## TALAT Lecture 2105.01

# Case Study on Pressure Vessels

19 pages, 16 figures

Basic Level

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**Objectives:**

To help create an understanding of how material properties, costs of materials and of their fabrication, required product life, and product liability interact in different ways depending on the product.

**Prerequisites:**

Second year engineering course (UK university), i.e. a student with some knowledge of fabricating processes and the significance of such factors as fatigue, fracture toughness and environmental performance on material selection.

**Date of Issue: 1994**

# 2105.01 Case Study on Pressure Vessels

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## Some Considerations in the Design of Three Types of Pressure Vessels

Although at first glance there is little in common between an aircraft fuselage, a gas cylinder and a beer can, they are in fact all pressure vessels which must be designed to meet very specific requirements of integrity and cost, although the exact match of these vary widely. Also, the impacting issues of life expectancy, environmental effects, effect of cyclic loading, inspection during manufacture and use, together with product liability considerations all have to be taken into account.

The reasons for the choice of the best aluminium alloys for the designs are described and an indication given of how the alloys were developed to meet the requirements. In addition, the likely further changes necessary to maintain the market as customer requirements change are discussed, as well as competition from other materials, such as carbon fibre composites, titanium, various alloy steels and tin-plate.

## Introduction

In deciding how aluminium and its alloys can best be used for stressed components it is essential that the potential user should be familiar with the range of available alloys and the forms in which they can be obtained. While there are many sources of such data (1)(2)(3) it has to be accepted that in recent years the aluminium industry, with some exceptions (4)(5)(6), as a whole has not produced a great deal of information directly related to design. TALAT has of course sought to remedy this situation. That is not to say that such information does not exist, but much of it resides with those who have used aluminium for their particular products. And by design, we do not only refer to the methods by which stress calculations are made, but rather the wider aspects of alloy choice, availability in required form, cost and manufacture.

This case study discusses some of the issues which have had to be taken into account in achieving successful designs. Also it indicates the problems and opportunities that exist for the further development of the products chosen and shows how aluminium alloys are fitted to meet the challenge.

Consideration of three types of pressure vessels, an aircraft pressure cabin, a high pressure gas cylinder and a beverage can enables a set of comparisons to be made which illustrate these points. Much of the philosophy applies to other materials, although there are features of aluminium which make it different, if not unique, and these are highlighted.

## The Products

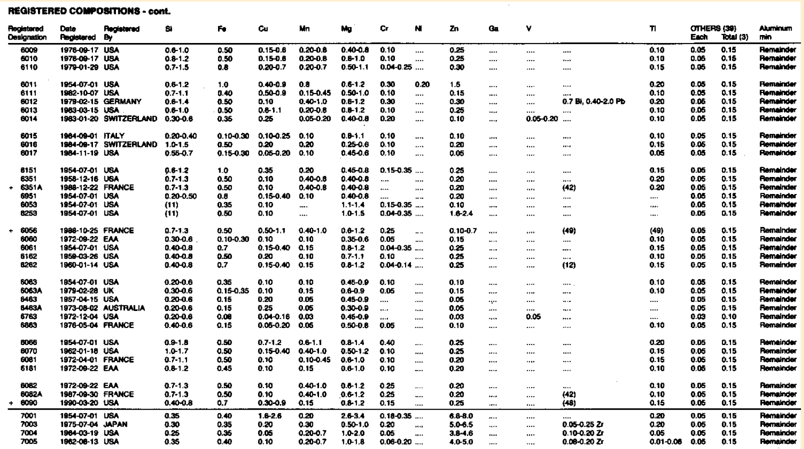
High pressure cylinders for the storage and transport of gases have been available in steel for over one hundred years and were widely used before aluminium became a viable engineering material. Aluminium cylinders were first used in the 1930s but have been in general use since 1960. On the other hand aircraft or at least air frames, and aluminium, have grown up together; indeed it can be debated that the aluminium and the aircraft industries have spurred each other’s growth since the time when they were both born at the beginning of the 20th century. Beer has been contained in barrels or bottles for hundreds of years and in tin-plate cans since before 1940. The first aluminium beer cans came into use in the 1950s.

The one thing they have in common, apart from the fact that they are subject to an internal pressure, is the need to preserve and deliver the contents in good condition at acceptable cost, whether that content is a high purity gas, a brand of lager, or you and me. A whole host of other considerations vary widely from product to product and with time, and it is shown how they are met and interact.

## The Alloys

In a recent record of International Alloy Designations published by the Aluminum Association (7) there are listed nearly 300 compositions for wrought alloys alone. Add to this all of the possible temper and heat treatment variables and it can be seen that the user has a very wide range of materials from which to choose (for extract from „Registration Record of International Alloy Designations and Chemical Composition Limits for Wrought Aluminium and Wrought Aluminium Alloys“ see **Figure 2105.01.01**). In fact, some of the alloys are very similar with just minor changes in some elements to create small, but nevertheless significant, changes in some characteristic of the alloy performance during manufacture and/or end use. In other instances, several alloys have much the same overall set of properties, but each is the choice of a particular country of origin. As a consequence of this large selection there is the good news and the bad news; good news that there is a wide choice, bad news because the user might not be able to decide on the best alloy. To counter the latter issue it is, therefore, essential that the user works closely with the supplier in deciding which alloy to choose.

Extract from "Registration Record of InternationalAlloy Designations and Chemical Composition Limits for Wrought Aluminium And Wrought Aluminium Alloys"

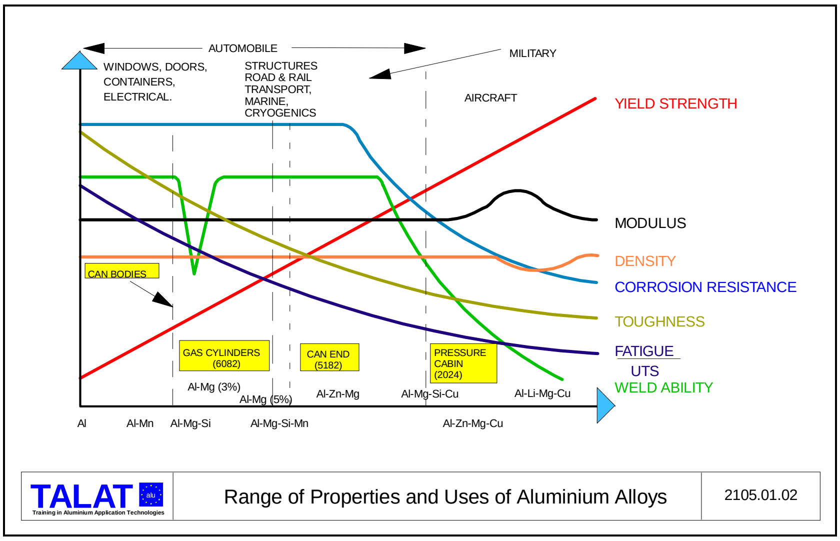


REGISTERED COMPOSITIONS - cont.

| Registered Designation | Date Registered | Registered By | Si | Fe | Cu | Mn | Mg | Cr | Ni | Zn | Ga | V | | Ti | OTHERS (39) | | Aluminum min |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | Each | Total (3) | |
| 6009 | 1976-09-17 | USA | 0.6-1.0 | 0.50 | 0.15-0.6 | 0.20-0.8 | 0.40-0.8 | 0.10 | .... | 0.25 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6010 | 1976-09-17 | USA | 0.8-1.2 | 0.50 | 0.15-0.6 | 0.20-0.8 | 0.6-1.0 | 0.10 | .... | 0.25 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6110 | 1979-01-29 | USA | 0.7-1.5 | 0.8 | 0.20-0.7 | 0.20-0.7 | 0.50-1.1 | 0.04-0.25 | .... | 0.30 | .... | .... | .... | 0.15 | 0.05 | 0.15 | Remainder |
| 6011 | 1954-07-01 | USA | 0.6-1.2 | 1.0 | 0.40-0.9 | 0.8 | 0.6-1.2 | 0.30 | 0.20 | 1.5 | .... | .... | .... | 0.20 | 0.05 | 0.15 | Remainder |
| 6111 | 1982-10-07 | USA | 0.7-1.1 | 0.40 | 0.50-0.9 | 0.15-0.45 | 0.50-1.0 | 0.10 | .... | 0.15 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6012 | 1979-02-15 | GERMANY | 0.6-1.4 | 0.50 | 0.10 | 0.40-1.0 | 0.6-1.2 | 0.30 | .... | 0.30 | .... | .... | 0.7 Bi, 0.40-2.0 Pb | 0.20 | 0.05 | 0.15 | Remainder |
| 6013 | 1983-03-15 | USA | 0.6-1.0 | 0.50 | 0.6-1.1 | 0.20-0.8 | 0.8-1.2 | 0.10 | .... | 0.25 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6014 | 1983-01-20 | SWITZERLAND | 0.30-0.6 | 0.35 | 0.25 | 0.05-0.20 | 0.40-0.8 | 0.20 | .... | 0.10 | .... | 0.05-0.20 | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6015 | 1984-09-01 | ITALY | 0.20-0.40 | 0.10-0.30 | 0.10-0.25 | 0.10 | 0.8-1.1 | 0.10 | .... | 0.10 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6016 | 1984-09-17 | SWITZERLAND | 1.0-1.5 | 0.50 | 0.20 | 0.20 | 0.25-0.6 | 0.10 | .... | 0.20 | .... | .... | .... | 0.15 | 0.05 | 0.15 | Remainder |
| 6017 | 1984-11-19 | USA | 0.55-0.7 | 0.15-0.30 | 0.05-0.20 | 0.10 | 0.45-0.6 | 0.10 | .... | 0.05 | .... | .... | .... | 0.05 | 0.05 | 0.15 | Remainder |
| 6151 | 1954-07-01 | USA | 0.6-1.2 | 1.0 | 0.35 | 0.20 | 0.45-0.8 | 0.15-0.35 | .... | 0.25 | .... | .... | .... | 0.15 | 0.05 | 0.15 | Remainder |
| 6351 | 1958-12-16 | USA | 0.7-1.3 | 0.50 | 0.10 | 0.40-0.8 | 0.40-0.8 | .... | .... | 0.20 | .... | .... | .... | 0.20 | 0.05 | 0.15 | Remainder |
| + 6351A | 1988-12-22 | FRANCE | 0.7-1.3 | 0.50 | 0.10 | 0.40-0.8 | 0.40-0.8 | .... | .... | 0.20 | .... | .... | (42) | 0.20 | 0.05 | 0.15 | Remainder |
| 6951 | 1954-07-01 | USA | 0.20-0.50 | 0.8 | 0.15-0.40 | 0.10 | 0.40-0.8 | .... | .... | 0.20 | .... | .... | .... | .... | 0.05 | 0.15 | Remainder |
| 6053 | 1954-07-01 | USA | (11) | 0.35 | 0.10 | .... | 1.1-1.4 | 0.15-0.35 | .... | 0.10 | .... | .... | .... | .... | 0.05 | 0.15 | Remainder |
| 6253 | 1954-07-01 | USA | (11) | 0.50 | 0.10 | .... | 1.0-1.5 | 0.04-0.35 | .... | 1.6-2.4 | .... | .... | .... | .... | 0.05 | 0.15 | Remainder |
| + 6056 | 1988-10-25 | FRANCE | 0.7-1.3 | 0.50 | 0.50-1.1 | 0.40-1.0 | 0.6-1.2 | 0.25 | .... | 0.10-0.7 | .... | .... | (49) | (49) | 0.05 | 0.15 | Remainder |
| 6060 | 1972-09-22 | EAA | 0.30-0.6 | 0.10-0.30 | 0.10 | 0.10 | 0.35-0.6 | 0.05 | .... | 0.15 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6061 | 1954-07-01 | USA | 0.40-0.8 | 0.7 | 0.15-0.40 | 0.15 | 0.8-1.2 | 0.04-0.35 | .... | 0.25 | .... | .... | .... | 0.15 | 0.05 | 0.15 | Remainder |
| 6162 | 1959-03-26 | USA | 0.40-0.8 | 0.50 | 0.20 | 0.10 | 0.7-1.1 | 0.10 | .... | 0.25 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6262 | 1960-01-14 | USA | 0.40-0.8 | 0.7 | 0.15-0.40 | 0.15 | 0.8-1.2 | 0.04-0.14 | .... | 0.25 | .... | .... | (12) | 0.15 | 0.05 | 0.15 | Remainder |
| 6063 | 1954-07-01 | USA | 0.20-0.6 | 0.35 | 0.10 | 0.10 | 0.45-0.9 | 0.10 | .... | 0.10 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6063A | 1979-02-28 | UK | 0.30-0.6 | 0.15-0.35 | 0.10 | 0.15 | 0.6-0.9 | 0.05 | .... | 0.15 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6463 | 1957-04-15 | USA | 0.20-0.6 | 0.15 | 0.20 | 0.05 | 0.45-0.9 | .... | .... | 0.05 | .... | .... | .... | .... | 0.05 | 0.15 | Remainder |
| 6463A | 1973-08-02 | AUSTRALIA | 0.20-0.6 | 0.15 | 0.25 | 0.05 | 0.30-0.9 | .... | .... | 0.05 | .... | .... | .... | .... | 0.05 | 0.15 | Remainder |
| 6763 | 1972-12-04 | USA | 0.20-0.6 | 0.08 | 0.04-0.16 | 0.03 | 0.45-0.9 | .... | .... | 0.03 | .... | 0.05 | .... | .... | 0.03 | 0.10 | Remainder |
| 6863 | 1976-05-04 | FRANCE | 0.40-0.6 | 0.15 | 0.05-0.20 | 0.05 | 0.50-0.8 | 0.05 | .... | 0.10 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6066 | 1954-07-01 | USA | 0.9-1.8 | 0.50 | 0.7-1.2 | 0.6-1.1 | 0.8-1.4 | 0.40 | .... | 0.25 | .... | .... | .... | 0.20 | 0.05 | 0.15 | Remainder |
| 6070 | 1962-01-18 | USA | 1.0-1.7 | 0.50 | 0.15-0.40 | 0.40-1.0 | 0.50-1.2 | 0.10 | .... | 0.25 | .... | .... | .... | 0.15 | 0.05 | 0.15 | Remainder |
| 6081 | 1972-04-01 | FRANCE | 0.7-1.1 | 0.50 | 0.10 | 0.10-0.45 | 0.6-1.0 | 0.10 | .... | 0.20 | .... | .... | .... | 0.15 | 0.05 | 0.15 | Remainder |
| 6181 | 1972-09-22 | EAA | 0.8-1.2 | 0.45 | 0.10 | 0.15 | 0.6-1.0 | 0.10 | .... | 0.20 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6082 | 1972-09-22 | EAA | 0.7-1.3 | 0.50 | 0.10 | 0.40-1.0 | 0.6-1.2 | 0.25 | .... | 0.20 | .... | .... | .... | 0.10 | 0.05 | 0.15 | Remainder |
| 6082A | 1987-09-30 | FRANCE | 0.7-1.3 | 0.50 | 0.10 | 0.40-1.0 | 0.6-1.2 | 0.25 | .... | 0.20 | .... | .... | (42) | 0.10 | 0.05 | 0.15 | Remainder |
| + 6090 | 1990-03-20 | USA | 0.40-0.8 | 0.7 | 0.30-0.9 | 0.15 | 0.8-1.2 | 0.15 | .... | 0.25 | .... | .... | (48) | 0.15 | 0.05 | 0.15 | Remainder |
| 7001 | 1954-07-01 | USA | 0.35 | 0.40 | 1.6-2.6 | 0.20 | 2.6-3.4 | 0.18-0.35 | .... | 6.8-8.0 | .... | .... | .... | 0.20 | 0.05 | 0.15 | Remainder |
| 7003 | 1975-07-04 | JAPAN | 0.30 | 0.35 | 0.20 | 0.30 | 0.50-1.0 | 0.20 | .... | 5.0-6.5 | .... | .... | 0.05-0.25 Zr | 0.20 | 0.05 | 0.15 | Remainder |
| 7004 | 1964-03-19 | USA | 0.25 | 0.35 | 0.05 | 0.20-0.7 | 1.0-2.0 | 0.05 | .... | 3.8-4.6 | .... | .... | 0.10-0.20 Zr | 0.05 | 0.05 | 0.15 | Remainder |
| 7005 | 1962-08-13 | USA | 0.35 | 0.40 | 0.10 | 0.20-0.7 | 1.0-1.8 | 0.06-0.20 | .... | 4.0-5.0 | .... | .... | 0.08-0.20 Zr | 0.01-0.06 | 0.05 | 0.15 | Remainder |

TALAT Training in Aluminium Application Technologies | Example of Range of Aluminium Alloys to Choose from | 2105.01.01

**Figure 2105.01.02** and **Figure 2105.01.03** show where the various alloy types are used and where the three products which form the basis of this paper lie. Because the initial use of aluminium for these products occurred at different times, the numbers of alloys available at those times were different and the way in which alloy modifications were made to suit the particular requirements is part of the design story. These modifications, of course, were added to the alloy list, and no doubt further adjustments will be necessary to meet changing customer demands. The extent to which this development to meet the specified requirements of one application can be exploited in other areas would constitute separate case studies, but some reference is made to it in the context of the effort which can be afforded in attempting to bring about a change; the wider the possible use of the alloy the more likely it is that the investment will be seen as worthwhile.



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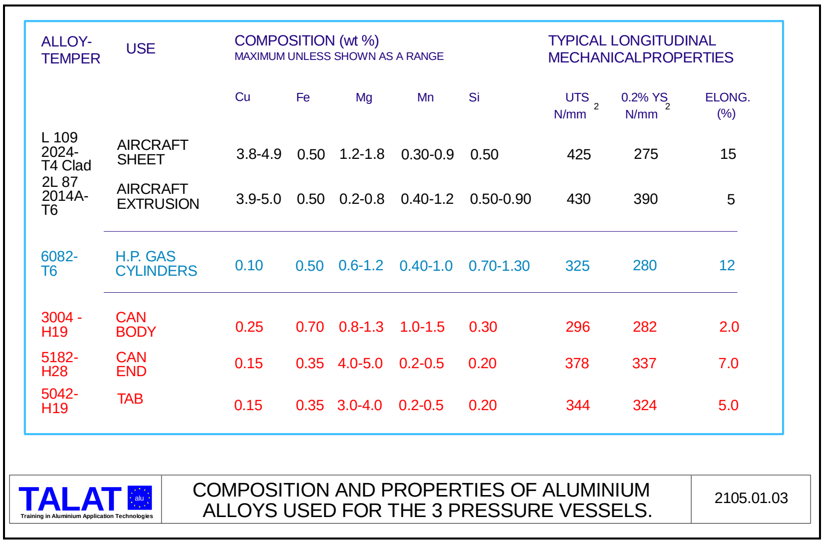
Range of Properties and Uses of Aluminium Alloys

2105.01.02



| ALLOY-TEMPER | USE | COMPOSITION (wt %) MAXIMUM UNLESS SHOWN AS A RANGE | | | | | TYPICAL LONGITUDINAL MECHANICALPROPERTIES | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cu | Fe | Mg | Mn | Si | UTS N/mm$^2$ | 0.2% YS N/mm$^2$ | ELONG. (%) |
| L 109 2024-T4 Clad | AIRCRAFT SHEET | 3.8-4.9 | 0.50 | 1.2-1.8 | 0.30-0.9 | 0.50 | 425 | 275 | 15 |
| 2L 87 2014A-T6 | AIRCRAFT EXTRUSION | 3.9-5.0 | 0.50 | 0.2-0.8 | 0.40-1.2 | 0.50-0.90 | 430 | 390 | 5 |
| 6082-T6 | H.P. GAS CYLINDERS | 0.10 | 0.50 | 0.6-1.2 | 0.40-1.0 | 0.70-1.30 | 325 | 280 | 12 |
| 3004 - H19 | CAN BODY | 0.25 | 0.70 | 0.8-1.3 | 1.0-1.5 | 0.30 | 296 | 282 | 2.0 |
| 5182-H28 | CAN END | 0.15 | 0.35 | 4.0-5.0 | 0.2-0.5 | 0.20 | 378 | 337 | 7.0 |
| 5042-H19 | TAB | 0.15 | 0.35 | 3.0-4.0 | 0.2-0.5 | 0.20 | 344 | 324 | 5.0 |

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COMPOSITION AND PROPERTIES OF ALUMINIUM ALLOYS USED FOR THE 3 PRESSURE VESSELS.

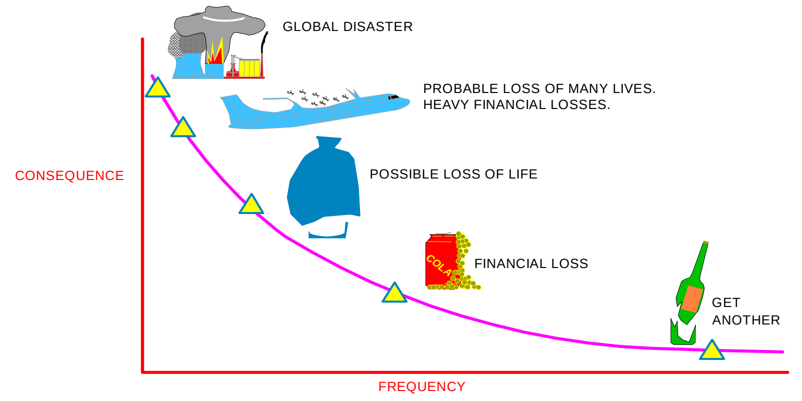
2105.01.03

# Product Integrity

Any product must do what is required of it, if the manufacturer and the supplier of the material from which it is made are to escape criticism, loss of future business, financial claims or possibly legal issues which can involve criminal proceedings. Indeed, the introduction of strict product liability in many countries adds a very sharp incentive to sound design!

## Consequences of In-Service Failure

It is essential, therefore, to look at the consequences of failure of a product as well as the modes by which it can fail if not properly designed (**Figure 2105.01.04**).



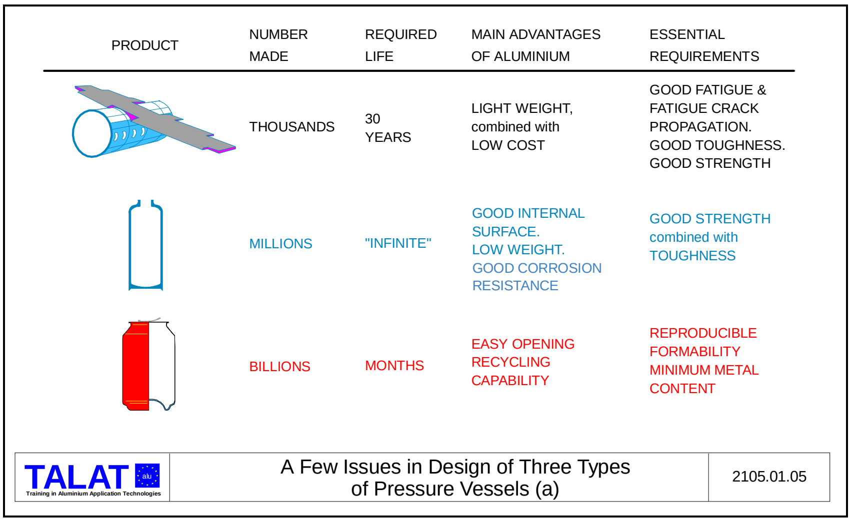
TALAT Training in Aluminium Application Technologies | Relative Consequences of In-Service Failure | 2105.01.04

In the case of the aircraft pressure cabin, sudden loss of pressure in flight would almost certainly result in passenger death and loss of the aircraft. Also, unless the reasons for the failure were immediately obvious and applicable only to the aircraft in question, the remaining fleet of that type would be grounded or at least subject to expensive surveys.

For the high pressure gas cylinder the consequences of failure could be almost equally dramatic, for if a burst occurred in a crowded area many lives could be lost. Also, the escape of the gas could be dangerous, even if no burst were involved. A less dramatic, but nevertheless important issue is the degree to which the contents of the cylinder retains its properties, the composition of the contained gas might need to be stable to parts per million for many years and since many such gases are very expensive, severe financial penalties can result if the stability is lost. A failure of a beverage can might not be as catastrophic as the other two, but a condition which was found to be common to a large number of such cans and which caused them to release their content prematurely, for example corrosion, or some failure of the easy-opening feature which rendered the content inaccessible, would result in very serious financial loss. While the inert nature of aluminium in contact with beer and soft drinks avoids any issue of dangerous product contamination the retention of taste of the product is essential and the coating applied to the can interior must be correct.

### Production Volume

The numbers of each component produced and in service are of course very different (**Figure 2105.01.05 and Figure 2105.01.06**). There are some thousands of pressure cabins, tens of millions of gas cylinders and many thousands of millions of beer cans in use. It is obvious that the need for integrity will govern the frequency and degree of thorough inspection; it is as well that the need to inspect is loosely inversely proportionate to the numbers!



| PRODUCT | NUMBER MADE | REQUIRED LIFE | MAIN ADVANTAGES OF ALUMINIUM | ESSENTIAL REQUIREMENTS |
|---|---|---|---|---|
|  | THOUSANDS | 30 YEARS | LIGHT WEIGHT,<br>combined with<br>LOW COST | GOOD FATIGUE & FATIGUE CRACK PROPAGATION.<br>GOOD TOUGHNESS.<br>GOOD STRENGTH |
|  | MILLIONS | "INFINITE" | GOOD INTERNAL SURFACE.<br>LOW WEIGHT.<br>GOOD CORROSION RESISTANCE | GOOD STRENGTH<br>combined with<br>TOUGHNESS |
|  | BILLIONS | MONTHS | EASY OPENING<br>RECYCLING CAPABILITY | REPRODUCIBLE FORMABILITY<br>MINIMUM METAL CONTENT |

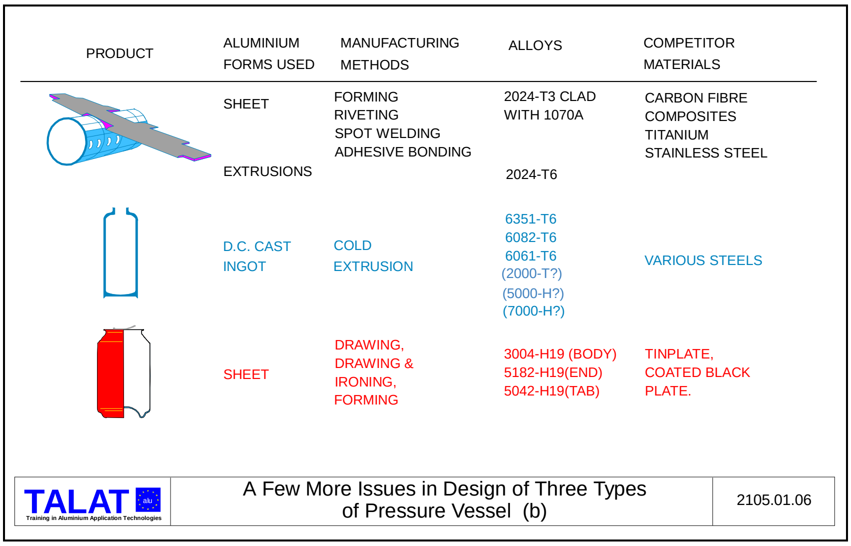
TALAT Training in Aluminium Application Technologies

A Few Issues in Design of Three Types of Pressure Vessels (a)

2105.01.05

### Life Cycle

A further factor is the expected life of the product (see again **Figures 2105.01.05 and 2105.01.06**). A gas cylinder is expected to have infinite life in that no limit is set by specifications providing the cylinder passes its periodic testing. The beer can has limited life by virtue of the desire of the packer to sell his product as quickly as possible. The pressure cabin is part of an aeroplane which will perhaps be in service for 30 years or more but the philosophy of aircraft design is to replace or repair components within that time if on inspection they are found to contain defects, or if they have exceeded a predetermined design life.



| PRODUCT | ALUMINIUM FORMS USED | MANUFACTURING METHODS | ALLOYS | COMPETITOR MATERIALS |
|---|---|---|---|---|
| | SHEET | FORMING<br>RIVETING<br>SPOT WELDING<br>ADHESIVE BONDING | 2024-T3 CLAD WITH 1070A | CARBON FIBRE COMPOSITES<br>TITANIUM<br>STAINLESS STEEL |
| | EXTRUSIONS | | 2024-T6 | |
| | D.C. CAST INGOT | COLD EXTRUSION | 6351-T6<br>6082-T6<br>6061-T6<br>(2000-T?)<br>(5000-H?)<br>(7000-H?) | VARIOUS STEELS |
| | SHEET | DRAWING,<br>DRAWING & IRONING,<br>FORMING | 3004-H19 (BODY)<br>5182-H19(END)<br>5042-H19(TAB) | TINPLATE,<br>COATED BLACK PLATE. |

TALAT

A Few More Issues in Design of Three Types of Pressure Vessel (b)

2105.01.06

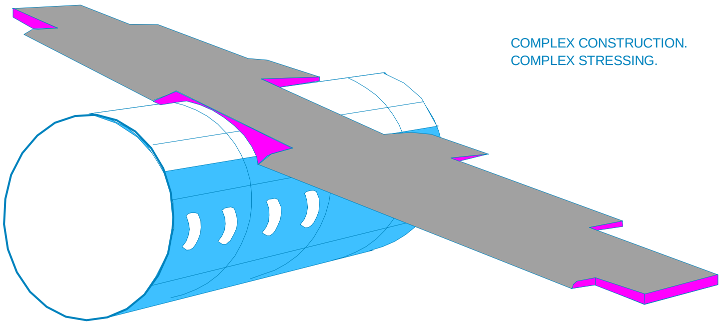
All three components have to be capable of resisting a range of incidental abuse but fortunately their fundamental design and operation seems to fit them to accommodate such mishap. An aircraft cabin might be dented by a loading truck but it would hardly go unnoticed, a beer can body could not be expected to withstand loads much greater than those which could be exerted by a human hand; many gas cylinders have to withstand gross handling abuse but the need to be able to withstand high internal pressure means that the walls are thick enough to guarantee this. In fact, for the pressure cabin and the gas cylinder there are also damage tolerance criteria which have been established by testing and which dictate if repair or rejection of the component should occur at the regular inspection periods.

## Design Considerations

In addition to the component doing what is required of it technically, an obvious requirement is that it can be made at a cost which will make it competitive with alternatives made from other materials, as well as with other manufacturers' products made in aluminium, and in this context both material and fabrication economics have to be carefully considered. The degree and nature of competition in the three chosen examples is very different.

### Pressure Cabin

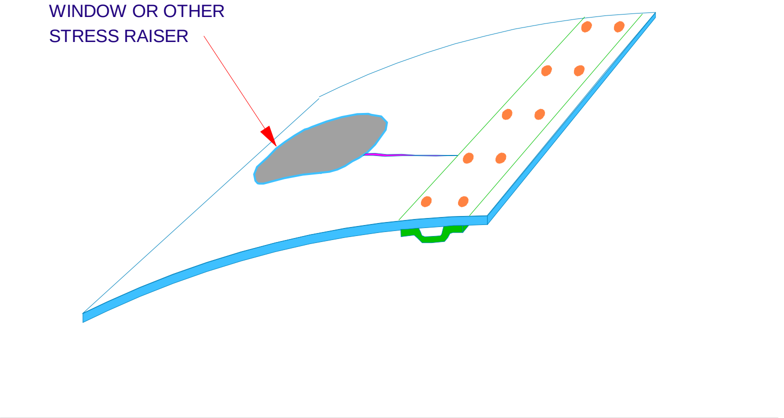
The recognised form of the cabin is basically a cylinder made up of thick sheet, stiffened and reinforced with stringers which are extruded or roll formed, and which are either riveted, spot-welded and/or adhesively bonded to the shell (**Figure 2105.01.07**). Individual aircraft builders obviously plan the construction to give them the most economic manufacturing route, for while the main objective is to provide the safest, lightest construction possible - a kilogram of weight saved safely is worth perhaps hundreds of dollars in the overall life of the aircraft - initial material and fabrication costs are nevertheless important. Thus, at the moment, although there are possible alternatives to aluminium, for example carbon fibre composites and titanium which could give a weight saving, the additional material cost and unknowns about the best way to fabricate safe structures from the alternative materials mean that for civil aircraft design, users stay with aluminium. Even the advent of the aluminium-lithium alloys with reduced density and increased elastic modulus does not automatically mean that the alloys used for many years will be replaced, since the increased cost of the new alloy may not be seen as worthwhile.



COMPLEX CONSTRUCTION.
COMPLEX STRESSING.

TALAT Training in Aluminium Application Technologies | Aircraft Fuselage - An Example of a Pressure Vessel | 2105.01.07

The cabin must be capable of withstanding the internal pressure in flight, that is about 0,6 $kg/cm^2$ as well as loads transmitted by wings and undercarriage, but it must withstand many repetitions of these loads without catastrophic failure (8). The Comet experience of the 1950s showed that if a fatigue crack does start as a result of some detail design error it must not propagate far enough to become of critical size and the careful arrangement of stringers, which act as crack stoppers, is very important. Thus, while the alloy chosen must be as strong as possible, that strength must be combined with a fatigue resistance and fracture toughness which give minimum weight together with an adequate protection against rapid crack growth. This does not mean that no crack can be allowed to occur, but rather that it should not occur before a certain time, and that if and when it does it should be detectable within a predictable period. In this context it is essential that inspection of likely crack locations can be made at minimum cost and this aspect must be considered in design (**Figure 2105.01.08**). The experience gained over 30 years design with well understood aluminium alloys, based on extensive testing and service experience will be hard to replace.



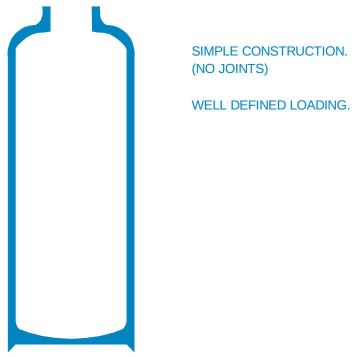
Aircraft Skin & Structure Construction - With Crack Constraint

2105.01.08

With all these considerations in mind and despite the many alloys available to select from, the almost universal choice of aluminium alloy for pressure cabins is 2024-T3. This alloy is used for both skin and stringers, although parts of the frame might include 2014-T6 for parts where both strength and fatigue resistance are required. Other parts where strength is the only important criteria can be made from 7075-T6.

## High Pressure Gas Cylinders

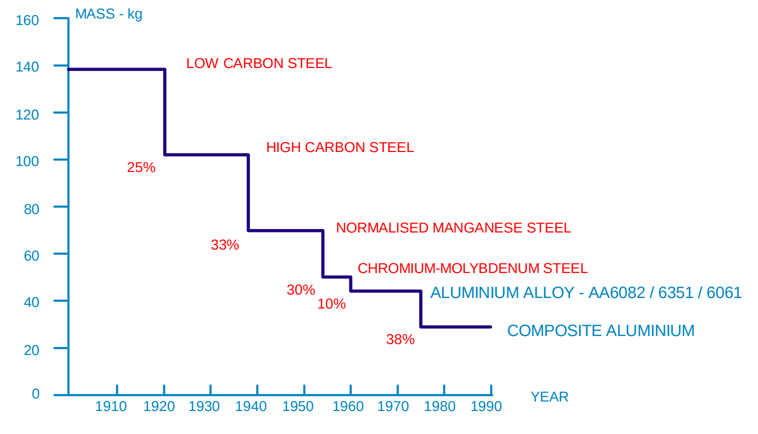
While aluminium is the undisputed material selection for civil airliner pressure cabins, it has to face severe competition from various steels in the fabrication of high pressure gas cylinders, and indeed can only compete successfully in certain sizes and markets (**Figure 2105.01.09**).



High Pressure Gas Cylinder - An Example of a Pressure Vessel

2105.01.09

In general, aluminium cylinders are lighter than steel, although the lower density of aluminium is largely countered by the high strength of many of the steels now in use (**Figure 2105.01.10**). Thus, for sizes which can be lifted by an individual, say up to 20 litre capacity, some weight advantage exists and in that size range aluminium has captured a large part of the market in most industrial countries including UK, USA, Europe, Australia and increasingly in Japan. Carbon Dioxide, Oxygen and Air are the gases most commonly packed. The additional attractions of good corrosion resistance and attractive appearance are often sufficient to counter any cost disadvantage. Increasingly, aluminium cylinders are being used over the whole size range, that is up to say 50 litres, for those gases which are required to retain high purity for long periods, and where the compatibility of aluminium with such gases is much better than it is with steel.



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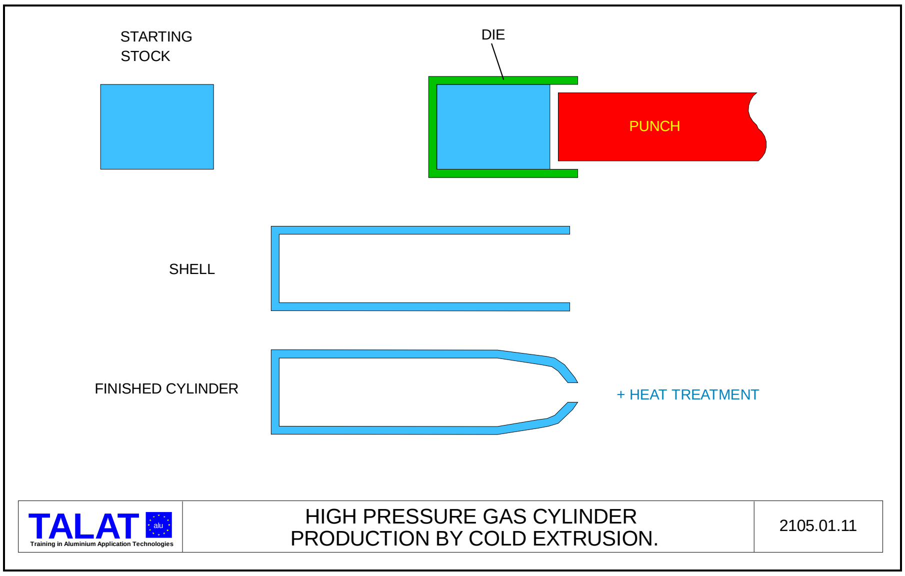
High Pressure Gas Cylinder - Weight Savings from Use of Different Materials

2105.01.10

Approximately 2.0 million aluminium high pressure gas cylinders are made each year and probably 90 % of them are made from one or two alloys and one process **(9)**. By virtue of their low as cast strength even quite strong alloys can be cold extruded to form the shell of the cylinder with one blow (**Figure 2105.01.11**). The presses for such production are of high capacity and are expensive, but they operate at up to 200 strokes per hour and when all auxiliary equipment is geared to match the press speed, production costs are relatively low compared with the methods used for making steel cylinders, thus to some extent countering the high cost of raw material. The alloys which best match the process and the necessary property requirements are of the aluminium/magnesium/ silicon group i.e. 6351 (6082) and 6061.

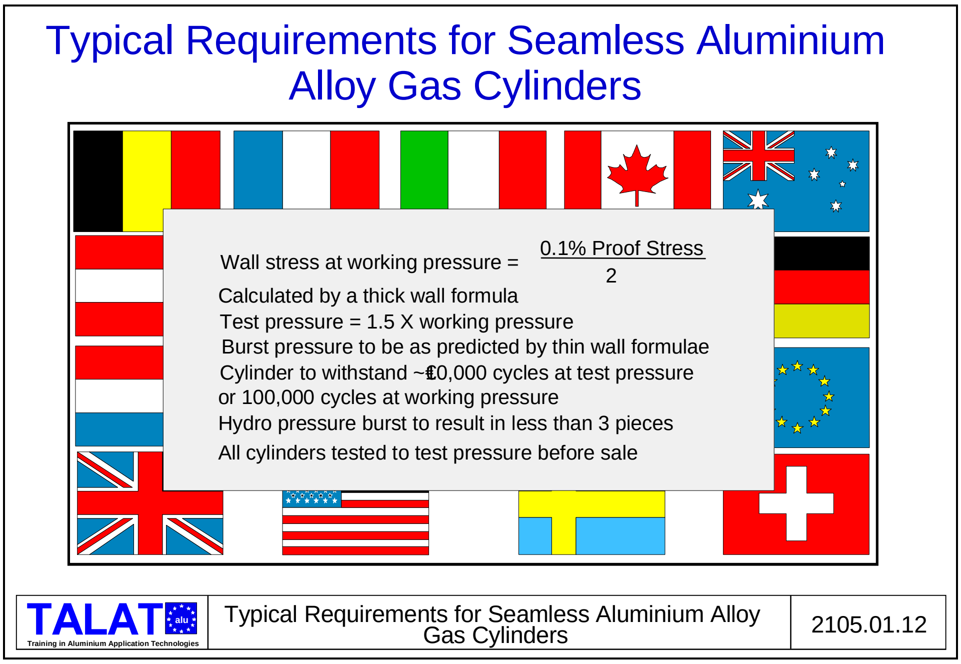
These alloys have little more than half the strength of the high strength 7000 series, but have much better deformation characteristics and better toughness, corrosion and stress corrosion resistance, as well as higher specific fatigue strength. This is not to say that cylinders cannot be, or indeed are not, made from stronger alloys, but like most components the exact end use has to be carefully observed if the correct alloy choice is to be made. Thus, for those cylinders which will be in service alongside steel cylinders for the gases listed above, and where in consequence occasional rough handling and varied environment must be expected, coupled with an inspection period which may be up to 10 or even 20 years, it is essential that the alloy has the right combination of properties, only one of which is adequate strength. The 6000 series are accepted as having this portfolio.



HIGH PRESSURE GAS CYLINDER PRODUCTION BY COLD EXTRUSION.

2105.01.11

Many countries have their own cylinder design codes for both steel and aluminium which differ in more or less minor ways from others, and although the small differences do make the introduction of any International Standard difficult, the main principles are the same (**Figure 2105.01.12**).



Typical Requirements for Seamless Aluminium Alloy Gas Cylinders

Wall stress at working pressure = $\frac{\text{0.1\% Proof Stress}}{2}$

Calculated by a thick wall formula

Test pressure = 1.5 X working pressure

Burst pressure to be as predicted by thin wall formulae

Cylinder to withstand ~€0,000 cycles at test pressure
or 100,000 cycles at working pressure

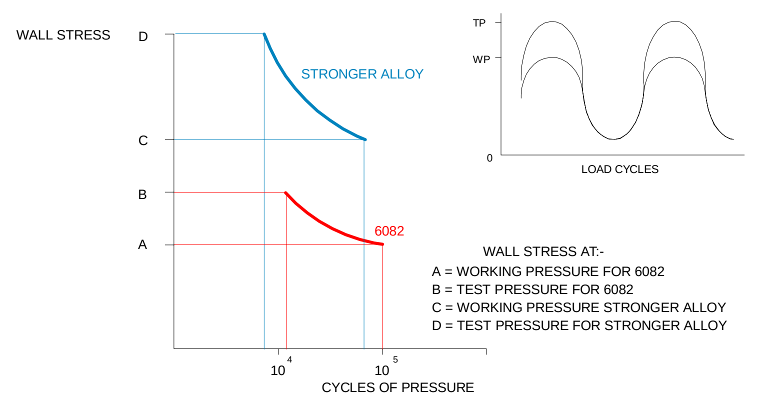
Hydro pressure burst to result in less than 3 pieces

All cylinders tested to test pressure before sale

Typical Requirements for Seamless Aluminium Alloy Gas Cylinders

2105.01.12

All require that the wall stress at a test pressure, usually 1.5 x the working pressure, shall be about three-quarters of the guaranteed minimum yield or proof stress of the material (**Figure 2105.01.13**). Despite the fact that different thick wall formulae are used to calculate that stress the resulting wall thicknesses for a given traffic are not very different. Most codes also require that the hydraulic pressure necessary to burst a cylinder shall be predictable by a simple thin wall equation and some require that a prototype hydropneumatic burst test should not result in violent shatter. Also, prototype cylinders must pass a very severe fatigue test which requires that about 10,000 test pressure reversals can be withstood without failure, and/or about 80,000 reversals at the working pressure. Every cylinder must undergo a proof test at the test pressure and some codes demand that any permanent expansion should be measured and limited to some agreed percentage of the total expansion (5 % in most cases but 10 % in the USA).



TALAT Training in Aluminium Application Technologies | FATIGUE CURVES FOR CYLINDERS MADE FROM 6082 AND A STRONGER ALLOY. | 2105.01.13

In consequence of these severe test requirements it is not surprising that cylinders made from the 6000 series whose general corrosion resistance is very good and which do not have any stress corrosion susceptibility have suffered few service problems. Increased competition from new or improved steels and the demand for further weight saving in some traffics will mean that stronger aluminium alloys will be considered for some of those cylinders now made from the 6000 series. As indicated above the 7000 series have been considered, although it is certain that the full T6 strength will not be utilised. In fact, artificial ageing practice will be such as to back off from optimum strength but increase stress corrosion resistance and toughness to "acceptable" levels. In the case of stress corrosion avoidance this might involve anodizing or coating to exclude the environment or perhaps restrict the use to those applications where the conditions of service can be guaranteed.

It is generally accepted that the toughness of gas cylinder materials will be seen as more significant in future, because the concept of leak-before-burst is becoming increasingly significant. Future specifications might well demand that should any defect be present at manufacture, or develop in service, the cylinder could not rupture at some pre-determined pressure, for example the maximum pressure which could be developed at the reference temperature which is usually 60 or 65 degree C. The fracture mechanics analysis and prototype testing necessary to ensure such a criteria depends on high toughness and some materials which would pass the present test required by specification would not be capable of being stressed to the currently allowable fraction of their yield strength. This does not, however, apply to the 6000 series aluminium alloys, which pass the hypothetical criteria outlined above and which could probably even accept an increase in allowable design stress and still have a satisfactory leak-before-burst performance.

In fact, if the design wall stress were increased, the limiting factor would be the fatigue test requirement which as indicated is very severe. Ironically, it is probable that originally set as the level which could be easily achieved by steel cylinders and is recognised by many experts as a check on detail design as distinct from a genuine performance requirement. If a cylinder were proof tested every two years, the minimum time for any current specification, it would only be raised to the test pressure 50 times in a life of 100 years, and in that same time it would have to be filled and discharged twice per day to achieve the required test life at service pressure.

It can in consequence be argued that some relaxation of the fatigue requirement would be logical in the interest of greater cylinder efficiency with no real reduction in safety.

The need for strength, together with toughness, as well as freedom from environmental sensitivity, suggests that some recent developments in aluminium alloy composites might have a part to play in future gas cylinder design. It seems probable, however, that the economics of manufacture with such materials combined with the considerably higher material costs would mitigate against their use except for special cases where minimum weight and/or volume were at a premium.

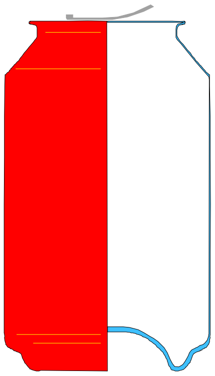
In the context of alloy choice it is worth noting that the aluminium alloys used for gas cylinder manufacture were all developed for hot extrusions, or as rolling alloys where hot and cold work are combined. Yet the usual method of making the cylinder is cold extrusion with a minority being made by warm extrusion followed by wall ironing. Why not use alloys designed to respond to cold working in a way which would combine manufacturing ease with optimum properties? Much has been learned in recent years about alloy design with respect to the effect of minor element additions, thermomechanical working etc. and it is indeed possible that alloys better than those now available will be developed if the effort seems to be worthwhile in the light of possible future markets.

### Beverage Cans

**(Figure 2105.01.14)**

In many respects the use of aluminium for cans to contain pressurized beer and soft drinks seems an obvious choice, particularly to an observer who looks only at the situation today. The easy opening end, which to date has only been possible with aluminium, coupled with the value of the recycled product in an environment which increasingly demands maximum utilization of materials and avoidance of litter, puts aluminium in a very favourable position. Add to the list the fact that it has such good corrosion resistance and attractive appearance and one could wonder how tin-plate or coated black plate containers could even be considered. Yet despite these very real advantages, the effort necessary to keep the aluminium beverage can in its dominant position has been massive and continuous over the 25 to 30 years since its introduction.

The attractive size of the potential market and the strength of the opposition from tin-plate matched each other to a degree which fuelled a long and exciting battle demanding much from the alloys used, the methods of producing them and the cans themselves, and the design of the can **(10)**. All of these factors interacted and while a detailed description of the developments is beyond the scope of this case study, some points can be discussed (A full description is contained in TALAT Lecture 3710).



COMPLEX CONSTRUCTION.
WELL DEFINED OPERATION.

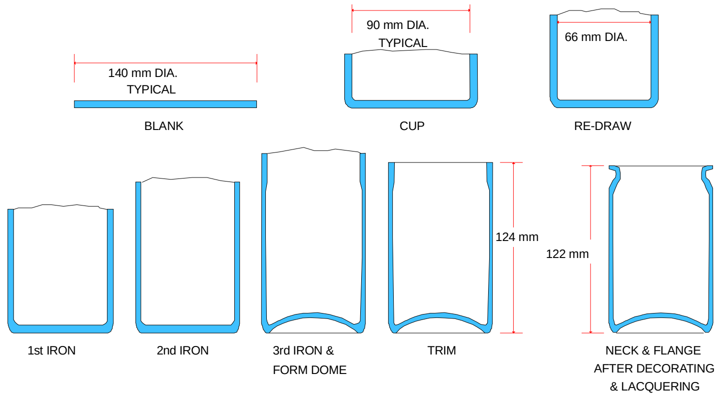
BEVERAGE CAN -
AN EXAMPLE OF A PRESSURE VESSEL.

2105.01.14

Although alloys very similar to that now used for the can-end (5182) were available when the development began, there have been necessary changes in composition and in the rolling sequence in the production of the end stock to provide a combination of strength and formability in a H19 temper which allows the production of an end which can be consistently scored, formed and seamed in a gauge which is a minimum for any particular end design. The need for this economy with metal cannot be over-emphasised since while it is an important feature in the successful design of the other two vessels considered in this paper, it is essential in the case of the beer can where metal cost is so large a part of the total cost. In this context it should be noted how the end diameter of the can has been reduced since the first aluminium cans were made. The smaller diameter means that less metal is used on two counts; lower gauge because internal pressure is acting on a smaller area plus the reduction of the area itself. This change in can shape was only possible when the can fillers adjusted their equipment to accommodate the shape difference, equipment which had previously been geared to three-piece tin-plate cans.

Further reduction in end gauge might be possible by use of heat treatable alloys which would have a higher strength than the work hardened 5182. The artificial ageing of such alloys could be combined with lacquer stoving, but it has to be remembered that such a change would have to involve a production route which, when combined with the gauge reduction, allowed an overall cost saving.

The alloy used for can bodies, 3004, was available before aluminium beverage cans were considered, but the development of a rolling practice to produce a H19 temper which could be drawn and ironed at high speeds (**Figure 2105.01.15**), together with the necessary ironing die technology, required very considerable effort by both the aluminium industry and various equipment makers.



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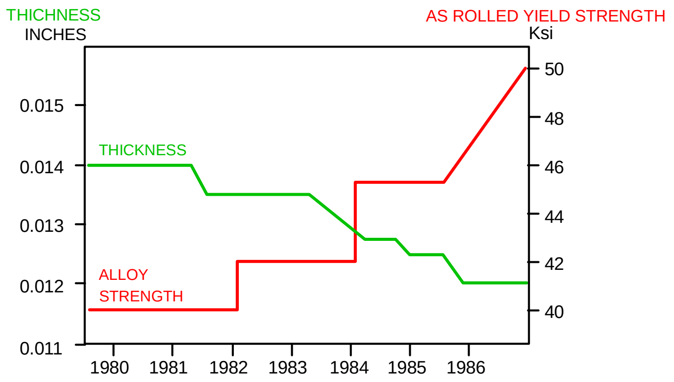
DRAW AND WALL-IRON METHOD
OF CAN MANUFACTURE. (33cl CAN)

2105.01.15

As with the can end, the base and wall thicknesses have been reduced over the period in which the aluminium can has been used and the current wall thickness is no more than 0.1 mm (**Figure 2105.01.16**). When this is compared with the 0,3 mm thickness of tin-plate employed 25 years ago, it is evident that the changes made in can handling equipment to accommodate the can shape also have to take account of the reduced rigidity of the cans as they are handled and filled. In fact the can wall is now so thin that it is only the internal pressure created by the beer or soft drink that enables the filled can to be handled during transport to, and by the customer; for those beverages that are not carbonated, it is necessary to provide an internal pressure with an inert gas!



NOTE: IMPROVED END DESIGN ALSO CONTRIBUTES TO THICKNESS REDUCTION.

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USE OF INCREASED STRENGTH
ALLOWS MATERIAL THICKNESS REDUCTION.

2105.01.16

## Conclusions

The three examples described involve the successful and long term use of aluminium in very different circumstances with respect to the volumes of aluminium employed, competition from other materials, likely future changes of both the markets and the available alloys and the consequences of any failure of the component to function. In all cases the economics of both material use and production are important, even when the use of alternative materials would be difficult or even impossible at the present time. The extent to which development or adjustment of alloys and properties can be undertaken, and the effort which can be put into the equipment needed to accommodate material changes, must be geared to the potential market. Once the product is established it may be necessary to devote an equal or even greater effort to maintain the market against competition from existing materials which have been improved, or new materials which have become available. The consequences of losing a market also have to be considered; a move away from aluminium beer cans would affect 10 % of the aluminium industry's total production. On the other hand if for any reason aluminium alloys were not available to the builders of civil aircraft, such vehicles would be impractical for some years to come!

Finally, let us look at recycling, an issue which had little or no significance when the three uses under consideration were first muted, but which now has to be taken into account in any design. For the aircraft cabin the life cycle is long and the volumes of aluminium used not great, so recycling is at first sight not too important. However, should the aluminium-lithium alloys be used the problem of contamination by lithium of other alloy scrap is recognised as one which has to be resolved. The collection and re-melting of used beverage cans is now a vital part of the logic of the use of aluminium and while the inherent advantages of the metal are certainly proved, it is probable that the continued use, at least in some countries, depends on its recycling capability. Interestingly, the legislation against litter which is increasingly topical, is easier to implement if there is value in the "rubbish" collected. Since the life of a gas cylinder is in theory infinite, there would appear to be no recycling issue; yet even in that application it cannot be escaped. Because of their known scrap value and often ready access, cylinders are sometimes stolen for illegal remelting, so much so that serious attention has been given to "fingerprinting" the alloys used so that identification in a scrap melt would be possible.

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## List of Figures