TALAT

Training in Aluminium Application Technologies

TALAT Lectures 2502

Material Aspects of Fire Design

21 pages, 19 Figures

Basic Level

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Objectives:

- to learn about characteristic behaviour of aluminium alloys and insulation materials at high temperatures
- to describe the philosophy of using aluminium alloy structures under risks of fire
- to give an example of fire risk analysis

Prerequisites:

- general engineering background
- TALAT lecture 2501

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2502 Material Aspects of Fire Design

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2502.01 Properties of Aluminium Alloys at High Temperatures

- Physical properties
- Mechanical properties

The physical and the mechanical properties of aluminium alloys are changing under exposure to high temperatures.

To improve the mechanical properties of aluminium, it is alloyed, heat treated and/or strain hardened. The resulting hardness condition is called "temper". With increasing temperature some mechanical properties, particularly the strength of the aluminium alloy will decrease.

Depending on alloy, temper and temperature, this decrease in strength can be permanent after the aluminium alloy structure has cooled.

Some physical properties are also changing with temperature: the specific heat, the thermal conductivity, the coefficient of linear expansion and the reflection capacity.

2502.01.01 Physical Properties [9]

– Specific Heat

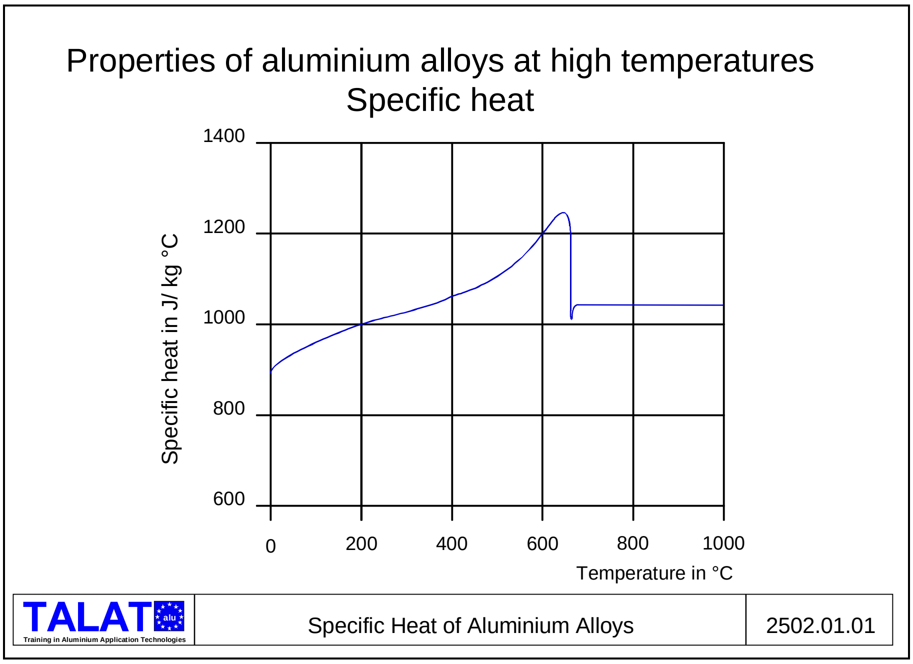
The specific heat varies very little with the type of alloy. For most alloys it is 900 J/kg °C at 0 °C increasing to 1240 J/kg°C at the melting point where it drops down to 1040 J/kg°C. At 700 °C it is 1060 J/kg°C and stays at this value until 1000 °C (**Figure 2502.01.01**).

In ENV 1999-1-2 [15] the specific heat for aluminium, c_{al} , is determined from the following:

for 0 ºC < θ_{al} < 500 ºC

$$c_{al} = 0,41 \cdot \theta_{al} + 903 \quad \text{(J/kg ºC)}$$

where : θ_{al} is the aluminium alloy temperature



– Thermal Conductivity

For structural alloys thermal conductivity varies with temperature: it increases from 170-200 W/m K at 0° C to 220 - 240 W/m K at 600° C (**Figure 2502.01.02**).

In ENV 1999-1-2 [15] the thermal conductivity of aluminium, λ_{al} , for 0 ºC < θ_{al} < 400 ºC is determined from the following:

for alloys in 1000, 3000 and 6000 series:

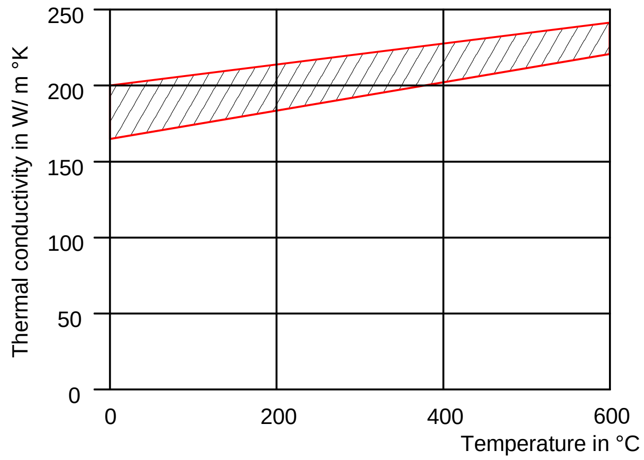
$$\lambda_{al} = 0{,}07 \cdot \theta_{al} + 190 \qquad \text{(W/mºC)}$$

for alloys in 2000, 4000, 5000 and 7000 series:

$$\lambda_{al} = 0{,}1 \cdot \theta_{al} + 140 \qquad \text{(W/mºC)}$$

where: θ_{al} : is the aluminium alloy temperature

Properties of aluminium alloys at high temperatures
Thermal conductivity



TALAT Thermal Conductivity of Aluminium Alloys 2502.01.02

– Coefficient of Linear Expansion

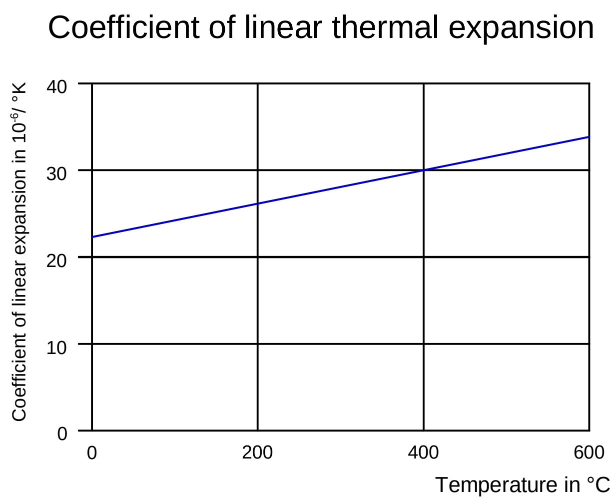
The coefficient of linear expansion varies little with alloy. In the temperature range between 20 to 100° C its mean value is about 23,5 • 10^{-6} / K for most of the structural alloys. This value will increase to about 25.5 • 10^{-6} /K for the range between 20 and 300°C (see **Figure 2502.01.03**). In calculations one takes the mean value of the coefficient between the respective temperature limits.

In ENV 1999-1-2 [15] the thermal elongation of aluminium, Δl/l , is determined from the following:

for 0 ºC < θ_{al} < 500 ºC

$$\Delta l / l = 0,1 \cdot 10^{-7}\, \theta_{al}^2 + 22,5 \cdot 10^{-6}\, \theta_{al} - 4,5 \cdot 10^{-4}$$

where: l : is the length at 20 ºC
Δl : is the temperature induced expansion
θ_{al} : is the aluminium alloy temperature (ºC)



TALAT | Coefficient of linear thermal expansion of alum.-alloys | 2502.01.03

– Heat of Fusion

The heat of fusion for aluminium is 390 kJ/kg. This value is almost constant for all common alloys.

– Melting temperature.

The melting temperature range, i.e. the difference between the solidus and liquidus points is a function of alloy content. For most structural alloys, however, it ranges from 590°C to 650°C.

– Reflection capacity.

When a clean aluminium surface is exposed to a heat radiation source most of the heat energy will be reflected. The amount of reflection is dependent of the condition of the surface and its temperature.

For old oxidized aluminium surfaces the reflection of heat radiation will be 80 - 85%. For polished aluminium surfaces the reflection can be up to 97%.

This reflection capacity will decrease little at higher temperatures. At a surface temperature between 500 and 600 °C the reflection can be as low as 70% for old heavily oxidized aluminium surfaces.

If the surface is covered by soot, or it is painted, the reflection capacity will be very low compared to clean surfaces. It may be as low as 20 - 30 %.

2502.01.02 Mechanical Properties

The strength of aluminium alloys is highest at absolute zero and decreases as the temperature increases up to the melting point, the absolute values of strength varying with the type of alloy and temper. (**Figure 2205.03.01**)

In fire protection engineering it is the strength variation between 0°C and 500 °C which is important.

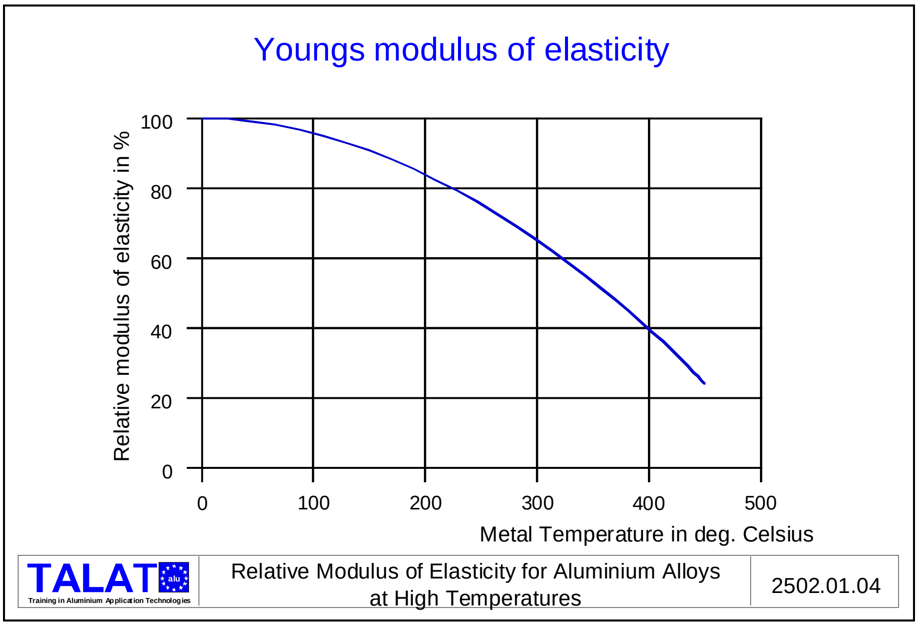
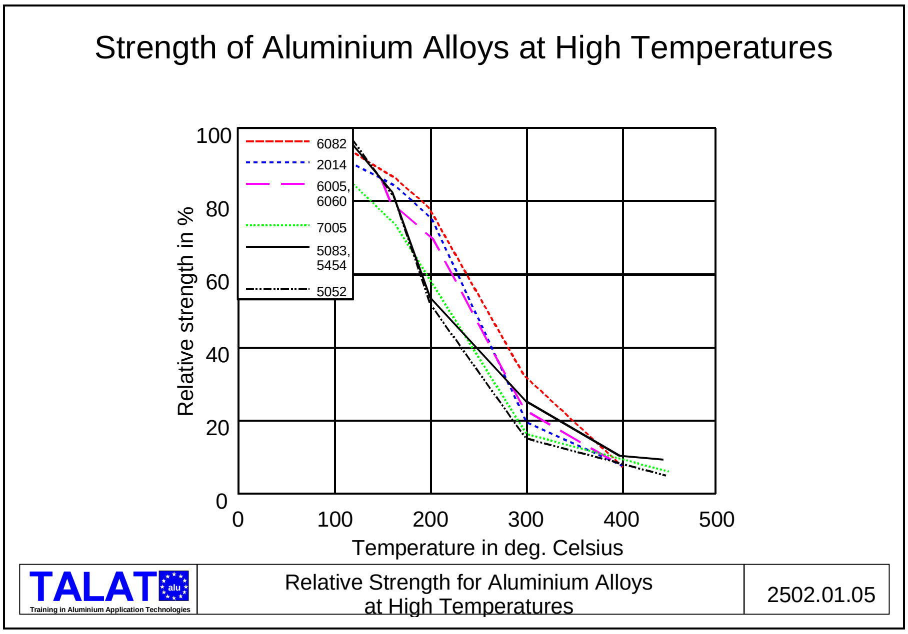
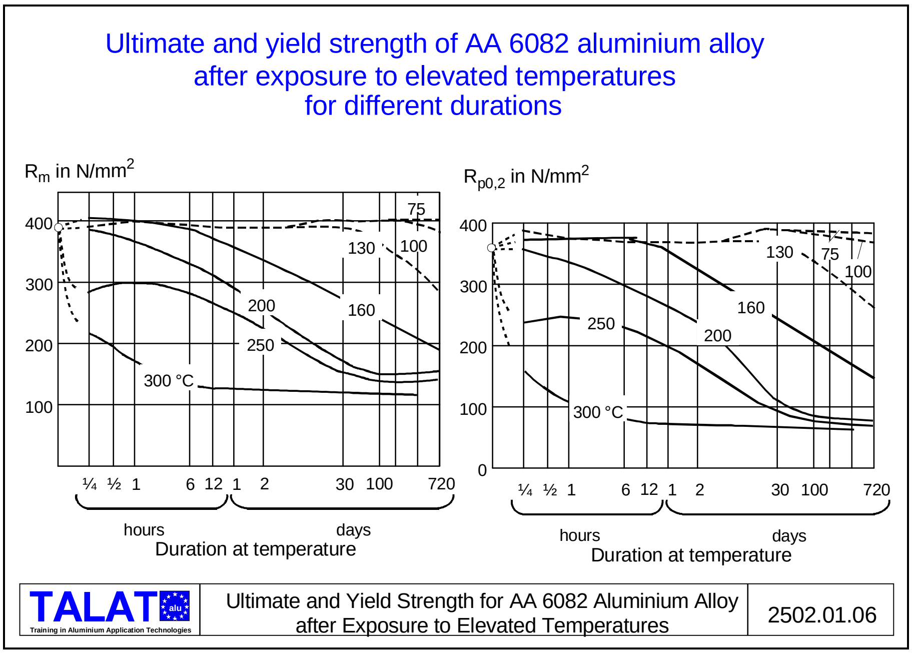


Figure 2502.01.05 shows the temperature dependence of strength (in % of room temperature values) for some aluminium alloys and tempers, **Figure 2502.01.04** the relative modulus of elasticity for aluminium alloys in general [12].



It is often interesting to know the extent of damages to an aluminium alloy structure after exposure to fire. Knowing the maximum temperature and the duration of exposure, the permanent strength reduction can be calculated from suitable data sources.

Figure 2502.01.06 shows the ultimate and yield strength of the AA 6082 aluminium alloy after exposure at various temperatures and times [9].



In ENV 1999-1-2 [15] the reduction of strength at elevated temperatures is given as stress ratios, $k_{0.2,\theta}$, for the 0,2 % proof stress and as exact values for the modulus of elasticity. The tables given in [15] are shown in the following.

Alloy	Temper	Aluminium alloy temperature °C							
		20	100	150	200	250	300	350	550
EN AW-5052	O	1,00	1,00	0,96	0,82	0,68	0,48	0,23	0
EN AW-5052	H34	1,00	1,00	0,92	0,52	0,33	0,22	0,13	0
EN AW-5083	O	1,00	1,00	0,98	0,90	0,75	0,42	0,22	0
EN AW-5083	H113	1,00	1,00	0,80	0,60	0,31	0,16	0,10	0
EN AW-5454	O	1,00	1,00	0,96	0,88	0,50	0,32	0,21	0
EN AW-5454	H32	1,00	1,00	0,92	0,78	0,36	0,23	0,14	0
EN AW-6061	T6	1,00	1,00	0,92	0,79	0,62	0,32	0,10	0
EN AW-6063	T6	1,00	1,00	0,90	0,74	0,38	0,20	0,10	0
EN AW-6082	T6	1,00	1,00	0,80	0,69	0,42	0,29	0,10	0

Aluminium alloy temperature, θ (°C)	Modulus of Elasticity, $E_{al,\theta}$ (N/mm²)
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

2502.02 Insulation Materials

- Rockwool
- Ceramic fibre
- Calcium silicate boards
- Gypsum boards
- Intumescent materials
- Spray-on cement based materials

For passive fire protection the following insulation materials can be used to insulate structures and partitions:

Rockwool
Ceramic fibre
Calcium silicate plates
Vermiculite plates
Gypsum plates
Intumescent materials
Spray-on cement based materials

The important properties of insulation materials for technical purposes are:

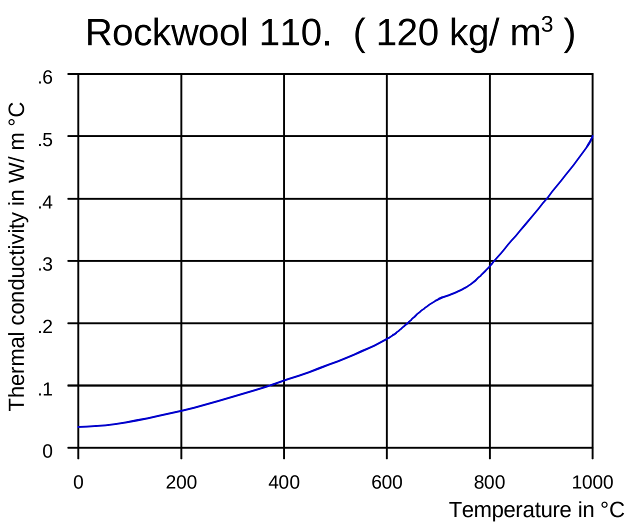
Thermal conductivity
Specific heat
Density

All these properties vary with temperature. Generally, the thermal conductivity decreases when the temperature is raised while the specific heat increases with increasing temperature. For most of the actual insulation materials the density is almost constant over the actual temperature range.

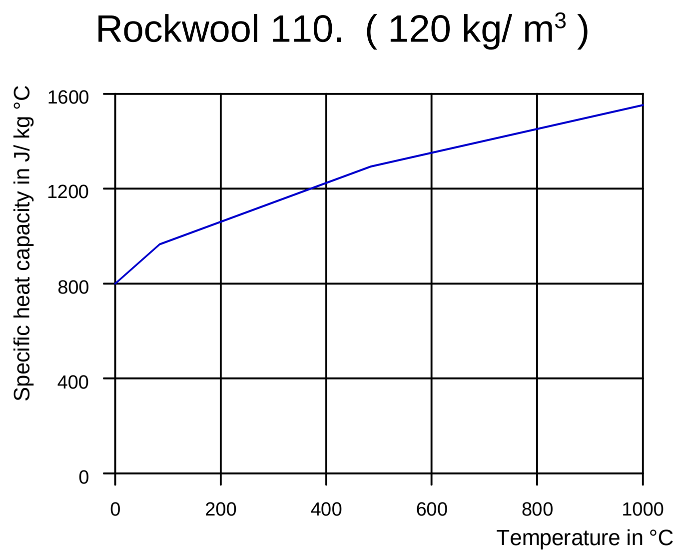
2502.02.01 Rockwool

As the name indicates rockwool is made of rock. The basic raw material is the volcanic rock called diabase. A fabrication process produces fibres which are compounded by a phenolic resin binder. During the production process the fibres are pressed to different densities of the wool. The density for commercial rockwool varies from 30 kg/m³ up to 1000 kg/m³. The heaviest rockwool types are produced as boards, the lightest as mats. Rockwool for passive fire protection will usually have a density between 100 and 300 kg/m³. Depending on the type of rockwool product, the working temperature is 250 - 750 °C. The fibre itself starts melting at about 1000 °C.

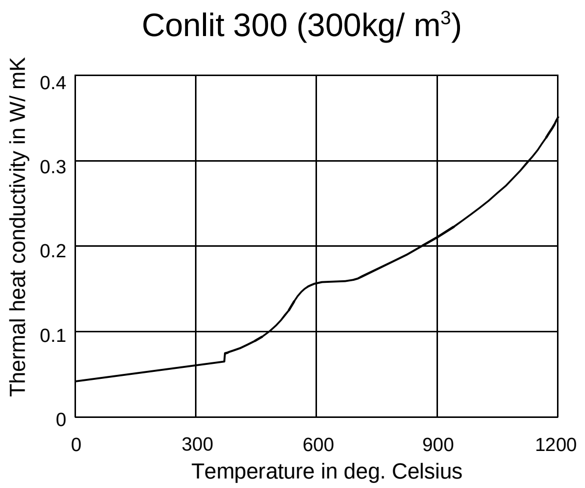
Thermal conductivity and specific heat capacity properties over the range of operating temperatures are illustrated in **Figure 2502.02.01**, **Figure 2502.02.02**, **Figure 2502.02.03** and **Figure 2502.02.04**.



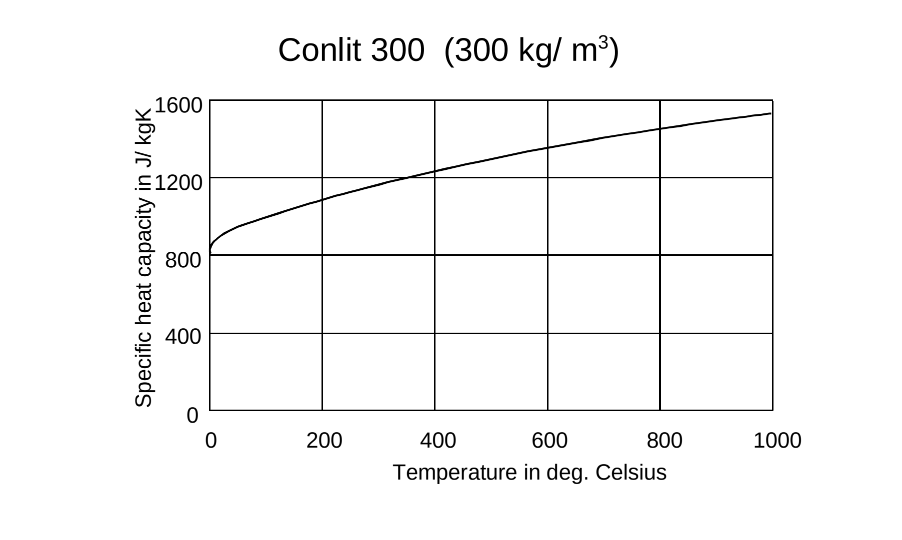
TALAT	Thermal Conductivity Versus Temperature for a Rockwool With Density 120 kg/ m ³	2502.02.01



TALAT Training in Aluminium Application Technologies | Specific Heat Versus Temperature for a Rockwool With Density 120 kg/ m^3 | 2502.02.02



TALAT Training in Aluminium Application Technologies | Thermal Conductivity Versus Temperature for a Rockwool With Density 300 kg/ m^3 | 2502.02.03

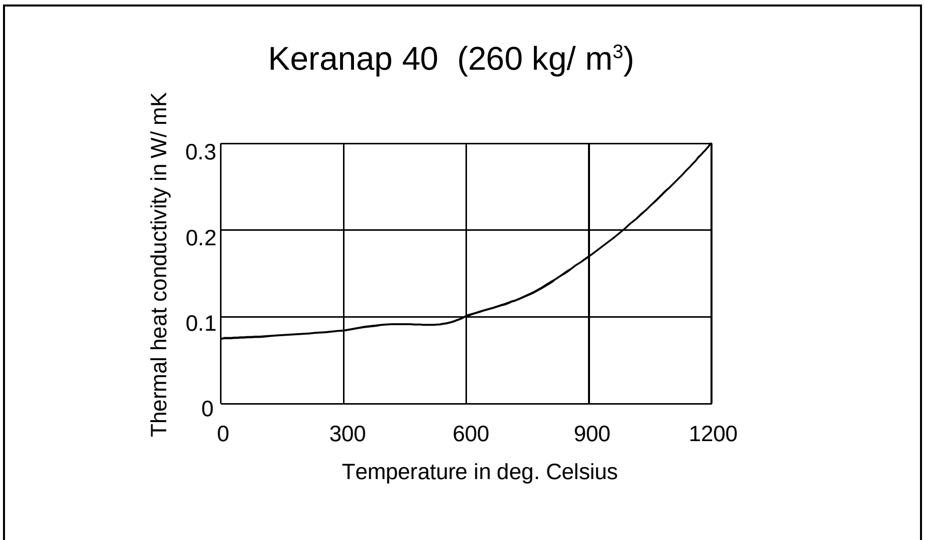


TALAT | Specific Heat Versus Temperature for a Rockwool With Density 300 kg/ m³ | 2502.02.04

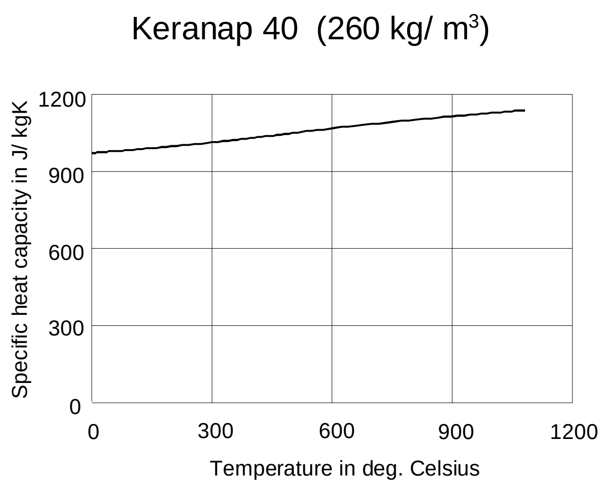
2502.02.02 Ceramic Fibres

Ceramic fibres have high purity alumina and silica as basic components. The lengths of the fibres vary from product to product. They are pressed together in a fabrication process, and the degree of pressure results in different densities. Commercial products are boards, mats, textiles, papers and bulk fibres. The density varies from 60 to 500 kg/m³. The working temperature is about 1200 °C and the melting point of the fibre is about 1750 °C.

Figure 2502.02.05 and **Figure 2502.02.06** show thermal conductivity and specific heat capacity properties over the range of operating temperatures for a ceramic fibre of density 250 kg/m³.



TALAT | Thermal Conductivity Versus Temperature for a Ceramic Fibre With Density 260 kg/ m³ | 2502.02.05



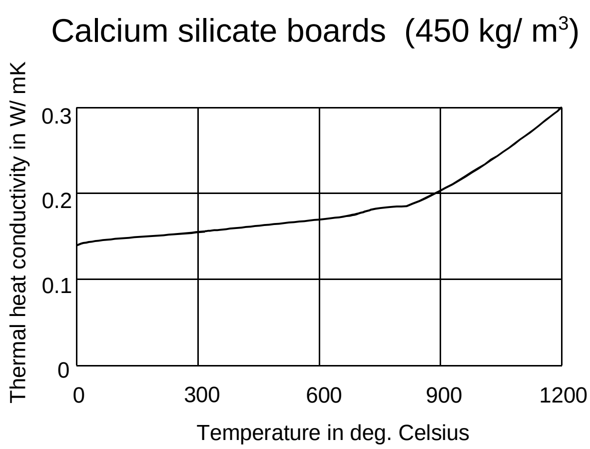
TALAT Specific Heat Versus Temperature for a Ceramic Fibre With Density 260 kg/ m³ 2502.02.06

2502.02.03 Calcium Silicate Boards

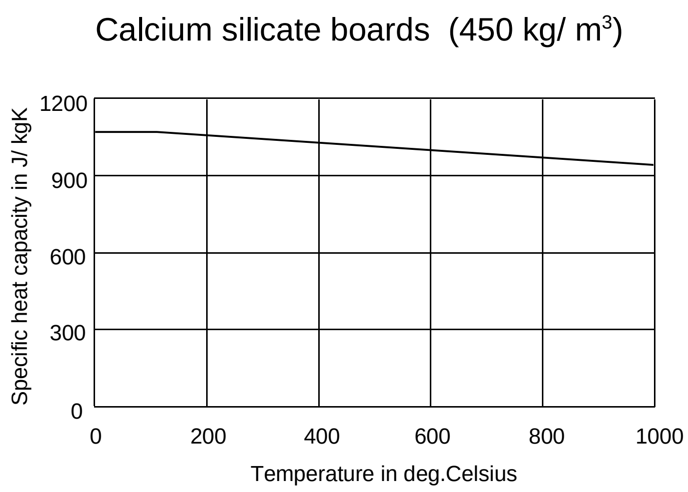
These boards are made of calcium oxide and silica. If they additionally contain vermiculite they are called vermiculite boards. There are a lot of different types of these boards on the market. The density of the calcium silicate boards is usually between 400 - 900 kg/m³.

Calcium silicate boards are used in fire-classified partitions and as laminates.

Thermal conductivity and specific heat properties for calcium silicate boards (vermiculite) are given in **Figure 2502.02.07** and **Figure 2502.02.08.**



TALAT Thermal Conductivity Versus Temperature for a Vermiculite Plate With Density 450 kg/ m³ 2502.02.07



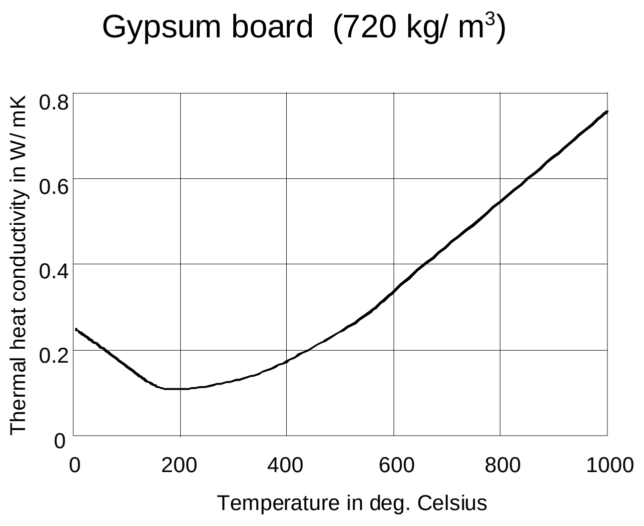
Specific Heat Versus Temperature for a Vermiculite Plate With Density 450 kg/ m³ — 2502.02.08

2502.02.04 Gypsum boards [14]

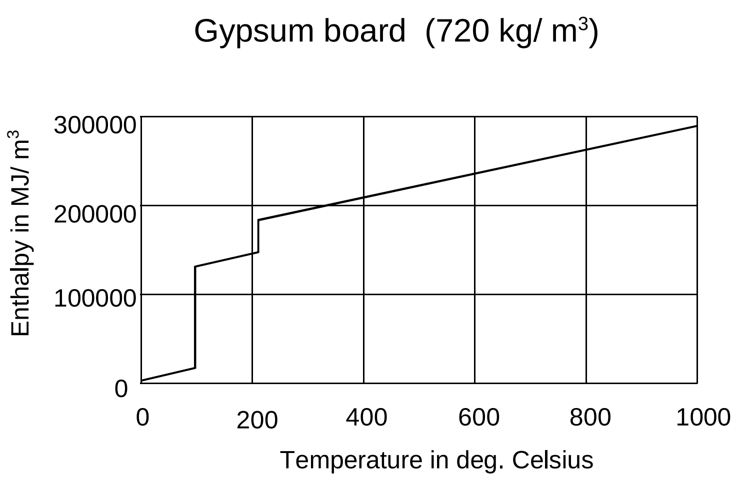
Gypsum consists of about 21% chemical bonded water and 79% calcium sulphate. The gypsum boards have a core of gypsum and a covering of pasteboard on both sides. Their good ability to serve as fire insulation is caused by the high energy required to release and evaporate the chemical bonded water in the gypsum core. Most of the decomposition of the gypsum will take place at 100°C. At 210°C it is totally destroyed.

Gypsum boards are used very much in the building industry as boards in fire classified partitions and as linings.The density of the boards are between 700 - 1000 kg/m³.

As an example **Figure 2502.02.09** and **Figure 2502.02.10** show the thermal conductivity and specific volumetric enthalpy over the range of operating temperatures for gypsum board with a density of 720 kg/m³



TALAT Training in Aluminium Application Technologies	Thermal Conductivity Versus Temperature for a Gypsum Board With Density 720 kg/ m^3	2502.02.09



TALAT Training in Aluminium Application Technologies	Specific Volumeric Enthalpy Versus Temperature for a Gypsum Board With Density 720 kg/ m^3	2502.02.10

2502.02.05 Intumescent Materials

As a common characteristic of these materials heat exposure initiates a chemical process that makes the material intumescent. It is the intumescent and porous part of the material which gives the insulation effect.

These materials are available as paint, as boards, blankets or spray-on masses. Most of the intumescent materials are classified as combustible and the density is usually high.

Used as fire protection on aluminium alloy structures, these materials require fire resistance tests in order to be rated fire classified.

Some special intumescent paints will have problems to meet the requirements as a fire insulation on aluminium alloy structures. This is caused by the rapid temperature rise in a fire test and the time needed for the material to intumesce and, therfore, serve as an insulator.

2502.02.06 Spray-on Cement Based Materials

These materials are using cement as binder, and are often used in the offshore oil industry and the process industry onshore to protect steel structures and equipment against fire.

The thermal conductivity and the specific heat is relatively high. The density is 500 - 1500 kg/m³.

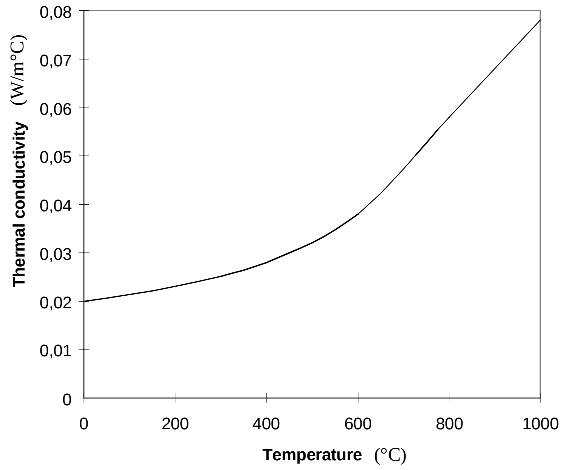
The content of cement in these materials will continuously destroy the passivation layer on the surface of the aluminium because the pH-value will be above 9,0. These materials, therefore, are not recommended as passive fire protection for aluminium alloy structures.

2502.02.07 Microtherm

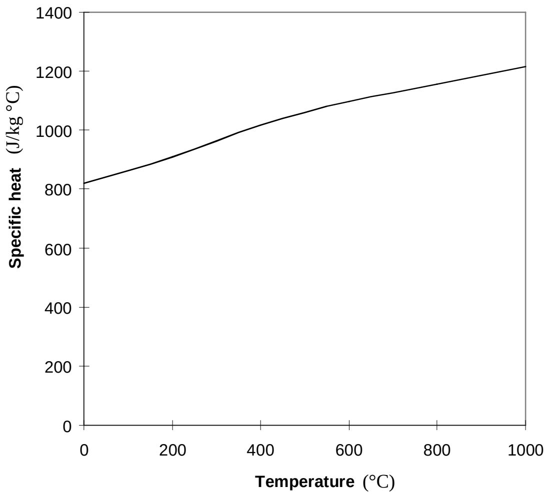
Microtherm is a very high efficiency thermal insulation material. It is a material consisting of microporous silicas, ceramic fibres and ceramic opacifiers which are intimately mixed and bonded to form a panel, block or moulded shape. The density is from 175 kg/m^3 to 275 kg/m^3.

Up to now it is mostly used in civil and military aircrafts, navel vessels, military vehicles and in nuclear plants and process industry. In the future, it may have an increasing use in structures where the need for light weight is essensial.

The thermal conductivity is very low also at elevated temperatures, the specific heat is about the same as for ceramic fibre. In the following graphs, the thermal conductivity in W/m°C and the specific heat in J/kg°C versus temperature in °C are shown.



TALAT	Thermal conductivity versus temperature for a Microtherm with density of about 230kg/m3	2102.02.11



TALAT	Specific heat versus temperature for a Microtherm with density of about 230kg/m3	2102.02.12

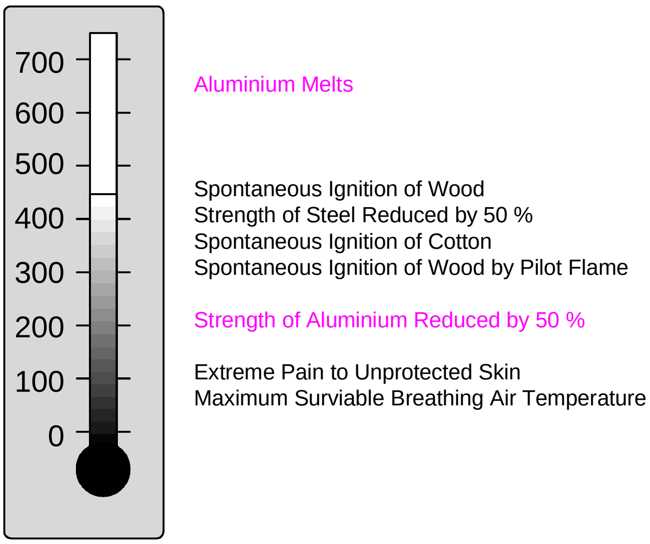
2502.03 Philosophy Regarding Aluminium Alloy Structures and Fire

With regard to the risk of fire, the properties of aluminium alloys are briefly summarized as follows:

- Aluminium alloys are noncombustible materials
- The strength of aluminium alloys is reduced by 50% between 150 and 300° C
- Aluminium alloys melt between 600 and 650° Celsius.

Most of the fire casualties are due to toxic gases and loss of oxygen before the rise of temperature becomes critical. At 160° C human beings feel extreme pain on unprotected skin and after a few seconds heavy burnings occur. 150 ° C is the maximum breathing air temperature if the air is dry, if humid the maximum breathing air temperature is even lower.

Whenever aluminium alloy structures have reached their critical temperature the temperature of the fire room is even higher and no human being can survive. Critical temperatures for men and materials are illustrated in **Figure 2502.03.01**.



TALAT	Important Temperature Regimes for Men and Materials	2502.03.01

Using unprotected aluminium alloys as materials in a compartment on fire will cause **no** extra risk for human safety. Many other materials are combustible and will contribute to the combustion, while aluminium alloys give no contribution to the fire. When fire rating is required aluminium structures have to be fire protected. Usually this is achieved by the use of passive fire protection precautions, but active fire protection methods may also be acceptable.

Cooling the structure by use of water/water spray will always keep the temperature of the aluminium alloy structure below 100° C as long as there is a water film on the structure. This may be an acceptable way of protecting aluminium alloy structures.

A risk analysis is helpful in cases where requirements and regulations are ambiguous with respect to the actual situation.

2502.03.01 Example of Risk Analysis

Escape towers on some oil platforms in the North Sea are an example, where the use of risk analysis led to the decision of using unprotected structural aluminium.

The input for the risk analysis consisted in the material properties of the used aluminium alloys, the fire scenario including the thermal load and the production of toxic gases and smoke, the lay-out of all escape routes and the environmental conditions. The conclusion from the risk analysis was that if the escape stairtower made of aluminium was engulfed either in smoke/toxic gases or in flames, it was useless and perilous as an escape way long before the structural aluminium was going to collapse. The lay-out of the escape routes always secured at least one safe escape way.

2502.04 References/Literature

[1] **Drysdale,** Dougal: An Introduction to Fire Dynamics. John Wiley & Sons. 1987, ISBN 0-471-90613-1

[2] NFPA/SFPE: Handbook of Fire Protection Engineering. NFPA/SFPE. 1988, ISBN 0-87765-353-4

[3] **Sterner**, E. / **Wickstrøm**, U.: TASEF - User Manual. Statens Provningsanstalt. 1990, ISBN 91-7848-210-0

[4] **Landrø**, Harald: Verification of the fire resistance of construction elements and structures. SINTEF 1983.

[5] ISO 834-1975 (E). Fire resistance tests - Elements of building construction.

[6] ECCS-TC3: European Recommendations for the Fire Safety of Steel Structures. Elsevier 1983. ISBN 0-444-42120-3

[7] GYPROC: Gyproc Håndbok. 1986. (In Swedish).

[8] **Holmen**, J.P.: Heat Transfer. McGraw-Hill. Publ. Comp. 1990. ISBN 0-07-909388-4

[9] **Aluminium-Zentrale** (Ed.): Aluminium Taschenbuch. Aluminium Verlag Düsseldorf, 1983. ISBN 3-87017-169-3 (In German)

[10] Carborundum Resistant Materials: Fiberfrax Manual 1987.

[11] Elkem Rockwool: Innføring i passive brannsikring. 1991. (In Norwegian).

[12] NBR: NS 3478. Design rules for structural member for fire resistance. 1979. (In Norwegian).

[13] Hydro Aluminium Structures a.s: Revisjon av NS 3471, Kap. 14.2 Brannteknisk dimensjonering. 1992. (In Norwegian).

[14] **Andersson**, Leif & **Jansson**, Bengt: En undersøkning av gipsskivans termiske egenskaper - Teori och försök. Lund University 1986 (In Swedish).

[15] CEN/TC 250/SC 9: ENV 1999-1-2. Design of aluminium structures. Part 1.2. Structural fire design. 1997.

[16] CEN/TC 250/SC 1: ENV 1991-2-2. Basis of design and actions on structures. Part 2.2. Actions on structures exposed to fire. 1995

[17] CEN/TC 250/SC 9: ENV 1999-1-1. Design of aluminium structures. Part 1.1. General rules. 1997

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