GRANTA
TEACHING RESOURCES

ADVANCED INDUSTRIAL CASE STUDIES

Aerospace Pressure Vessels

Claes Fredriksson and Luca Masi
Granta Design, 300 Rustat House, 62 Clifton Rd, Cambridge, CB1 7EG, UK

First published June 2016

Contents

Summary

This Case Study demonstrates how CES EduPack can aid in the selection of materials for light and safe pressure vessels in typical aerospace applications. In particular, we show how to minimize mass, while safety performance including the material properties toughness and strength at low temperatures, is maximized. The Case Study is inspired by a paper presented by NASA [1] and is pertinent to materials used for, *e.g.*, Space Shuttle tanks and the cryogenic tanks of Ariane rockets. CES EduPack enables informed materials choices while clearly showing the steps of the process for the purpose of teaching and training. In this particular Case Study, the ability to plot, compare and discuss multiple material indices in parallel is showcased. We have included relevant equations to facilitate a strength/mechanics of materials perspective.

1. Introduction

There are many examples of pressure vessels in aerospace applications. Pressurized cabins in airplanes and space crafts, for instance, are exposed to large variations in pressure as the external pressures vary from atmospheric conditions down to almost zero in space or at very high altitudes. There are also examples of compressed gas tanks that contain fuels, creating distributed forces from the inside onto the container wall. These applications all have many design requirements for an optimal material choice but one common limiting constraint is that an explosion due to fast fracture needs to be avoided.

Safety is a priority in the design of pressure vessels and this is particularly true for aerospace applications. Moreover, mechanical properties are always considered in relation to the mass of the pressure vessels, since this affects the range and the performance of the vehicle. Pressure vessels are also typically subjected to large changes in temperature − and, in cryogenic tanks or space, near-zero K temperatures − which adds constraints for the choice of materials.

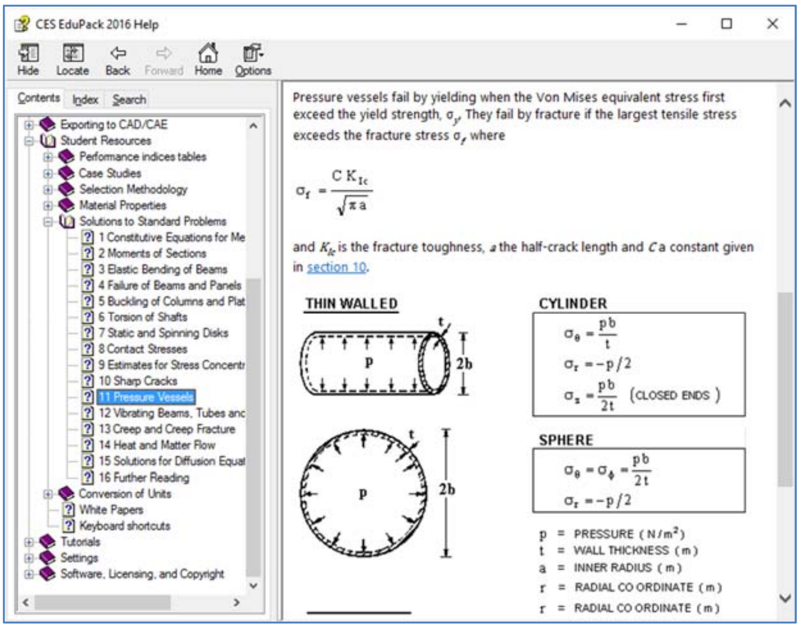
Applications

- Aircraft pressure cabins
- Space orbiters
- Rocket fuel tanks (LHX)
- Rocket oxidizer tanks (LOX)
- Helium pressurizer tanks
- Reaction Control System (RCS) tanks
- Orbital Manoeuvre System (OMS) tanks
- Cryogenic storage systems (ground segment)

2. What do the pressure vessels look like?

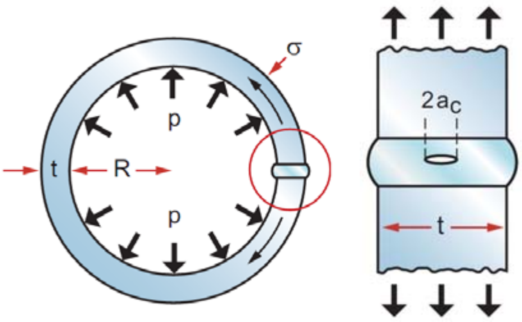
Pressure vessels are normally divided into thick-walled and thin-walled for the sake of deriving stress equations. The shapes we will consider here are cylindrical (with closed ends) or spherical, both with a radius, R. Whereas in a thick wall, the variation of the stress inside the material needs to be considered, a thin wall can be treated as a membrane, which is a reasonable approximation if the thickness is much smaller than the radius. Since low weight is a major consideration in all aerospace applications, we are interested in the thin-walled ones. The relevant stress equations are given below for thin-walled cylindrical and spherical pressure vessels, respectively.

The enhanced HELP function in CES EduPack 2016 provides most of the necessary theory and background to this Case Study. The basic equations for stress in cylindrical and spherical pressure vessels, as seen to the right, are accessible via the HELP button for Student Resources. They can be found by searching for 'Pressure Vessels'. As can be seen in the pictures above and of the Soyuz below, these shapes are prevalent in aerospace applications. The largest stress for both shapes is along the azimuthal direction (Θ).



3. What is the Problem?

If the main objective is to minimize mass while maximizing performance, and safety is considered as a design constraint, there are five material indices (derived below) that may be visualized as index lines in property charts. These will help us to explore the problem.



To minimize mass, we will consider mass, *m*, for a cylinder of length *L* with hemispherical ends *or* a sphere:

$$m = 4\pi R^2 t\rho + 2\pi R L t\rho \text{ (cylinder) or } m = 4\pi R^2 t\rho \text{ (sphere)} \qquad \text{[eqs. 1a and 1b]}$$

Since we will treat thickness as a free design variable, we will eliminate *t* to enable a free material choice. From the basic equations in the HELP window above, we see that the maximum stress in a thin wall pressure vessel is:

$$\sigma = \frac{pR}{t} \text{ (closed-end cylinder) or } \sigma = \frac{pR}{2t} \text{ (sphere)} \qquad \text{[eqs. 2a and 2b]}$$

Using these equations at the limit of material failure ($\sigma=\sigma_y$), we can substitute:

$t = \dfrac{pR}{\sigma}$ *or* $t = \dfrac{pR}{2\sigma}$ into eqs. 1a and b, respectively, rendering thickness-independent expressions:

$$m = 2\pi R^2 p(2R + L)\frac{\rho}{\sigma_y}\text{(cylinder)} \quad or \quad m = 2\pi R^3 p\frac{\rho}{\sigma_y}\text{(sphere)} \qquad \text{[eqs. 3a and 3b]}$$

To avoid fast fracture (explosion), we need to look at the link between the stress in the material and the critical crack size, illustrated in the figure above.

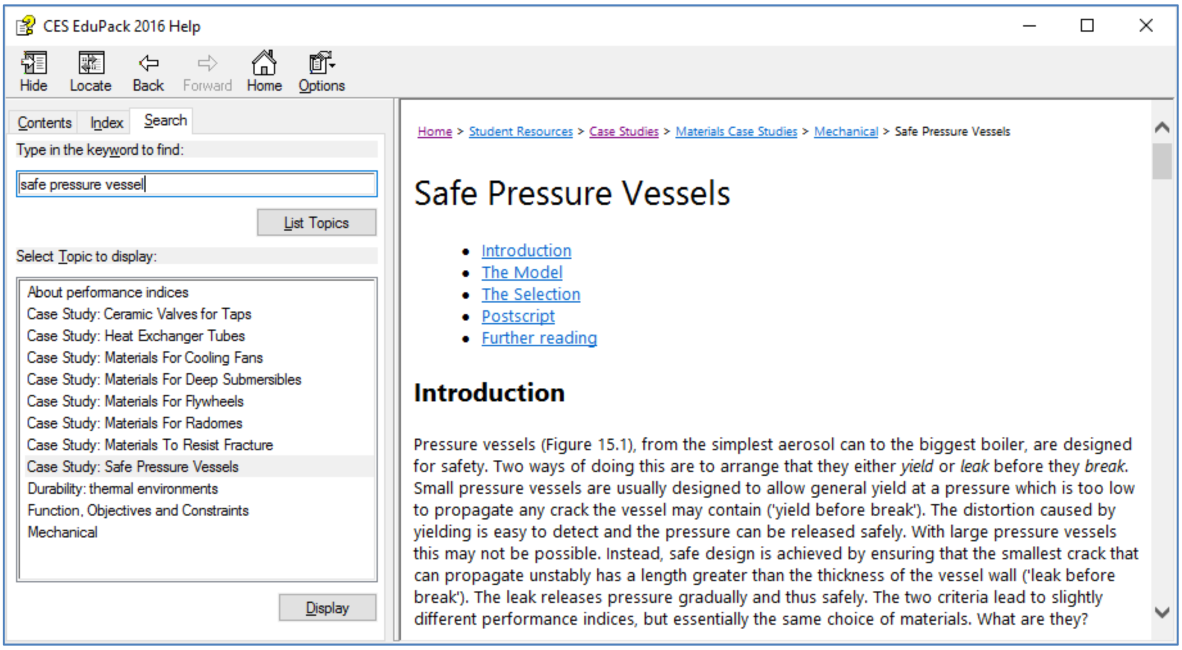
From fracture mechanics [2], we know that the stress necessary to propagate a crack is:

$$\sigma = C\frac{K_{Ic}}{\sqrt{\pi a_c}}, \qquad \text{[eq. 4]}$$

where K_{Ic}=Fracture toughness and C≈1 for small cracks. Eliminating the stress by substitution of eqs 2a and b at the limit of material failure ($\sigma=\sigma_y$) into eq. 4 gives requirements on pressure, to avoid crack propagation:

$$p \le \frac{t}{R}\frac{K_{Ic}}{\sqrt{\pi a_c}}\text{ (cylinder) or } p \le \frac{2t}{R}\frac{K_{Ic}}{\sqrt{\pi a_c}}\text{ (sphere)} \qquad \text{[eqs. 5a and 5b]}$$

The above equations are used in the next section as a basis to create index lines for safe pressure vessels. Further background and details on the derivation of these are given in an embedded Case Study available from the HELP function of CES EduPack, as shown below:



4. How to select aerospace materials in CES EduPack

In order to investigate potential materials, we will follow the rational selection methodology by Ashby *et al* [3], illustrated schematically in the diagram below. We will use Level 3 of the ***Aerospace database*** but the Standard Level 3 MaterialUniverse data can also be used to some extent. The selection is started by clicking **Chart/*Select*** in the main toolbar and choosing ***Aerospace materials***. This results in an initial subset of nearly 500 materials, metal alloys and composites. High gas permeability and poor low temperature performance will, however, make composites less attractive in comparison to metals. Some tanks therefore consist of high-strength composite materials surrounding a metal shell on the inside to contain the pressure. In this Case Study, we will focus on weldable materials, which are mainly metal alloys.

The subset of all Aerospace materials is plotted in a property chart of Yield strength *vs* Fracture toughness, below. These two properties are key to 4 out of our 5 material indices:

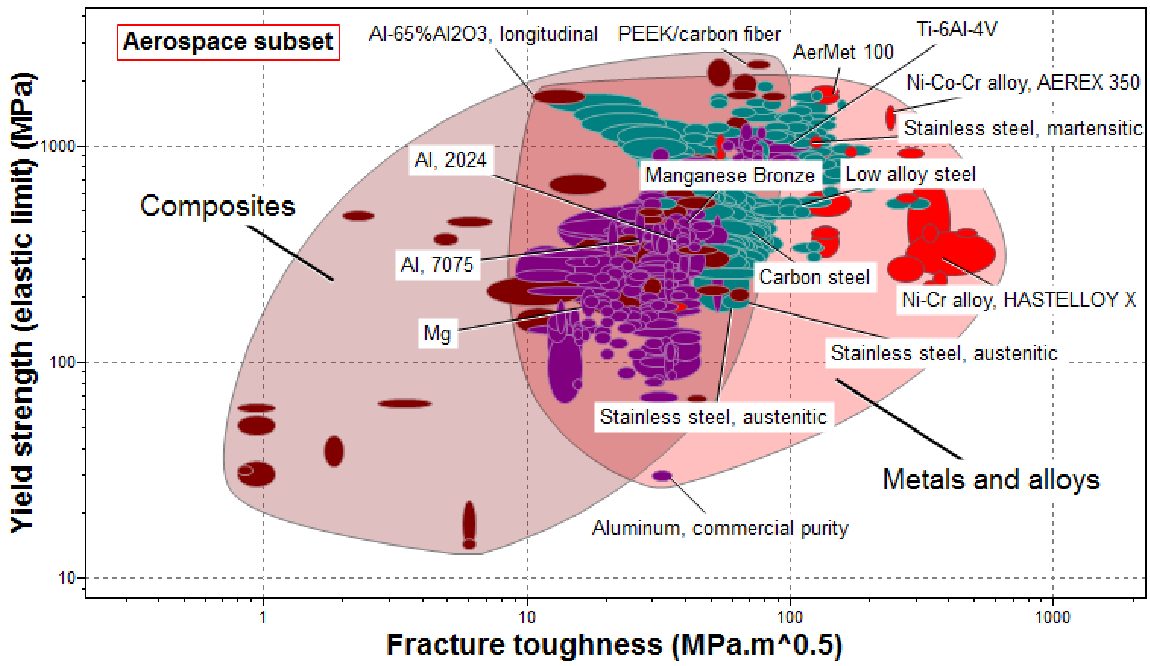
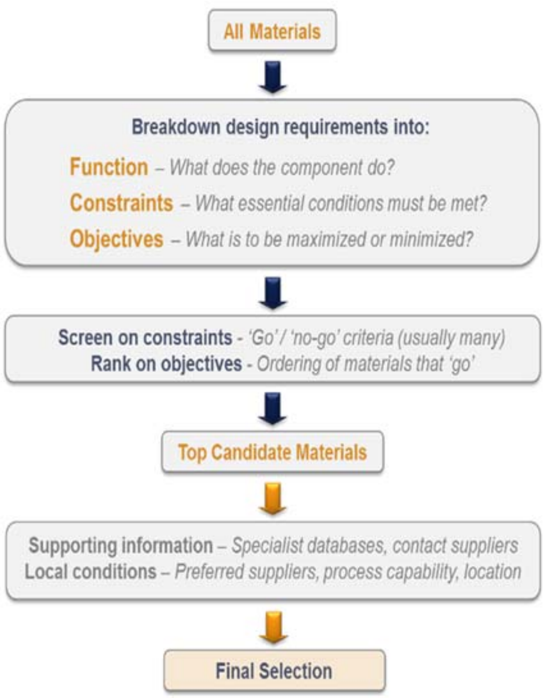


Chart 1: The subset of Aerospace materials in the Aerospace edition of CES EduPack



Function:

We are looking to select materials for a *Pressure vessel*, in an aerospace application. The **function** is, therefore, to contain pressure (see Eqs. 5a and b).

Constraints:

The constraints can be applied in any order, before or after plotting the relevant chart. Here, we apply the limited subset of Aerospace materials first, as well as requiring weldability and a minimum service temperature below liquid hydrogen (-253°C). After plotting, we will consider two alternative safety constraints implicitly.

List of constraints

- Only *Aerospace materials* are considered
- Must yield before break *or* Must leak before break
- Materials can be processed by *welding*
- *Minimum Service Temperature* at -260°C or colder

Objectives:

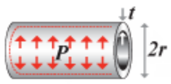
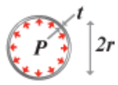
A *Strength-limited design* is considered and the main objective is to ***Minimize mass*** with thickness as the free design variable. We will also look to ***Maximize safety***.

Both the above expressions for mass in eqs 3a and b yield the same material index, M1 (see table below). We will chose to maximize M0 (Bar Chart 2) for minimum mass which means that M1 becomes the specific strength:

$$M1=\sigma_y/\rho$$

A material index table is supplied within the CES EduPack HELP, as shown below (see maximize):

Strength-limited design at minimum mass

FUNCTION AND CONSTRAINTS[1, 3]			MAXIMIZE[2]	MINIMIZE[2]
Cylinder with internal pressure		radius fixed; wall-thickness free	σ_y/ρ	ρ/σ_y
Sphere with internal pressure		radius fixed; wall-thickness free	σ_y/ρ	ρ/σ_y

The Aerospace materials that remain after screening for materials that can be welded and sustain minimum service temperatures below -260°C are shown below (non-grey). A dashed line (M1) indicates a proposed screening level for relevant materials. The material price is plotted on the X-axis, just to facilitate comparison. Most Superalloys, such as Inconel 718, have undesired combinations of high density and high price per kg.

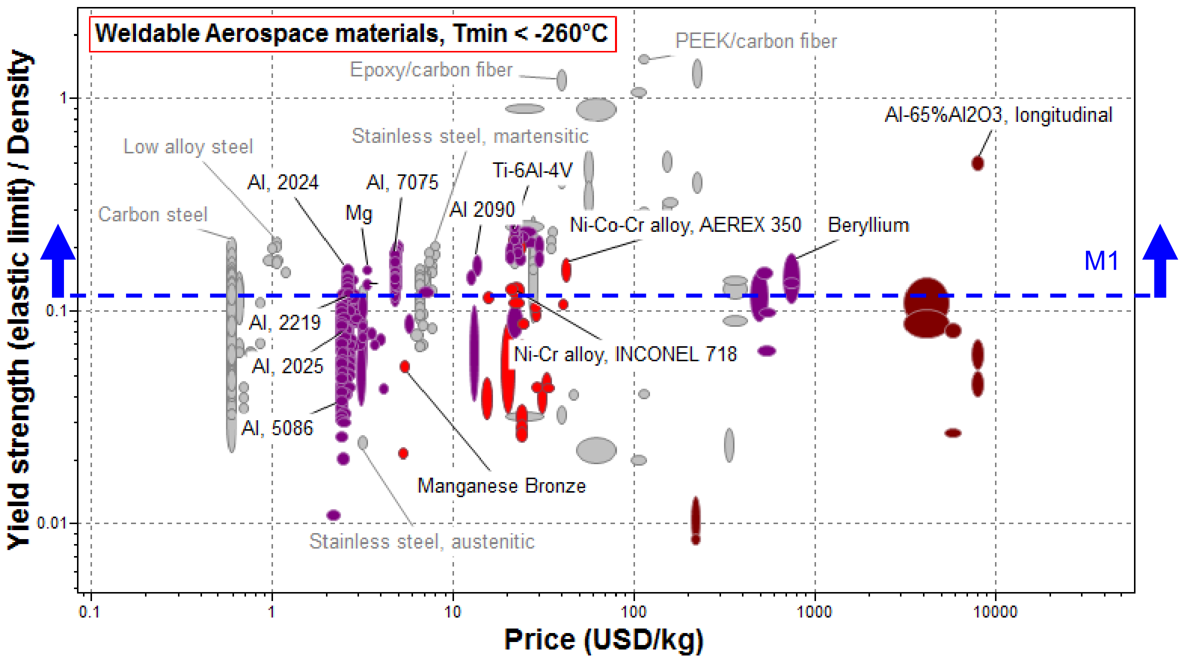


Chart 2: Aerospace materials that are weldable and can sustain a Service Temperature below -260°C

5. Material Indices for pressure and safety

In this Case Study, we have chosen to include equations to support a deeper understanding desirable in teaching and to connect the materials selection to the subject of strength/mechanics of materials.

Finding materials that maximize safety is linked to the function (contain pressure) of the pressure vessel. For a given geometry (R, t, L), the first material index to explore comes straight from the pressure eqs. 5a and b:

$$p \le \frac{t}{R}\frac{K_{Ic}}{\sqrt{\pi a_c}} \text{ (cylinder) } or \text{ } p \le \frac{2t}{R}\frac{K_{Ic}}{\sqrt{\pi a_c}} \text{ (sphere)}$$

Regardless if the shape is spherical or cylindrical, the material that enables maximum pressure for a given thickness, before fast fracture, is the one with the highest value of the *Fracture toughness*.

M2=K_{Ic}

A horizontal index line M2 is plotted in Chart 3 in the next section. Three additional index lines, M3-M5, are derived below and plotted in the same Chart. This is because max M2 is no guarantee against fast fracture.

To derive the *yield-before-break* constraint, eq. 4 can be squared, leading to the expression (still using C≈1):

$$a_c \le \frac{C^2}{\pi}\left(\frac{K_{Ic}}{\sigma_y}\right)^2. \qquad \text{[eq. 6]}$$

The maximum allowable crack size is thus obtained for the material with maximum value for:

M3=K_{Ic} / σ_y

This will allow the pressure to reach the limit where the material starts to yield (and hence the deformation can be spotted), before fast fracture occurs. M3 is also shown as an index line in Chart 3.

If there are no means of monitoring the tank, it is better to let the crack propagate safely to a value just above the wall thickness, *t*, creating a small leak, preventing fast fracture, *i.e.*, *leak-before-break*. So: $2a_c \ge t$.

This inserted into eq 6 and combined with eqs 2a *or* b at the limit of material yield ($\sigma=\sigma_{y}$,) results in:

$$p \le \frac{2C^2 K_{Ic}^2}{\pi R \sigma_y} \text{ (cylinder) } or \text{ } p \le \frac{4C^2 K_{Ic}^2}{\pi R \sigma_y} \text{ (sphere)} \qquad \text{[eqs. 7a and b]}$$

which gives us the next material index:

M4=K_{Ic}^2 / σ_y

The material indices M3 and M4 both have yield strength in the denominator, meaning that a small value of the strength may be compatible with good performance. This is, however, an anomaly, since this would result in a large value for the thickness (eq 1) and thus a heavy tank. Therefore, M3 or M4 must be combined with an index based on eq. 1 to minimize the thickness or, equivalently, to maximize the Yield strength. This supporting material index can be plotted directly as a vertical line in Chart 3.

M5=σ_y

6. Result

Property Chart 3, below, shows the materials remaining after applying the constraints (materials that fail the screening are greyed out). If the proposed selection line in Chart 2 is applied, around 100 materials remain. The two material indices M2 and M5 are increased as far as to include the large group of Al alloys, Ti alloys and a few remaining Superalloys. This is done visually, since we don't have specific values to use. We can see that the safety constraints, resulting in index lines M3 (slope=1) or M4 (slope=1/2) can be applied and explored visually and that they result in similar material outcomes. The leak-before-break index, M4, slightly favors Ti alloys. If Chart 3 is performed in a new stage following Chart 2, the combined results are shown.

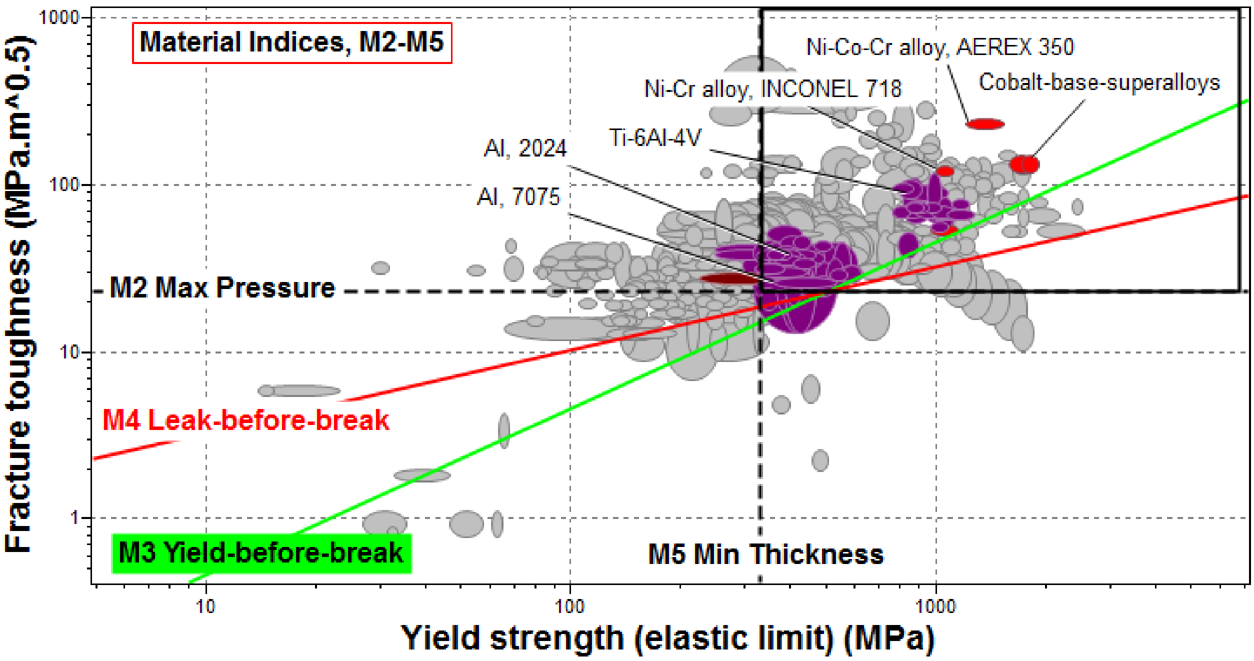
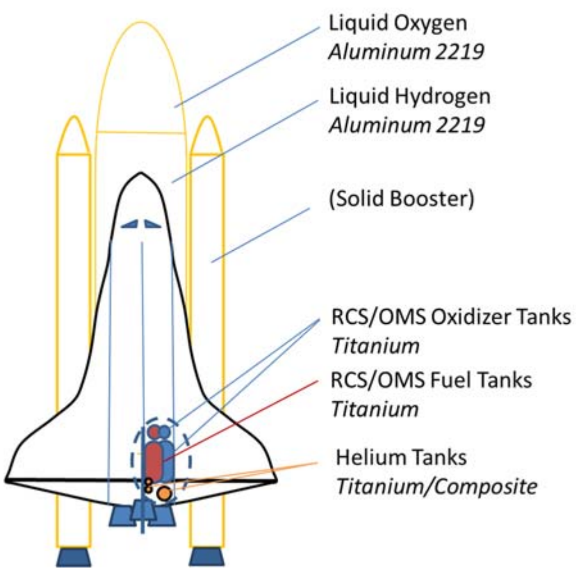


Chart 3: Final Property chart, showing the four index lines pertaining to toughness and strength

7. Analysis and reality check

The outcomes of the selection performed and shown in Charts 2 and 3 can be compared broadly with materials used in the space shuttle tanks [4] and cryogenic tanks of the Ariane 4 and 5 rockets, shown here.



Source: Cryogenic Tanks for Space Applications, Air Liquid				
Type	***Diameter***	***Height***	***Loaded Mass***	***Material***
Ariane 4 H10	2.6 m	8.3 m	12 t	Al 7020
Ariane 5 EPC	5.4 m	23.8 m	175 t	Al 2219
Ariane 5 ESC-A LOX	2.6 m	2.8 m	12 t	Al 7020
Ariane 5 ESC-A LH2	5.4 m	3 m	2.7 t	Al 2219

Titanium (unspecified alloy), Al 2219 and Al 7020 are commonly used in these two applications. Al 7020 is currently located in the Level 3 database but many alloys of the 2000-, 2200- and the 7000-series Al, as well as Ti alloys appear as top candidates in the selection outcome.

CES EduPack, combined with an educator's materials expertise, suggests the following conclusions:

- If we take the main objective to be minimum mass, CES EduPack is able to propose a number of suitable aerospace materials that pass the constraints of low temperature and weldability: Aluminum 2200 and 7000 series, Titanium alloys as well as Nickel and Cobalt based Superalloys, Beryllium alloys and a few composites.
- Although the cost performance was not the primary aim of this case study, the cost of the materials considered in Chart 2 indicates one reason why the Nickel and Cobalt based Superalloys, the Al-ceramic composite or Beryllium-based alloys are not common for aerospace pressure vessels in reality.
- If safety performance is maximized, the main function being to contain pressure, we can explore up to four material indices without needing numerical values, using the visualization tool in one single property chart. This chart can be coupled with the result of the selection for minimum mass.
- The multiple selection lines are useful to compare different design requirements and to discuss important concepts, such as the difference between alternative constraints and objectives, or performance indices in general.

8. What did CES EduPack contribute?

This selection Case Study [5] provides a rich platform for discussion of material selection in a very exciting field for most students: Aerospace applications. In our case, we wanted to explore and compare objectives, using basic equations and visual methods.

The software makes it possible to investigate this problem systematically, step-by-step, and visually, using two coupled property charts and multiple index lines. In this case, we were able also to find supporting information via the HELP function. It provided basic pressure equations and derivations of relevant performance indices. The search terms used were: "pressure vessel" and "safe pressure vessel".

The MaterialUniverse database allows us to consider a subset of Aerospace materials and concentrate on two of the most important objectives, typical of such applications: mass minimization and pressure performance linked to safety.

In this example, we have taken some realistic constraints into consideration: safety, extreme service temperatures and manufacturing processes. It is possible to enter many more constraints, for example in terms of numerical values, but this was beyond the scope of this study.

References

1. Steven M. Arnold, David Cebon and Mike Ashby, "Materials Selection for Aerospace Systems", NASA/TM-2012-217411 (Technical Memorandum). Available online: http://everyspec.com/NASA/NASA-General/NASA_TM-2012-217411_47675/

2. For example, see Hellan, K (1985) '**Introduction to fracture mechanics**', McGraw-Hill.

3. For example, see Ashby, M.F. (2005) "Materials Selection in Mechanical Design", 3nd edition, Butterworth Heinemann, Oxford, UK. ISBN 0-7506-6168-2.

4. Luca d'Agostino, ***Lecture Notes***, Dipartimento di Ingegneria Aerospaziale, University of Pisa, Italy.

5. Other case studies can be found here: http://teachingresources.grantadesign.com/Type/casestudies

