Chapter 9

FIRE RESISTANCE OF ALUMINIUM

9. FIRE RESISTANCE

WHETHER for a ship or a building on land, the resistance to fire of the materials that are used in its construction is one of the factors – without doubt the most important factor – affecting the safety of the persons who use it and of the survival of the vessel in the event of fire.

A material's behaviour in a fire is determined by its intrinsic physical properties (melting point, specific heat etc.), its tendency to ignite and to give off smoke and fumes in the event of combustion, and changes in its mechanical characteristics. Any decrease in the latter as temperature rises will reduce the material's ability to support a load etc.

However fire resistance also depends on the conditions of use of the material, e.g. its position within a structure, any means of protection provided for it, its performance in a fire (retention of rigidity, extent to which it heats up etc.), generally imposed by regulations such as SOLAS and the HSC collection for high speed ships.

In shipbuilding, aluminium was first used during the period 1920 – 1930 to make furniture for passenger cabins on liners to replace wooden furniture that was considered to be dangerous in the event of a fire as it represented a fire load and its combustion gave off smoke and fumes whose catastrophic effects were already well known [1, 2].

The use of aluminium has long been challenged in a number of industries, e.g. petrochemical and offshore, that are highly exposed to fire hazards.

However despite a number of reservations relating in particular to its low melting point and the controversy that arose following the Falklands conflict in the Eighties, the marine applications of aluminium have advanced steadily since 1960 in naval construction, in passenger ships, living quarters, link bridges and in offshore structures [3, 4].

VESUVIO JET

OF ALUMINIUM

1.

THE FALKLANDS CONFLICT

The resistance to fire of aluminium was the subject of much controversy during the Falklands conflict in May 1982, in which British naval forces were attacked by Argentine aircraft and nine British ships were sunk [5].

Among these nine were two Type 42 destroyers, and one of these – HMS Sheffield –was struck by an Exocet missile.

It was subsequently reported in certain sections of the media that these vessels had sunk because their aluminium alloy superstructures had caught fire upon impact from missiles or bombs dropped from aircraft.

The enquiry that followed showed that out of the nine ships damaged and sunk, only three had aluminium alloy superstructures, *and the Sheffield's superstructure was made of steel* !!!

There is nothing that establishes a cause and effect relationship between aluminium and the loss of these ships.

In a "White Paper" published by the Ministry of Defence on the 14 December 1982, the British authorities concluded that "there is no evidence that aluminium has contributed to the loss of any vessel" [6].

2.

REACTION TO FIRE OF ALUMINIUM

It is now a generally accepted and established fact that "solid" aluminium (1) does not burn, does not give off smoke when exposed to fire and does not emit sparks on impact.

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(1) Like most metallic powders, aluminium powder is very flammable and so hazardous to handle. Its behaviour in fire is wholly different from the behaviour of the "solid" metal covered with its natural oxide film. The solid fuel motors of rockets usually consist of a pyrophoric charge based on specially conditioned aluminium powder.

HSV2

2.1 Non-flammability

There is no evidence that solid or liquid aluminium catches fire by itself in a fire [7]. and this has been confirmed by experience and by numerous laboratory tests.

Tests have shown that in *pure oxygen*, at a pressure of 1013 bar, the ignition temperature of aluminium is above 1000 °C, higher than that of other common metals such as 930 °C for steel and 900 °C for zinc. The level of ignition temperatures is not dependent on melting point [8]. There are metals whose ignition temperature is below their melting point, and vice versa (table 62).

The extreme difficulty in getting aluminium to burn is because the natural oxide layer inhibits the reaction of the metal with air or oxygen by "locking" the liquid metal in an envelope that provides a seal from the surrounding environment tight enough to prevent ignition (2). Put another way, we can say that there are two competing processes: the formation of the oxide layer (oxidation) and the combustion of aluminium (3).

Moreover, in mixtures of oxygen and argon, aluminium will only burn if the temperature exceeds the melting point of alumina (2250 °C) and aluminium only burns by itself if the temperature attains its boiling point (3073 °C) [9].

In recycling foundries, aluminium scrap of all alloys is fed into open furnaces as it is. The temperature of the melt is in the region of 750 - 800 °C !!!

The molten aluminium can be sprinkled with jets of water. The amount of water broken down by the molten aluminium is minimal because the metal's reactivity is inhibited by the formation of the oxide film. Very little hydrogen is given off and so there is no risk of explosion.

2.2 No release of smoke

As with all common metals and alloys, aluminium does not give off any smoke or toxic gases when heated up or melted (4).

2.3 No sparking

It is worth noting that neither aluminium (nor its alloys) produce sparks upon low impact [4], which is why aluminium alloy equipment has been used in coal mines for a long time (5).

RADAR MAST

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(2) Experience shows that it is impossible to set fire to aluminium cooking foil 6 to 7 microns thick with any type of flame.

(3) The oxide film can form under very low pressures of oxygen (approx. 1 millibar and less) and at high speeds of the order of 1 millisecond. This explains why the machining and sawing of aluminium present no risks.

(4) Except those from the combustion or hot decomposition of any coatings.

(5) In Europe, most road tankers that carry petroleum products have aluminium alloy tanks (made from 5083, 5186 and XTral728).

IGNITION TEMPERATURES IN OXYGEN

Metal	Ignition Temperature in Pure Oxygen (°C)	Melting Point (°C)
Magnesium	623	650
Molybdenum	750	2 620
Lead	870	327
Zinc	900	419
Iron	930	1 540
Aluminium	1 000	666

Table 62

3.

CLASSIFICATION OF ALUMINIUM

Aluminium is classed as non-flammable:

- according to British standard BS 476 [10],
- according to ASTM test E136 [11].

The International Convention for the Safety of Life at Sea (SOLAS) [12] classes aluminium among the non-combustible materials, and explicitly permits the use of aluminium alloys in naval construction (6):

Steel or other equivalent material: Whenever the words "steel or other equivalent material" occur, the term "equivalent material" shall be taken to mean any non-combustible material which, by itself or with insulation, possesses properties equivalent to those of steel in regard to mechanical strength and integrity at the end of the standard fire test (e.g. a suitably insulated aluminium alloy).

4.

PASSIVE PROTECTION OF ALUMINIUM

The rules for the protection of aluminium alloy structures are therefore the same as for steel structures (7), and can obviously be applied without any difficulty:

- to type A ship divisions:

- they must be constructed to prevent the passage of smoke and flames until the end of a standard one-hour fire test, according to resolution A.754 (8),

- they must be insulated with approved non-combustible materials such that the mean temperature on the unexposed surface does not rise by more than 139 °C above the initial temperature, and the temperature at any point on that surface, including joints, does not rise by more than 180 °C above the initial temperature, at the end of the following times:

Class A – 60	60 minutes
Class A – 30	30 minutes
Class A – 15	15 minutes
Class A – 0	0 minutes

- to type B ship divisions:

- these must be constructed to prevent the passage of flames until the end of the first half-hour of a standard one-hour fire test,

- they must have a level of insulation such that the mean temperature on the unexposed surface does not rise by more than 139 °C above the initial temperature, and the temperature at any point on that surface, including joints, does not rise by more than 225 °C above the initial temperature, at the end of the following times:

Class B – 15	15 minutes
Class B – 0	0 minute

More effective thermal insulation products are now used on board aluminium alloy ships [13]. These are "synthetic vitreous fibres (of silicates) of random orientation, whose percentage by weight of alkaline oxides and alkaline-earth oxides (Na_2O + K_2O + MgO + BaO) exceeds 18%".
They are non toxic and conform to European directives [14].

They have an improved insulation capacity but are much thinner and so easier to apply.

They therefore represent a significant weight saving of some 40 % compared with traditional "rockwool", as shown in table 63.

Experience shows that for a 40 metre passenger ship, 700 to 800 kg of INSULFRAX blanket is enough to insulate those parts of the ship that are classed type A.

EXAMPLE OF INSULATION WITH UNIFRAX FIBRES

Structure	Type	Thickness (mm)	Weight (*) (Kg m^{-2})
Deck	A30	38	3,65
	A60	50	4,80
Bulkhead	A30	38	3,65
	A60	50	4,80

(*) on a flat surface.

Table 63

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(6) Solas, Chapter II-2, Rule 3, Section 7.

(7) Solas, Chapter II-2, Rule 3, Section 3.

(8) Resolution A.754: Recommendations on fire resistance tests for "A", "B" and "F" class divisions. International code for the application of fire test methods, Code FTP IMO publications.

5.

THERMAL PROPERTIES OF ALUMINIUM

The melting point of aluminium is much lower than that of steel, 666 °C as against 1530 °C (table 64).

The thermal properties of aluminium are distinctly superior to those of steel:

- its thermal conductivity is 3 times higher for the 5000 series alloys and 4 times higher for the 6000 series,
- its specific heat is twice that of steel.

As a result, aluminium's thermal behaviour is quite different from that of steel (9). For an equal mass of metal, far more calorific energy is needed to heat aluminium than steel; the energy is dissipated more readily because of aluminium's very good thermal conductivity. Its superior ability to conduct heat away eliminates hot spots and increases the period of serviceability.

However, in facilitating the diffusion of heat energy, aluminium will help to heat up contiguous elements (volumes or structures), and aluminium alloy structures must be insulated to avoid this.

Aluminium's reflective power is very high, 80 to 90 % of incident radiation compared with 5 % for painted steel and 25 % for stainless steel. The effect of this high emissivity is that aluminium alloy structures that are exposed to heat radiation emitted by a fire take longer to heat up, so limiting the spread of the fire.

Aluminium's reflective power falls very little when its surface is exposed to high temperatures. For a surface temperature of between 500 and 600 °C, the reflective power remains at a high level – in the region of 70 % – even on surfaces that are very old and oxidized.

When the surface is painted and covered in soot, the reflective power falls very significantly to less than 20 to 30 % of a clean surface [15].

6.

CHANGE IN THE PHYSICAL PROPERTIES OF ALUMINIUM AS A FUNCTION OF TEMPERATURE

Like most common metals, a rise in temperature modifies the physical properties of aluminium to a greater or lesser degree.

6.1

Change in mechanical properties

This is a very important parameter and one that must be taken into consideration to maintain the integrity of structures and their ability to take the initial loads.

The longitudinal modulus of elasticity of aluminium alloys decreases with temperature (table 65) [xvi] as shown in figure 116.

The mechanical properties of aluminium alloys, including the elastic limit, start to fall as the temperature rises above 150 °C, dropping to 50 % between 200 and 250 °C (see table 64 and figure 118). The mechanical properties of steel also decrease with temperature, with the 50 % threshold coming at around 600 °C (figure 119).

THERMAL PROPERTIES OF ALUMINIUM

Property	Aluminium 1050A O	5083 O	6005A T5	Steel E24
Melting range (°C)	645/658	574/638	605/655	1 400/1 530
Boiling point (°C)	2 425	2 425	2 425	2 860
Melting heat (kJ.Kg^{-1})	390	390	390	250
Specific heat (J.Kg^{-1}.K^{-1})	900	900	940	420
Thermal conductivity (W.m^{-1}.K^{-1})	229	117	188	54
Coefficient of linear expansion (10^{-6}.K^{-1}, 20/100 °C)	23,5	24,2	23,6	13,5

Table 64

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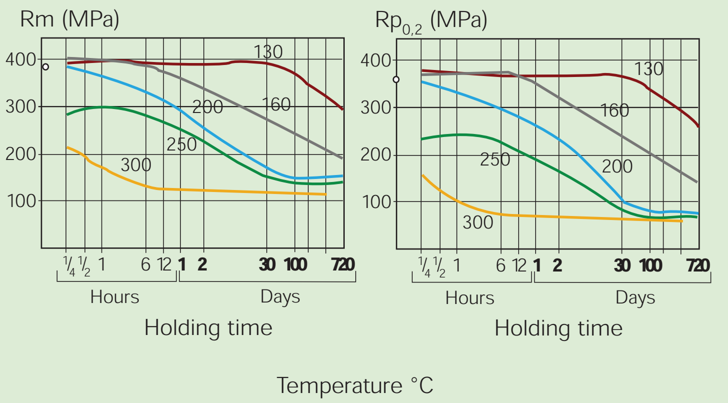
(9) Cf. Chapter 6.

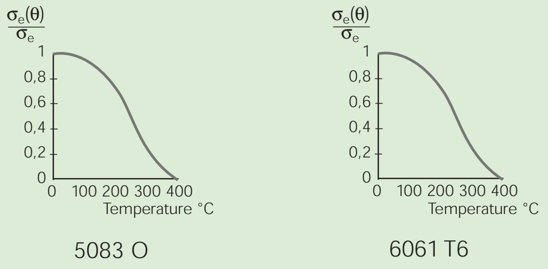
CHANGE IN MECHANICAL CHARACTERISTICS OF 6082



From TALAT de l'EAA

Figure 117

CHANGE IN THE ELASTIC LIMIT OF 5083 O AND 6061 T6



5083 O

6061 T6

Figure 118

CHANGE IN THE MODULUS OF ELASTICITY OF ALUMINIUM ALLOYS

Temperature (°C)	Modulus of elasticity (MPa)
20	70 000
50	69 300
100	67 900
150	65 100
200	60 200
250	54 600
300	47 600
350	37 800
400	28 000
550	0

Table 65

CHANGE IN YOUNG'S MODULUS

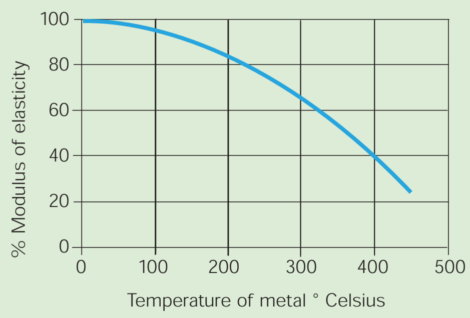


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Figure 116

The period of exposure to temperature (10) has little effect on the mechanical characteristics of strain hardened alloys when they are in the annealed condition, 5083 O and H111, 5086 O and H111, etc. However it will have an annealing effect on age hardened alloys such as 6005A, 6061, 6082 in the T6 temper when the temperature exceeds 150 °C.

In practice, if a load-bearing structure made from age hardened aluminium alloys is exposed to temperatures above 150 °C for several hours, then the residual mechanical characteristics of components made from alloys belonging to the 6000 series will have to be tested after the fire. The higher the temperature to which the alloy has been heated, the faster its loss of mechanical characteristics (figure 117).

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(10) Cf. table 23, Chapter 3.

CHANGE IN THE ELASTIC LIMIT OF STEEL [17]

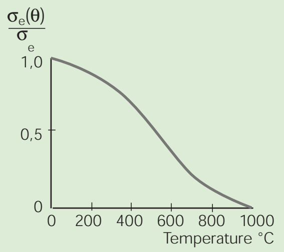

Figure 119

6.2

Change in physical properties

Aluminium's thermal conductivity increases with temperature between 0 and 400 °C according to the empirical formulae (figure 120):

- $\lambda_{al} = 0.07\ \theta + 190$ for alloys belonging to the 1000, 3000 and 6000 series,
- $\lambda_{al} = 0.10\ \theta + 140$ for alloys belonging to the 2000, 5000 and 7000 series.

Its specific heat also increases with temperature, between 0 and 400 °C, (Figure 121) according to the empirical formulae:

- $Cp_{al} = 0{,}418\ \theta + 900$ for the 5083 alloy
- $Cp_{al} = 0{,}710\ \theta + 880$ for the 6061 alloy.

Its coefficient of linear expansion increases with temperature between 0 and 500 °C (figure 122) according to the formula:

$\Delta l/l = 0{,}1.10^{-7}\ \theta^2_{al} + 22{,}5.10^{-6}\ \theta_{al} - 4{,}5.10^{-4}$

with :

- l = length at 20 °C,
- Δl = expansion due to temperature,
- θ_{al} = temperature.

CHANGE IN THERMAL CONDUCTIVITY

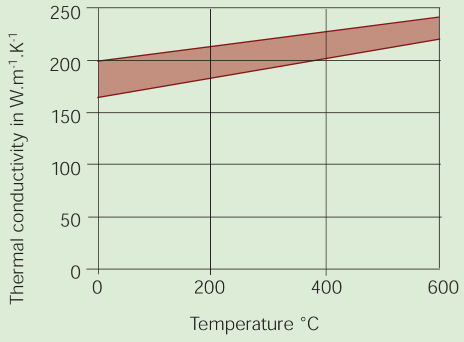

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Figure 120

CHANGE IN MASS THERMAL CAPACITY

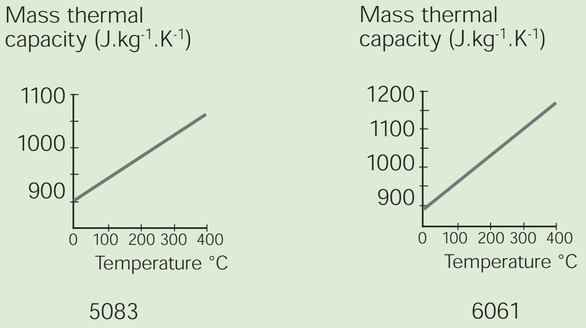
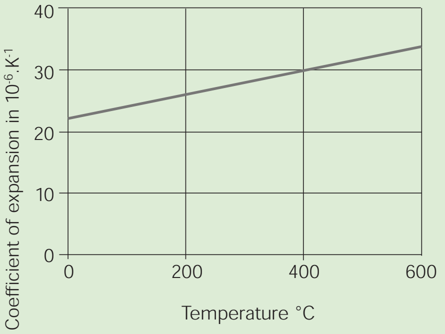


Figure 121

CHANGE IN THE COEFFICIENT OF LINEAR EXPANSION



From TALAT de l'EAA

Figure 122

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