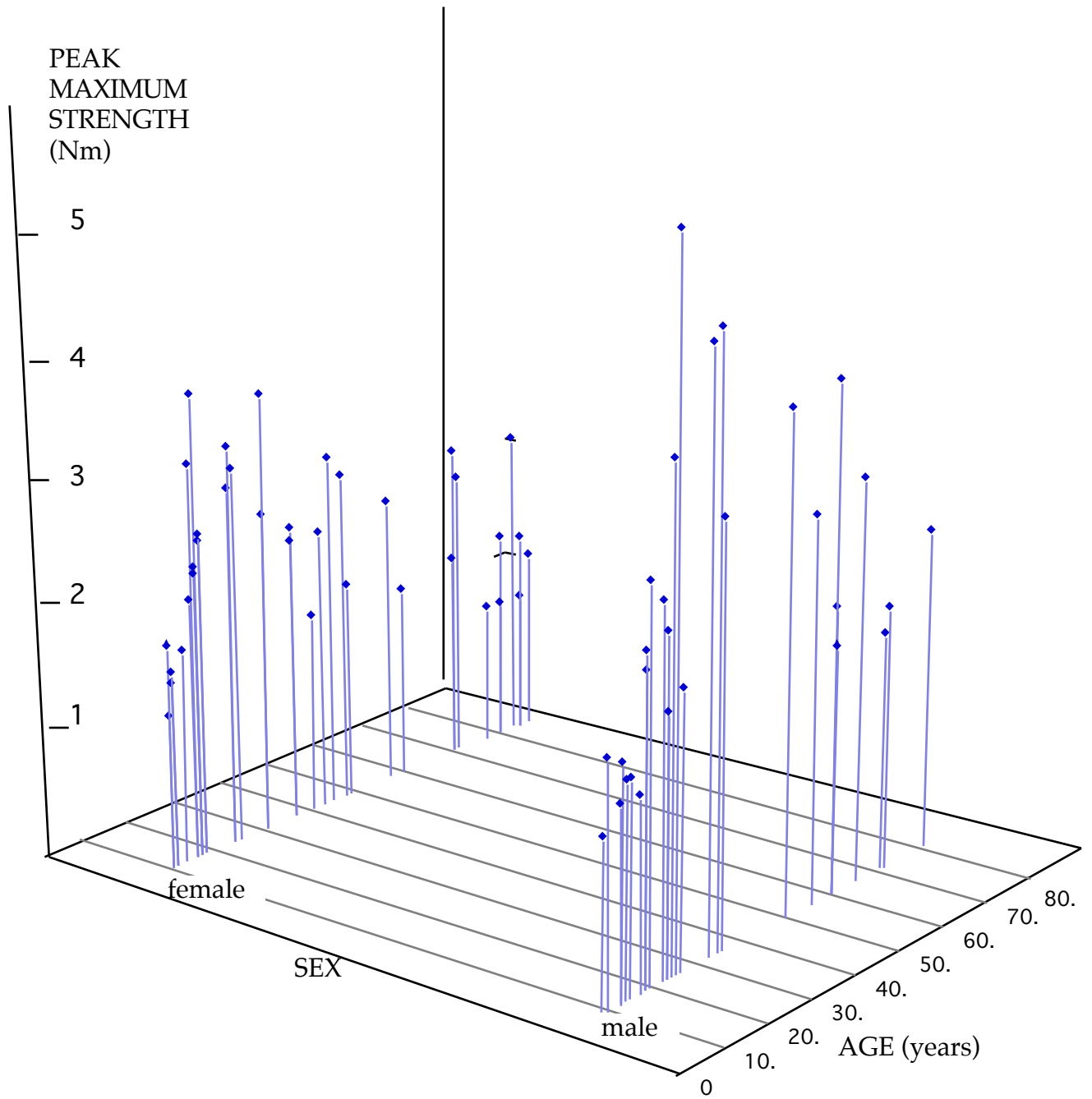


Figure 3: Peak maximum opening strength according to sex and age

Table 6 presents the peak value of the three strength measurements: ‘maximum’ and comfortable. Peak maximum strength is shown graphically in figure 3. Table 7 presents the mean of the three measurements. For the purposes of this report, no analysis has been made of differences in strength according to sex, age, maximum versus comfortable force, posture, technique or grip. Peak maximum torque strength recorded in this study is compared to those reported in the literature and to the torque with which caps are currently applied in table 8.

Table 8 shows that although different measurement techniques were used and the age groupings are not directly comparable, data from this study agrees with that found in the literature. Most importantly, the results show that children and the elderly are likely to have difficulty opening bottles. Closer examination of the results shows that of sixty four subjects who successfully completed the strength measurements, nearly half (46%) had peak maximum torque strength less than 2.034 Nm, the value quoted by industry as the applied torque on bottle closures. Of these, most were children or the elderly (Table 9).

Age group	Age (years)	Source of data	Cap diameter (mm)	Method	Mean torque (Nm)
children	4	Rohles 83	27 & 29	cap only	0.58 - 0.63
	5-9	This study	29	movable bottle	1.51
elderly	10-14	This study	29	movable bottle	2.43
	60-97	Imrhan 86	31	vertical fixed bottle	1.62
teenagers	62-92	Rohles 83	27 & 29	cap only	0.92 - 2.04
	60-86	This study	29	movable bottle	1.53
adults	students	Konz 89	28	cap only	2.44
	15-19	This study	29	movable bottle	2.86
adults	20-70+	Berns 81	28	movable bottle	1.18
	20-39	This study	29	movable bottle	3.12
	40-59	This study	29	movable bottle	2.59
		Industry applied torque	29		2.03

Table 8 - Comparison of published torque strength to that recorded in this study and applied torque

Age	n	No. of subjects with peak strength < 2.034 Nm	% of sample
5-9	10	10	100
10-14	12	4	31
15-19	6	2	29
20-39	12	1	8
40-59	10	3	30
60-86	14	10	67
Total	64	30	46

Table 9 - Comparison of torque strength measured in this study to the torque with which closures are applied

4.3.2 Opening difficulty

Results are presented jointly from both the home study questionnaire and user trials. When asked, nearly 65% of all subjects said that they had difficulty opening bottles (table 10). Observation of subjects opening bottles in the user trials supported this: nineteen of sixty-eight subjects failed to open at least one of the bottles they were given (table 11); all but one of these were children and adults over sixty. One female subject in her seventies couldn’t open any of the bottles. Most of the

bottles that couldn't be opened had caps put on by the manufacturer, as opposed to the caps which had been applied in the laboratory by hand, although ostensibly to the same torque (table 12).

	% of sample reporting opening difficulties				
	n	Always	Sometimes	Never	No answer
Home study	40	57.5	20	22.5	-
User trials	68	37	20	34	9
Total	108	44.4	20.4	29.6	5.6
Total reporting any difficulty = 64.8%					

Table 10 - Percentage of respondents who said they have difficulty opening bottle closures

Ages	n	males	females	all	%
5-9	11	3	4	7	64
10-14	13	2	1	3	23
15-19	7	-	-	-	0
20-39	12	1	-	1	8
40-59	10	-	-	-	0
60-69	6	1	-	1	17
70-79	5	4	-	4	80
80-89	4	3	-	3	75
Total	68	14	5	19	28%

Table 11 - Number of subjects who were unable to open at least one bottle during the user trials

Cap type	3 litre bottle		1.5 litre bottle		% of sample unopened
	n	unopened	n	unopened	
Manufacturer applied	68	14	68	16	22.5
Laboratory applied	68	4	68	9	9.5
Total	136	18	136	25	15.8

Table 12 - The number of caps unopened during user trials according to method of applying closure and bottle size

4.3.3 Opening technique

Grip

Four types of grip were used to open bottles. All four grip types were commonly used (table 13). Nearly half (33) of the subjects used only one type of grip and a further twenty-five used only two types of grip, suggesting that opening technique is habit-forming. Different grips were usually used by subjects having difficulty opening bottles. It was felt that the type of grip is unlikely to effect the chance of missing.

Handedness

Nearly all subjects used the same hand throughout the trials. Handedness did not predict which hand would be used to open the bottle caps: although most of the subjects were right-handed (60) less than half of the total sample (31) used only their right hand. Also, of seventeen subjects who consistently used their left hand on the bottle cap, ten were right-handed. From observations these subjects used their stronger hand to support or hold the bottle and the weaker hand to turn the top.

their stronger hand to support or hold the bottle and the weaker hand to turn the top.

Bottle Position

Most subjects rested bottles on the available work surface during testing. As a result, bottles were usually vertical or tilted slightly with the cap pointing towards the subject’s face. Even when held in the hands, bottles caps were usually pointing towards the face.

Grip type	No. of subjects who used each grip type	No. of subjects using only one grip
1	45	12
2	23	5
3	32	12
4	13	4
Total		33

Table 13 - Frequency of occurrence of each grip (number of subjects who used that grip) and number of subjects who used only one grip

4.3.4 Opening strength using tools

The results of missiling tests described in section 3.2.1 indicated that a significant factor in the risk of missiling was over-tightening closures when using tools. Closures that missiled had been ‘over-tightened’ to a torque of approximately 30 inch pounds (3.39 Nm) using either nutcrackers or special grippers. The maximum exertable torque using tools was therefore measured in a second programme of tests using ten adult subjects (mean age twenty-seven years,). Torque was measured in both directions (opening and over-tightening) using the hands, a rubber mat, a rubber cone and nutcrackers.

Results

Table 14 shows that this sample had hand strength comparable to the larger sample used in the first stage of the user trials. Mean strength was similar in both directions (one particularly strong male subject raises the maximum opening strength). Maximum strength was actually slighter lower when turning anticlockwise (opening) when using the cone, even though this is specially designed as an aid for the disabled. Opening and tightening strength increased when using both the rubber mat and nutcrackers. All of the subjects tested were able to exert an over-tightening torque greater than that applied for the caps to missile (3.39 Nm) when using either of these tools.

ages (years)	male					female					all				
	n	mean	sd	min	max	n	mean	sd	min	max	n	mean	sd	min	max
OPENING															
hand	5	3.5	1.9	1.8	6.8	5	2.3	0.3	2.1	2.8	10	2.9	1.4	1.8	6.8
rubber cone	4	1.9	0.4	1.3	2.4	5	2.1	0.4	1.3	2.6	9	2.0	0.4	1.3	2.6
rubber mat	5	6.8	1.6	4.0	8.2	5	4.2	1.1	2.5	5.4	10	5.5	1.9	2.5	8.2
nutcrackers	5	9.7	4.1	5.2	14.5	5	5.7	1.4	3.4	7.2	10	7.7	3.5	3.4	14.5
TIGHTEN- ING															
hand	4	2.2	0.5	1.4	2.7	5	2.3	0.5	1.5	2.9	9	2.2	0.5	1.4	2.9
rubber cone	4	6.1	2.3	4.1	8.5	5	3.7	0.6	3.0	4.4	9	4.8	1.9	3.0	8.5
rubber mat	5	6.8	2.3	3.9	9.1	5	4.7	0.7	3.8	5.7	10	5.7	1.9	3.8	9.1
nutcrackers	5	11.0	4.2	5.9	15.8	5	6.4	1.9	4.4	8.5	10	8.7	3.9	4.4	15.8

Table 14 - Peak maximum torque strength (Nm) according to direction and use of hands or tools

4.3.5 Turning closures the wrong way

4.3.5 Turning closures the wrong way

Some subjects were observed turning the caps the wrong way (clockwise) while trying to open bottles. During strength measurements when there was no feedback, four subjects consistently turned the caps the wrong way and a further eleven turned the cap the wrong way at least once. When opening bottles, ten subjects in total tried turning the cap the wrong way, including the same four subjects who had consistently turned the caps the wrong way during the strength testing. When opening bottles, most subjects eventually realised their mistake and turned the cap the correct way but a few (especially children) had to be told. Table 15 shows that those most likely to turn the cap the wrong way were children, teenagers or the elderly.

Age	No. of subjects
5-9	6
10-14	3
15-19	2
20-39	1
40-59	2
60-86	5
Total	19

Table 15 - Number of subjects turning closures the wrong way to open

4.3.6 Use of tools

Subjects were asked in both the home study and the user trials about their use of tools. Subjects in the home study were asked directly in a questionnaire whether they had ever used grippers, nutcrackers, teeth or a door jamb to open difficult bottles. In the user trials, subjects were asked what they did to open difficult bottles. Table 16 shows that over half the sample admitted to using tools such as grippers or nutcrackers, or misuse involving teeth or a door jamb etc.

	User trials	Home study	% of sample
Use nothing	7	8	13.9
Ask someone else	17	-	15.7
Cloth or rubber mat	13	2	13.9
Door	17	18	32.4
Teeth	9	8	15.7
Nutcrackers	4	4	7.4
Special grippers	6	10	14.8
Any misuse or tool (ie door, teeth, nutcrackers or grippers)	31	26	52.7
Total	68	40	

Table 16 - Number of subjects who admit to using tools or other methods to open difficult closures

Evidence of the use of tools

The bottle closures returned from the home study were inspected for evidence of the use of tools. The aim was provide comparative data between reported use of tools and evidence of use. The closures were inspected for marks likely to be caused by tools such as grippers, nutcrackers, teeth or door jambs. Over a quarter of the returned closures (122 out of 408) were marked. Although we were unable to confirm that these marks were made by tools, they are unlikely to be have made due to opening with the hands. These results support the reported data acquired by questioning subjects in the user trials and in the home study.

Observed use of grippers

Those who said they used tools during the user trials were observed doing so. Everyone who used a handled tool such as grippers or nutcrackers placed the bottle on the work surface. Subjects tended to turn the bottle as well as the cap. Most importantly, one adult female subject demonstrated her use of a pair of nutcrackers and although she had turned the caps the correct way when opening bottles with her hands, repeatedly tried to open the bottles by turning the caps the wrong way when using the nutcrackers. She eventually said that the caps were too tight to open.

4.3.7 Use of bottles in general

Cutting the tamper-evident band

Seven out of the one hundred and eighty people interviewed about their use of carbonated drinks bottles volunteered the information that they often use a knife or scissors to cut the tamper-evident band already in use on caps. These tamper-evident bands are at present designed to either be removed with the cap or to be retained on the bottle neck and should not need to be cut.

Storage

Subjects in the home study were asked about storage of carbonated drinks bottles. Of forty respondents, eight said that they store bottles on a work surface in the kitchen, where they might be exposed to increased temperatures.

5 Conclusions

The stability of PET bottles and closures under normal conditions was demonstrated in tests carried by manufacturers on production-line samples. Bottles were shown to burst at around 150 psi and closures were shown to resist pressures up to 175 psi. Measurements in this study showed that the pressure inside a two litre bottle is unlikely to be higher than 57 psi under normal conditions. However, an increase in temperature raises internal pressures up to 69 psi and, combined with agitation, which must be realistically anticipated through normal transportation and handling, pressure can reach up to 118 psi. Liquid temperatures between 40 and 59°C were used, which have been said by industry to be achievable, for instance, when bottles are left in a car in sunlight.

The security of closures under 'normal' conditions were demonstrated: closures can resist internal pressures up to 400 psi and this is a level unlikely ever to be reached inside a carbonated drinks bottle. However, specific conditions have been identified under which closures can missile. The combination of raised temperature and over-tightening closures using tools such as nutcrackers or special openers caused four closures (out of a sample of fifty-eight) to missile at pressures as low as 50 psi, much lower than the 118 psi threshold. It was also shown that closures can missile at pressures as low as 100 psi if they have been over-tightened with tools without an increase in temperature, but at air temperature internal pressure is unlikely to reach this level. However, on the basis of this evidence the risk of over-tightening closures with tools per se, regardless of temperature, should be highlighted, particularly given the unreliability of detecting exposure to increased temperature

Missiling velocity was measured giving maximum velocities of 60 ms⁻¹ (135 mph) although the sample size was too small to support any previously suggested relationship between headspace and velocity.

The probability of closures missing or exploding from PET bottles, whilst still low, was markedly higher for one basic design of closure than another. Differences in performance maybe due to the differences in flexibility of the materials, however, it is not possible to make comments on the relative safety of different closures but that closure design may need further investigation.

The human factors investigation suggests that people are quite likely to use tools to open closures, particularly children under ten years and the elderly. Measurements of opening strength showed the torque with which closures are applied to bottles (2.034 Nm) is too high for these age groups. Of more than a hundred people interviewed, over two thirds said that they have at some time found bottles difficult to open and over a half admitted to using tools, their teeth or a door jamb. The torque with which closures are applied is based on inappropriate data, measured on a Spanish population and using metal caps. The young and the elderly are the age groups also likely to get confused about which way to turn the closure to open it; over a quarter of the people observed turned closures the wrong way to open them. The use of a tool itself may make people more likely to turn the cap the wrong way. Opening strength increases markedly when using tools eg a nutcracker and a rubber mat. In adults was shown to be far higher than that needed to cause closures to missile in this study.

In summary, the study has produced bottle closure test protocols and independent performance data which were previously unavailable. It has been shown that under normal circumstances, the missiling of closures from PET bottles is highly unlikely. However, although still likely to be rare, missiling can happen when bottles have been exposed to conditions that can produce liquid temperatures of between 40 to 59(C and if closures are turned the wrong way during opening using tools such as nutcrackers or special openers. The use of tools is fairly common and may be more likely amongst the young and elderly who may find closures are currently too tight for them open unaided.

Human factors development of appropriate closures, tools and public information to reduce the risks of missiling closures may be necessary.

6 Recommendations

1. The evidence of this study is that bottle closures can missile or explode but only under certain conditions, namely inappropriate opening behaviour (turning the closure the wrong way and using tools to open caps) combined with storage of bottles in high temperatures. The relatively small number of reported accidents compared to the high exposure rates for these products indicates that incidents are likely to be rare. However, given that specific risk factors have now been identified it may be appropriate to inform industry and/or the public of these specific risks.
2. It may be possible to reduce the likelihood of tools being used or caps being turned the wrong way by making closures easier to open. This could be achieved either by slightly reducing the torque with which closures are applied or through redesign of the cap to provide better grip, but the need for contents integrity and security may rule out a substantial reduction in closure torque.
3. The study has provided some evidence that closure design/material may effect the likelihood of missiling. Further work is recommended in order to specify more closely the particular design features which lead to these differences in missiling probability.
4. The printing of arrows on the tops of caps indicating the direction of opening would help prevent confusion over opening direction such as when tools are used.

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