MATERIALS FOR ACCELERATOR VACUUM SYSTEMS

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Abstract

Materials used in vacuum systems of accelerators are described. In the first part, general properties of materials such as the mechanical strength, thermal and electrical conductivity and transparency are discussed. In the second part the most important materials: stainless steel, aluminium, copper and ceramics are described, followed by details of the joining of different materials.

1. INTRODUCTION

Particle accelerators are operated in the 10^{-10} mbar pressure range in the case of hadron storage rings and 10^{-9} in the case of electron storage rings where a high gas load is caused by synchrotron radiation induced gas desorption. In order to get such a low pressure, the main criteria are a low gas desorption rate and no penetration of gases from the outside. The desorption and penetration of gases are the subject of separate lectures within these proceedings. In addition to these properties the material should fulfil some further criteria which are the subject of this lecture:

- Used as vacuum envelope, the material must withstand the atmospheric pressure. This favours a material with a high modulus of elasticity and high mechanical strength.
- Since Ultra High Vacuum (UHV) systems are baked, the materials used should have a negligible equilibrium pressure at the foreseen baking temperatures (150°C –350°C). Thus metals like zinc, magnesium or lead, or alloys containing these, which have a significant vapour pressure at relatively low temperatures, should not be used. Vapour pressures as a function of the temperature are given in the appendix.
- Obviously gases should not penetrate through the envelope of the vacuum system. There is some penetration of He and H_2 through glasses and some metals at higher temperature (palladium can be used as a filter for hydrogen) but for most materials discussed here, penetration is negligible. Gases can penetrate through elastomers such as Viton generally used for sealing High Vacuum (HV) systems.
- The materials should be easy available, which favours materials of general use in industrial application, for chemical plants, for building ships or aeroplanes.
- The materials should be easy to form mechanically by machining, turning, folding or deep drawing and be easy to join by welding or brazing.
- For some special applications the material should be a good thermal or electrical conductor in order to distribute the heat load or to reduce the impedance of the system. For other applications it should be non- or less-conducting in order to reduce eddy currents or for electric isolation.
- For an interaction region or for windows, the material should be most transparent for radiation, while normally it should shield radiation as much as possible.
- But increasingly the choice of the material is determined by economic criteria, it should fulfil its purpose at a minimum price.

Concerning the envelope, the most used materials are stainless steel, aluminium and copper. For small systems the material of choice is often a standard off-the-shelf solution, stainless steel. For larger systems and special requirements other materials become interesting since the costs that are put into their development and testing often pays off.

2. PHYSICAL RESTRICTIONS

2.1 Mechanical stability

Some important material properties will now be explained but for more details the reader is referred to a text book such as Ref. [1]. The main criteria for a material used as an envelope for a vacuum system is its mechanical stability under atmospheric pressure. If a pressure or **stress** (force per area) is applied to a material it will be deformed by a certain **strain** (change in length per length). The behaviour of a material under stress is shown in Fig. 1. For small strains the deformation is elastic, it recovers when the stress is released and the strain is proportional to the stress. The factor of proportionality is called **Young's modulus** or the **modulus of elasticity**.

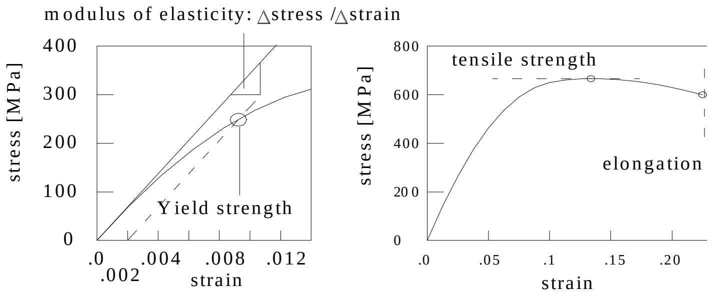
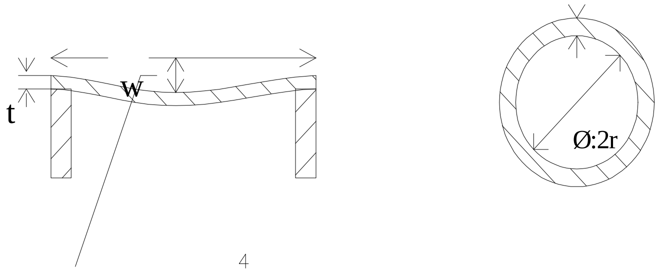


Fig. 1 Definition of modulus of elasticity, yield and tensile strength and elongation.

For large strains the deformation becomes plastic, the stress/strain relation is no longer linear. The stress value for which the stress/strain function crosses an offset of 0.002 of the linear behaviour is defined as the **yield strength**. For further increase of the strain, the stress increases until a maximum value is achieved which is defined as the **tensile strength**. For further strain, less stress is needed and the material will rupture when a maximum elongation is reached. Materials which can be deformed by several percent until rupture are called plastic or **ductile** (most metals), materials which cannot be deformed plastically are called **brittle** (ceramics). The strain at which the material ruptures is called the **elongation**.

From a mechanical point of view the critical parts of a vacuum chamber are the non-circular chambers: flat chambers like those in a dipole or an undulator, schematically shown in Fig. 2. The deflection (dy) is proportional to the fourth order of the width divided by the third order of the thickness times the modulus of elasticity. The stress is proportional to the second order of the width divided by the second order of a thickness. Obviously materials with a high modulus of elasticity are favoured but a difference in the modulus of elasticity by a factor 3 (aluminium compared to stainless steel) can be compensated by a slightly larger thickness of 1.45. Thus the design of chambers becomes important and the design has to be appropriate to the material. It should be noted, that the formulas given are only rough estimates. For realistic values of deformation and stress, finite element programs like ANSYS should be used.



deflection $\sim \frac{p\,w^4}{32\,E\,t^3}$

stress $\sim \frac{p\,w^2}{t^2}$

buckling $\frac{t}{r} > (4p/E)^{1/3}$

stress $\sim \frac{p\,r}{t}$

Fig. 2 Deflection and stress of vacuum chambers by atmospheric pressure.

2.2 Hardness

The hardness of a material is another important mechanical property for the sealing of a vacuum system by a flange gasket system. It describes the resistance of a material to a local plastic deformation. For the flanges a hard material is used, mostly stainless steel. If aluminium is used for flanges an alloy with high hardness is selected and, in addition, the surface is often hardened by a special coating. For the gaskets a weak material is selected like copper, aluminium, gold, silver or indium.

There exist several measuring methods for the hardness. The Brinell hardness is measured by pressing a tungsten carbide ball (Diameter: D[mm]) with a standard load (F[kp]) into the test piece. The diameter of the imprint is measured (d[mm]) and the Brinell hardness is calculated as follows:

$$H_B := 2F/(\pi D(D-(D^2 + d^2)1/2))$$

The hardness is roughly proportional to the tensile strength T_s [Gpa] ~ 3.5 H_B.

2.3 Hardening

As mentioned in 2.1, a large stress applied to a material causes plastic deformation. The reason for this behaviour is explained by the structure of the metals that consist of grains with a non-perfect crystal structure. The failures or dislocations in the structure can easily move within the grains and cause their deformation. Since the movement of the dislocations is limited by the grain boundary, a small grain size increases the strength of a material.

An important possibility for increasing the strength is work hardening or cold working. If a material is cold-worked, i.e. by drawing or folding, additional dislocations are produced in the grains. The increased number of dislocations cause more friction since the dislocations hinder each other's movement. The increased strength is shown in Fig. 3 for OFHC copper as a function of the cold work. Starting from 70 M Pa for annealed copper, a yield strength of up to 300 M Pa can be achieved.

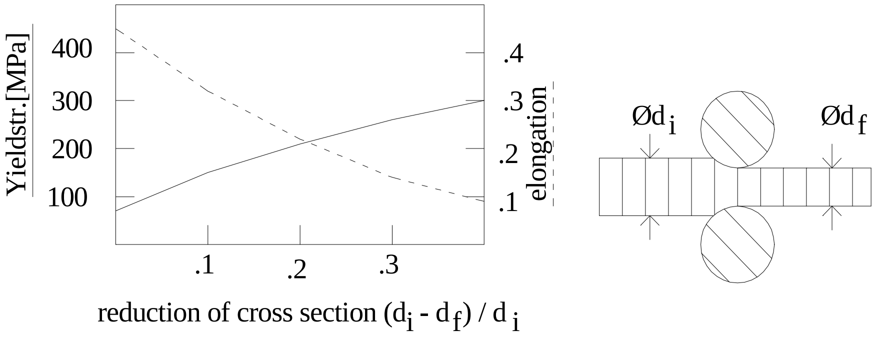


Fig. 3 Influence of cold work on yield strength and elongation.

The process of cold working can be reversed when the material is heated. At the annealing temperature all stresses in the material are released and the grain size begins to grow. This temperature is relatively low, about 1/3 of the melting temperature in [K]. The annealing temperature for some materials are given in Table 1.

Table 1
Annealing temperature for selected elements.

Material:	**Al**	**Al Cu Si**	**Cu OFHC**	**Stainless steel**
Annealing temp. [°C]	100	250	110	450

A further method for hardening some alloys is **precipitation hardening.** The strength of an alloy is generally higher since the particles introduced reduce the movement of dislocations. Some special alloys like Al Cu (5) Si (1) can be further hardened. The alloy is heated to a temperature of 400°C at which the copper is completely dissolved in the aluminium. Rapid cooling freezes this state at room temperature. (Normally the alloy consists of grains with aluminium and grains with Al-Cu.)

If the temperature is increased to 100 to 200 °C Al-Cu islands are formed within the aluminium grains. These islands constitute friction for the movement of dislocations and thus increase the strength of the alloy. The increased temperature must not be applied for too long since the strength will be reduced again. This behaviour is called over ageing. The temperature of the process as a function of the time and the yield strength as a function of the ageing time and temperature are shown in Fig. 4.

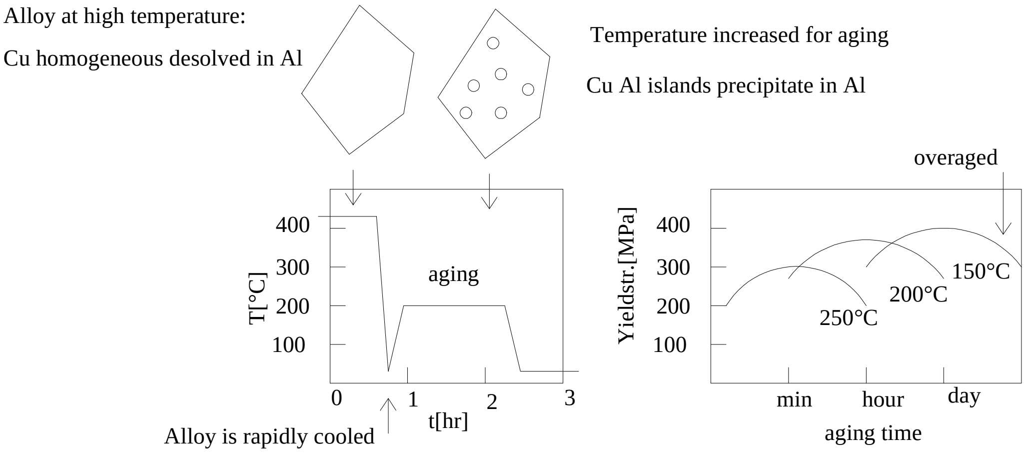
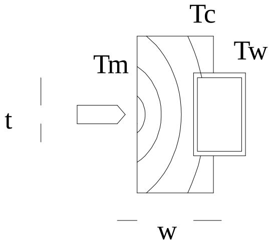


Fig. 4 Precipitation hardening i.e. the aluminium copper system.

2.4 Thermal conductivity

When a high heat load has to be transported materials with a high thermal conductivity are used. Thus the main lumped absorbers of synchrotron radiation sources are made from copper. When the heat load is directly absorbed on the wall of the envelope of the vacuum system aluminium (LEP) or copper (HERA, B factory) is used. For windows beryllium, beryllium-oxide or diamond are good candidates since the energy losses are small in these materials and the thermal conductivity is high. The maximum temperature at the heat source is the sum of the temperature step in the material (which increases with distance and the thermal conductivity) and the temperature step at the interface from the metal to the water (which decreases with the distance due to increased area for the heat transfer to the water). The situation of an absorber is demonstrated in Fig. 5 and the following estimates can be made:



$(Tm-Tc) \sim (P/l)\ln(w/t)/\lambda$

$(Tc-Tw) \sim (P/l)/(w\,h(v))$

$h(v) \sim v \quad h(3m/s) = 12\ kW/m$

λ : thermal conductivity

α : thermal expansion

(P/l): Power per length

h(v): heat transfer coefficient

Fig. 5 Conductivity of thermal load in an absorber.

As in the case of the deformation and stress, the given formulas are only for rough estimates, the exact temperature behaviour and stress should be calculated by programs like ANSYS.

Obviously the temperature of the water duct should be kept below the boiling point of the water (the boiling temperature increases by 10 °C for each bar over-pressure). In addition the maximum temperature at the heat source should be low enough to prevent fatigue failure or even melting. The parts of the material which are at higher temperature try to expand but are hindered by the bulk of the material, thus a stress occurs which can lead to cracks and rupture of the material. Since the stress is cyclic, fatigue failures occur at a much lower level than given by the tensile strength. The thermal stress is correlated to the strain that is given by:

$$s = \alpha \Delta T,$$

where α is the expansion coefficient of the material, ΔT the temperature difference between the bulk and the maximum temperature. This rupture depends on the number of cycles and the amount of stress from the temperature. Figure 6 shows this behaviour for copper [2] and GLIDCOP [3]. For 10^4 cycles (the assumed lifetime of an absorber in a synchrotron radiation source) the strain should be kept below 0.002 in the case of OFHC copper.

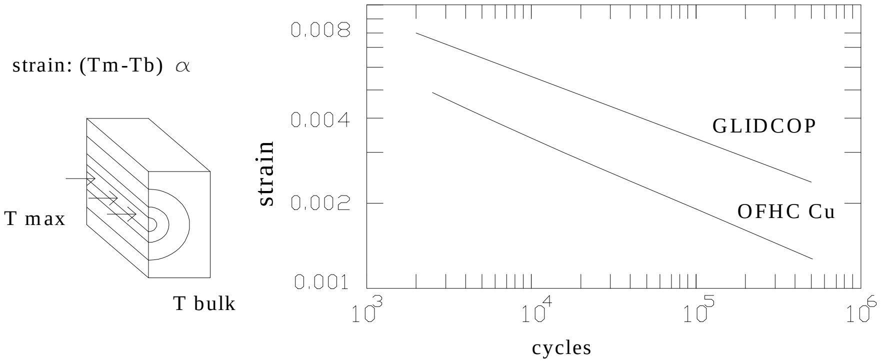


Fig. 6 Fatigue behaviour of copper.

This stress can be reduced by careful design. If the parts at higher temperature are allowed to expand (at least partially) the stress is reduced. For the crotch absorbers for ANKA and the SLS, the absorbers are split into two halves with comb-like structure and slightly separated. Each tooth can expand at the edges which reduces the stress by about a factor of two [4].

2.2 Electrical conductivity

Obviously high conductivity material namely copper is used wherever high currents have to be transported.

The vacuum impedance of a storage ring depends on the conductivity of the chamber material and the gap of the chamber. For insertion device chambers with extremely small gaps (5mm) the vacuum impedance can make a significant contribution to the total impedance. This is one reason for preferring aluminium as the material for the vacuum chamber of an insertion device or stainless steel with copper plating. Copper-plated stainless steel is also used for the LHC vacuum system [5] to reduce the resistive losses from the mirror currents and thus liquid helium consumption for cooling the heat load. A low-conducting steel alloy was chosen as the bulk material, since a high-conducting material (copper, aluminium) would cause destruction of the beam duct by the large forces from eddy currents when a super conducting field quenches.

In order to reduce the eddy currents, low-conductive materials are used for vacuum chambers which are situated in rapidly changing magnetic fields such as a Booster Synchrotron (operated in the 1-10 Hz range), Kickers (operated at about 1 MHz) or, as mentioned above, in the vicinity of superconducting magnets (LHC). Eddy currents cause magnetic fields opposite to the applied ones, reducing their effect. In addition they heat up the material. The dependency on frequency, conductivity and geometry is shown in Fig. 7.

The eddy currents are proportional to the electrical conductivity. Thus low-conducting materials like stainless steel, inconel or even ceramics are used, depending on the frequency of the magnetic field. The above estimates are only valid if the thickness of the material is not large compared to the skin depth which is given by: $d_{\mathrm{skin}} = (\pi \mu_{rel} \mu_0 \sigma \omega)^{-1/2}$.

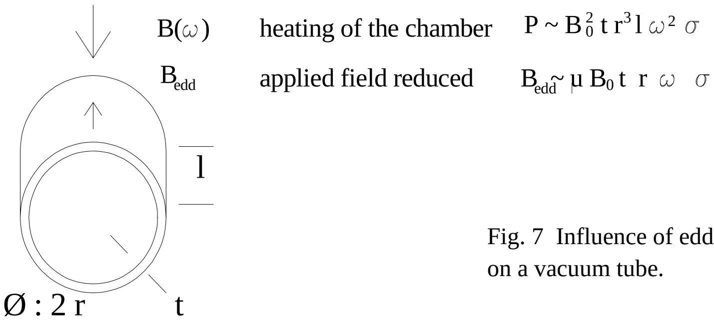


Fig. 7 Influence of eddy currents on a vacuum tube.

Kickers are interesting since their vacuum envelope is generally ceramic in order to avoid eddy currents, but a conducting layer is also needed in order to conduct the mirror currents of the particle beam, to preserve the impedance and to enclose the high field of the particle beam (500 MHz – 1GHz) to prevent heating of the ferrites. Thus a thin (about 2 µm) conducting titanium layer is sputtered onto the inner surface to shield the field. The thickness of the layer is a compromise between the rise time of the magnetic field and the eddy current losses, which favour a thin layer, and the resistive losses of the mirror currents and the need for a homogenous layer which favour a thick layer [6].

Obviously isolating materials are needed for electric feedthroughs like beam position monitors, kickers or septum magnets positioned in the vacuum, RF coupling loops etc. While plastics do their job for HV systems, especially materials like Vespel or Peek that can be baked up to 200°C, for UHV application and in radiation environment ceramics must be used.

2.6 Radiation penetration

At the interaction region of a collider the collision products should easily penetrate the wall of the vacuum chamber. Since most scattering processes depend on a higher order of the Z of the target material, a low Z and high mechanical strength are favoured. This was the reason that at the CERN SPS vacuum tubes made from carbon composite were developed for the 13-m long interaction region. For the shorter interaction region of the B factories and at DAFNE beryllium will be used. Beryllium is also used as windows for the synchrotron radiation in beam lines that separate the ultra-high-vacuum region of the storage ring from the user region. The left side of Fig. 8 shows the radiation lengths for selected elements [7].

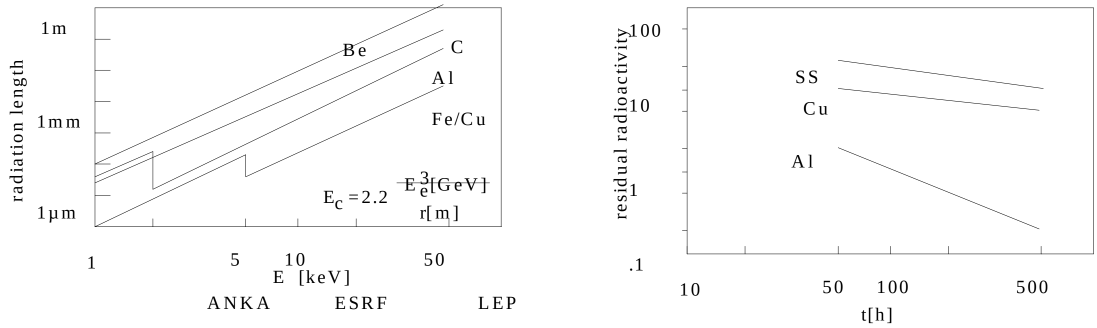


Fig. 8 Left side: Radiation length of synchrotron radiation. Right side: Residual activation of different materials.

In the normal region of a storage ring penetration of radiation is unwanted. Scattered and lost high energy particles and their reaction products cannot be shielded by the vacuum chamber. One-meter thick concrete walls or the equivalent in lead are needed. But in the case of high energy e-storage rings the emitted synchrotron radiation can also be high enough to penetrate the vacuum chamber if a light (Al) material is selected. This had been one reason for using copper (Z = 29) instead of aluminium (Z = 13) at the B factories or at HERA. At LEP a lead (Z = 82) shield was soldered onto the outside of the aluminium chamber to get a shielding effect.

2.7 Activation

Activation of material (by neutrons or ions) might be a nuisance for quick access to the accelerator after switching off, or by creating nuclear waste. Light materials, i.e. aluminium, (but take care of the other elements (Pb) in the alloy) are of advantage, as can be seen from Fig. 8, right side [8], the activation level is smaller and decays more rapidly. Obviously, activation also causes damage in materials, hardly in metals, but strongly in plastics which are not normally part of a UHV system. But cables for pressure gauges and electronics (often integrated into the gauges), turbo pumps and plastic or rubber water lines are indirectly part of the vacuum system and will be damaged. A list of the radiation resistance of the most used plastics is given in Table 2.

Table 2
Radiation damage of selected materials.

Material	**Polyuretan**	**Kapton, Peek**	**Polyethylene, PVC**	**Viton**	**Polyamide**	**Teflon**
Dose [gray]	10^8	10^7	$0.5\ 10^7$	10^5	10^4	10^2

3. SELECTED MATERIALS

3.1 Stainless steel

Stainless steel is the standard material for most vacuum components. Many manufactures have experience with this material. The mechanical strength (200 GPa yield strength) is sufficient for constructing dedicated vacuum systems. It is easy to weld. It is a standard material, generally used in construction work and easily available on the market. The high hardness (190 HB) protects flanges from scratches and leaks. The outgassing rates are low. Stainless steel can be baked in situ (150 to 350°C) to remove the water from the surface and it can be fired (at 900°C) to reduce the H_2 from the bulk of the material. Since austenitic steels are non-magnetic they can be used within magnets. A survey of the properties of stainless steel and its application to vacuum technologies is given in Ref. [9].

Steel alloys become corrosion resistant if the alloy contains more than 13% chrome, typically about 18%, since it produces a protective film of chrome oxide at the surface. The addition of nickel, typically 10%, maintains the austenitic structure (a face-centred cubic iron) at room temperature and is not magnetic.

Commonly the austenitic types 304 (Fe Cr(18)Ni(9)C(0.07)), 304L (Fe Cr(18)Ni(11)C(0.03)), 316L (Fe Cr(18)Ni(14)Mo(3)C(0.03)), 316LN (Fe Cr(18)Ni(14)Mo(3)N(0.2)C(0.03)) are used. The L stands for low carbon (less than 0.03%) which is important for conserving corrosion resistance when fired or welded. The N denotes the addition of nitrogen that increases the strength and the hardness of the steel. Within this text the chemical composition of alloys is given by the chemical elements of the alloys with its weight component in %, with the exemption of the main component. Concerning the mechanical properties austenitic steels are ductile with a relative low yield strength (200 GPa) and a high elongation (70%). The yield strength and also the hardness can be improved (300 GPa) by adding nitrogen to the alloy.

Hydrogen is the main gas component of UHV vacuum systems. While water is concentrated rather at the surface, hydrogen is dissolved in the bulk of the material (due to the production process). The hydrogen can be considerably reduced when the material is heated to 900°C. Thus the vacuum chambers of many accelerators are vacuum fired, partly before and partly after their manufacture. Since the high temperature also reduces the hardness the stronger alloy 316LN is mainly used when the material is fired.

When austenitic steels are fired or welded care must be taken to avoid the formation of carbide which can cause micro cracks and reduce the corrosion resistance. Carbon is normally completely dissolved in the alloy, but if the alloy is heated to temperatures higher than 600 °C and the cooling is later not done rapidly enough, carbon diffuses to the grain boundary to a larger extent than the chrome and the chrome content can fall below a critical limit. The formation of carbide can be avoided if the carbon content of the alloy is low (less than 0.03%) and the critical temperature range (600 – 750°C) is passed in less than an hour [9].

Due to the production process stainless steel contains a high amount of impurities and inclusions (mostly sulphides and oxides). When the iron is cast into ingots the relatively lighter impurities collect at the surface but partly penetrate into the ingot when cooled. These impurities are the reasons for cracks and micro leaks. Forming the ingots into sheets and bars will further distribute them. The amount of impurities can be reduced considerably if the material is remoulded by an electro-slag refining process, schematically shown in Fig. 9. The impurities are collected at the top of the ingot which will be cut away. In addition the homogeneity of the steel can be improved if the ingots are hot forged. If the steel is machined to flanges etc the surface parts (3-5mm) of the bars should not be used.

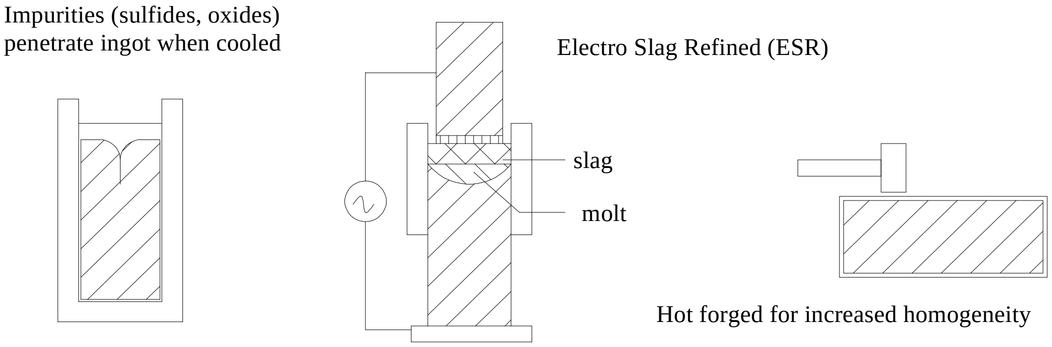


Figure 9: Quality improvements for stainless steel.

The steel quality is defined by the number of inclusions and the corn size. These items are determined by comparing a steel probe with standard probes. The corn size is classified by grain size numbers, the higher the number the smaller the grain size. The number is inversely proportional to the root of the grain size. A grain size number of 1 corresponds to a grain diameter of 0.25 mm. The inclusions are classified according to sulphides (A), oxides (B), silicates (C) and globular oxides (D). For each a severity level between 0.5 and 3 can be given. The more inclusions the higher the number. For UHV application a level of maximal 1 for inclusions (A, B, C), 1.5 for D and a grain size number of minimal 4 should be fulfilled.

Tubes and vessels are normally made from cold-rolled plates. Cold refers to the recrystallization temperature which is about 400°C for stainless steel. Cold-rolled plates have a finer surface.

While aluminium and copper are often formed by extrusion or machining from blocks, stainless steel is formed mainly by rolling, folding and deep drawing of sheets. Welding should be done without filler. Welding of long straight seams is normally done by e-beam while the flanges are welded by DC TIG (tungsten inert gas). TIG welding can lead to a distortion of the material (reduction in length and increase of the thickness close to the weld seam) due to the smaller energy density compared to e-beam welding. This distortion is in the order of the thickness of the weld and has to be taken into account for the dimensioning before welding. If the welding is not symmetric the whole vacuum chamber can be considerably deformed as experienced with the ANKA prototype vacuum chamber, when the supporting ribs were welded at the outer side of the chamber, see Fig. 10. Such a distortion can be removed by heating up the chamber at the opposite side, but has to be done by experienced workers to get acceptable results.

3.2 Aluminium

Aluminium has been used as the material of many electron synchrotrons (PETRA, TRISTIAN, LEP, LEAR, ALS, SRRC, APS, LEP, Pohang, Spring8). A summary of aluminium technology is given in Ref. [8]. The main reason for using aluminium has been that long beam tubes including the antechambers for distributed pumps and cooling ducts can economically be produced by extrusion. Furthermore complex chambers can be machined from solid blocks. Figure 11 shows the cross section of the LEP vacuum chamber made from extruded aluminium [10] and the cross section of the ALS vacuum chamber at a quadrupole which was machined from thick plates. The good thermal conductivity of aluminium allows an easy distribution and cooling of heat load. Thus the power density of the synchrotron radiation can be absorbed directly on the chamber wall if the power is not to high. In addition the cooling ducts can be conveniently used for mild baking (150°C) by using pressurised water. Standard parts (tubes, fittings, T and cross pieces) are now available from industry [11]. Additional advantages are that it is completely non-magnetic, has a low activation cross section and a rapid decay of radioactivity.

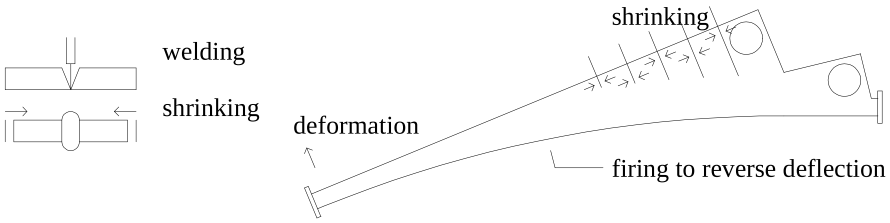


Fig.10 Weld distortion of the ANKA prototype chamber.

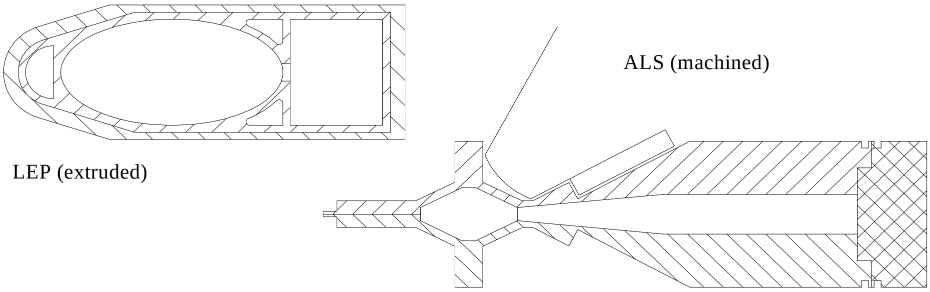


Fig. 11 Aluminium vacuum chambers of LEP and ALS.

However, aluminium has several disadvantages. Initially at least, it has an order of magnitude higher desorption yield compared to stainless steel or copper. The mechanical properties (E module, hardness) are weaker compared to stainless steel and have to be compensated by an appropriate design. Furthermore it is not so easy to make welds vacuum tight compared to stainless steel. A high heat load must be applied in order to break the thick oxide layer but the heat is rapidly diffused due to the good thermal conductivity. Thus the design of the weld should be done in such a way that only a minimum heat load is needed by doing small welds and introducing grooves close to the weld to confine the exposed area. The AC TIG method helps to remove the oxide layer more efficiently.

Both the high desorption yield and the difficulties with welding are related to the relatively thick oxide layer (15 nm) on the surface. In order to reduce this problem all extrusion and machining processes were done under argon atmosphere at KEK [8]. As a result a 3 nm low-porous oxide layer was obtained. For the same reason all machining was done with ethanol lubricant at SRRC [12]. At APS weld leaks were reduced when a filler wire extruded in argon was used [13].

For tubes the alloy 6063 (Al Mg(0.7)Si(0.4)) is mainly used, which can be extruded and is less expensive. For aluminium flanges, screws and nuts the harder 2219 Al Cu(6.3)Si(0.3) is preferred. In order to enhance the surface hardness of aluminium flanges a 2-µm TiN coating can be applied.

Connecting of aluminium chambers is partly done by using aluminium flanges, partly by using aluminium/stainless steel transitions and stainless steel CF flanges. Sealing is done with pure (1050) aluminium Conflat gaskets or diamond-formed gaskets in combination with aluminium screws and nuts. Also the Helicoflex system is used when aluminium flanges are connected to stainless steel flanges. The variety of these techniques, shown in Fig. 12, demonstrates that the sealing of an aluminium system is not as reliable as the standard stainless steel system with copper gaskets.

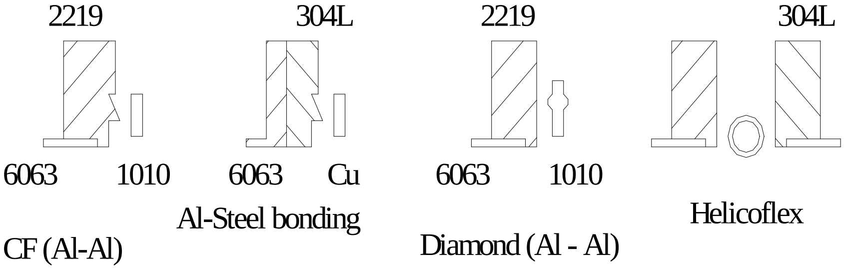


Fig.12 Sealing of aluminium vacuum systems.

3.3 Copper

Copper is used for the vacuum system at HERA [14] (DESY) and at the B factories [15, 16]. In nearly all accelerators it is used as an absorber for synchrotron radiation. The profile of the KEK B factory vacuum chamber is shown in Fig. 13. Normally OFHC copper is used. At HERA copper-tin (3%) bronze was used in order to have a higher stiffness and to avoid softening during brazing. Compared to aluminium large beam tubes can be produced by extrusion, but only with one duct. Therefore the antechamber for distributed pumps and the cooling duct have to be extruded separately and e-beam welded or brazed to the beam chamber. Thus the production process is more complex and expensive. Since copper vacuum systems are only used for storage rings with large radius in the dipoles, the arc sections can be formed by stretching them axially and bending them over a pre-shaped mandrel.

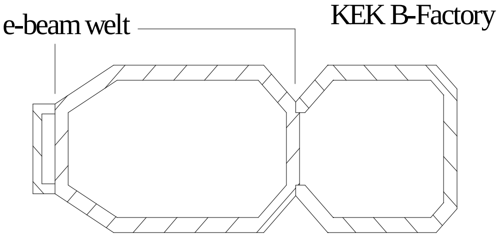


Fig. 13 Profile of the copper vacuum chamber of the KEK B factory.

Comparable to aluminium, the high thermal conductivity allows the chamber wall to be used as the absorber for the SR power. In contrast to aluminium the desorption yields are low comparable to stainless steel, albeit the differences between machined and extruded surfaces, as shown in Fig. 14.

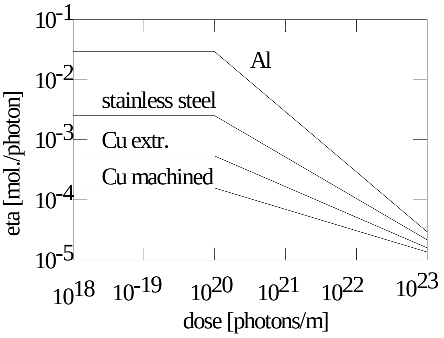


Fig.14 Desorption coefficient for aluminium, copper and stainless steel.

Of disadvantage is the fact that reliable joints can only be made by e-beam welding or brazing. At DESY different brazing techniques are used for joining copper to copper or copper to stainless steel [14]. If the brazing is done in a vacuum oven an additional cleaning is achieved. Sealing the copper vacuum system is done by using copper-to-stainless-steel transition pieces and the reliable CF system with stainless steel flanges and copper gaskets. These transitions are made by explosion bonding, roll bonding, e-beam welding or brazing.

The main absorbers of most SR sources are made from OFHC copper blocks with brazed water lines or drilled cooling ducts. Since the temperature of an absorber is not homogeneous thermal stress occurs leading to cracks and failure as described in Sec. 2.4. In order to avoid failures when the heat load is too high for OFHC copper, GLIDCOP a copper aluminium oxide Cu Al_2O_3(0.3) alloy which allows more stress is used [13, 17]. But GLIDCOP is rather expensive and brazing it to copper is not easy.

Copper gaskets are standard for sealing. Mainly OFHC copper is used. For baking temperatures higher then 200°C a copper-silver alloy (0.1%) should be used which has an increased recrystallization temperature and prevents flowing of the copper. In addition a silver coating can prevent sticking of the gasket.

3.4 Carbon-fibre composite material

Vacuum chambers made from carbon-fibre composite have been developed for the collider region of the Super Proton Synchrotron (SPS) at CERN [18]. For this region (length 13 m) the material of the vacuum tube has to be highly transparent for the collision products on their way to the detector. Therefore a material with low Z and high strength should be used. Beryllium would have been the best choice, but it is rather expensive especially for a 13-m long beam duct. As a comparable alternative a carbon-fibre tube (thickness 1 mm) with an inner aluminium layer (40 µm) was developed, having a comparable transparency to beryllium but only about 15% of the cost. The aluminium layer was needed as a barrier for gas diffusion through the composite in order to obtain a low outgassing rate and to shield the detectors electromagnetically from the high frequency field of the stored beam. The chambers were designed for 1.5 bar pressure difference. One chamber was tested to 1.95 bar before imploding.

Several techniques have been tested in co-operation with industry (Dornier System GmbH Friedrichshafen, Germany). The final technique is schematically shown in Fig. 15. For the production of the final tubes 20 µm thick 40 mm wide aluminium ribbons were wound and glued with 50% overlap around a mandrel. Liners with thickness larger than 100 µm lead to adherence problems during curing or baking due to the different thermal expansion of the carbon composite and the aluminium liner. Thin layers deform plastically without breaking the bond between the layers. The long spiral glue line did not contribute significantly to the outgassing rate. Prestressed carbon-fibre bundles (overall diameter 0.1 mm) were wound in several liners around the aluminium layer after having passed through a bath of liquid resin. The tubes were then cured at 150° – 200°C. The metallic end pieces were glued to the inner surface of the composite tube with a glue curing at room temperature, in order to avoid thermal stress.

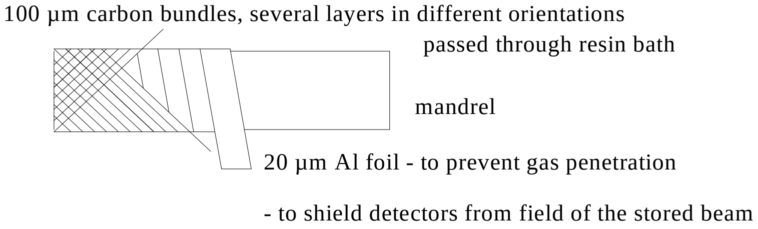


Fig. 15 Production of the CERN carbon-fibre vacuum tubes.

Chambers without an aluminium liner had a penetration rate for He (10^{-8} mbar l/(s cm^2)) and water pressure. Chambers with an aluminium liner had a He penetration rate of 10^{-9} mbar l/(s cm^2). An outgassing rate of 10^{-12} mbar l/(s cm^2) could be obtained after two 24-h 120°C bakes.

3.5 Ceramics

Ceramics (mostly aluminium oxide which can be produced without porosity) are used as insulators (feedthroughs, breaks) and for vacuum chambers in rapidly changing magnetic fields (kickers) where conducting material cause unacceptably high eddy currents. Compared to glass, ceramic has the advantage of better mechanical strength. In addition the compressive strength is higher by a factor of ten compared to the tensile strength. Therefore the design of ceramic systems should only foresee compressive stress. Ceramics are formed out of a clay (oxide powder with water) which is moulded to fine particles, pressed in forms or extruded and left to dry. After drying, machining is possible. Then the parts are sintered at 2000°C. During this process the material shrinks by up to 20 % in length. The sintered parts can then only be processed by diamond tools [19].

Most ceramic components are connected to metal (flanges) by brazing. For the standard brazing procedure the ceramic surface foreseen for brazing is metalized by a MoMn or titanium hydride coating before sintering. Metals, preferably with an expansion coefficient comparable to the ceramic (nickel iron, nickel cobalt iron, titanium, molybdenum) can then be brazed to the ceramic. Copper-silver eutectic is used as filler. The interface metal can then be connected to stainless steel flanges by electron beam welding. In order to get a reliable connection different designs are used, as shown in Fig. 16. For round ceramics a thin metal is brazed from the outside like a collar. If the metal is brazed to the axis of the ceramic the metal part is sandwiched between ceramic to have a symmetric stress, or a thin transition metal is used which is more flexible.

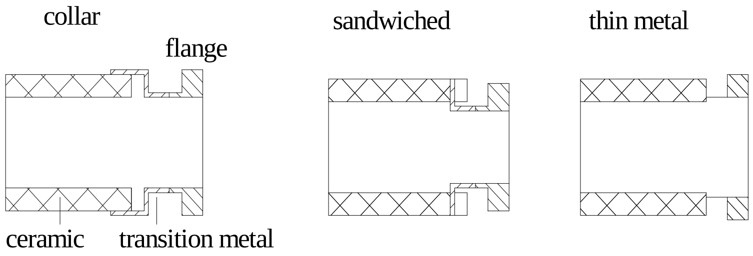


Fig. 16 Ceramic metal transition for Kicker chambers.

3.6 Magnetic materials

Normally, magnetic materials (ferrites, high µ iron, permanent magnets) are not used inside a UHV vacuum, since they all show a considerably higher outgassing rate compared to stainless steel. Due to the production process they might be porous and/or sensitive to corrosion. But since the performance of insertion devices increases with reduced gap some additional strength is gained by placing the magnets inside the vacuum. This is often accompanied by the installation of a high pumping speed to compensate the higher gas load.

Laminated silicon iron Fe Si(3) was used for the high field in the vacuum septum of ELETTRA [20] and BESSY II. The large surface due to the high number of thin (0.2 mm) laminations required caused considerable outgassing.

Ferrites are used for the pulsed magnetic fields found in kickers for example. Their relative permeability is about 1000 up to 10 MHz and a maximum field of 0.3 T. The general composition is (NiZn) Fe_2O_4. The production process is the same as for ceramics apart from the lower temperature of 1200°C for sintering [21].

Most undulators are built with permanent magnets. As material for undulators FeNbB is used for the permanent magnets and soft iron or cobalt iron for the yoke. For the production of the permanent magnets a powder of the basic materials is milled to small sizes (2µm) and then pressed into a die in the presence of a magnetic field. Then the parts are sintered at about 1100 °C. This process leads to a reduction of 20% in length. The magnets must then be magnetised in a strong field with the same direction as during the pressing process [22]. FeNbB magnets are very sensitive to corrosion and should be nickel-plated for vacuum application. Further disadvantages are the low demagnetisation temperature of 100°C that does not allow a baking, and a low resistance to radioactivity. As an alternative, permanent magnets made from cobalt samarium can be used. They can be baked and are less sensitive to radiation damage but are more expensive and have a slightly lower remanent field.

3.7 Glass

Glass was the standard vacuum material in the years before the transistor replaced the electronic tube [23]. Nowadays its use is mainly restricted to windows (and some special electronic tubes (thyratrons)). Useful are silicon-oxide glasses either pure (quartz) or borosilicate (Pyrex: 81% SiO_2, 13% B_2O_3), soda glass (72% SiO_2, 16% Na_2O), or lead glasses (56% SiO_2, 30% PbO_2) if shielding of gamma radiation is required. Glass is a compound which after fusion cools to a solid without crystallisation, it has no specific melting point but its viscosity decreases until it becomes fluid. The temperature at which stresses are released is called the annealing point (Quartz: 1000°C, Pyrex: 500 °C). Borosilicate and soda glasses can be formed at about 1000 °C (working point). Quartz has a very low thermal expansion coefficient and a high working temperature range and is resistive to thermal shock. The surface desorption rate is low but helium and hydrogen can penetrate through thin glass tubes, especially quartz and to a less extent pyrex. The main disadvantage is its high fragility. Furthermore joints and transitions to metals are hard to make since the thermal expansion of the materials must be matched very closely.

3.8 Beryllium

Beryllium is used in vacuum systems wherever a highly transparent material is needed. At DAFNE a 0.7-m long tube with 90-mm diameter and a spherical middle part of 200-mm diameter with a thickness of 0.5 mm will be used [24]. The main application of Be at synchrotron radiation sources is for windows to separate the UHV vacuum of a storage ring from the UV or atmosphere of a beam line. A 0.5-mm thick Be foil absorbs less than 10% of 10 keV X-rays.

Beryllium has some interesting mechanical properties. It has a high modulus of elasticity and a high yield strength superior to stainless steel and a high thermal conductivity comparable to aluminium. But it is rather brittle with an elongation of 3% at room temperature. This makes it hard to form (practical only at high temperatures 700 °C), but machining and extrusion is possible [25].

Vacuum tight connection of the Be foil to stainless steel or aluminium can be achieved by electron-beam welding or brazing. The brazing can be improved (diffusion brazed) when pressure is applied to the parts to be jointed during the brazing process.

Beryllium-containing materials pose a health risk when improperly handled. Inhalation of air born beryllium particles (with a size of less than 10 µm) can cause serious lung disorders, contamination can cause skin disease, production of cancer is also possible. Thus the maximum permissible exposure limit for a working area is 2 $\mu g/m^3$. Machining is mostly done in water or in a highly-ventilated environment.

3.9 Further materials

Inconel, a nickel alloy Ni Cr(16)Fe(8), is used as an alternative material to stainless steel in pulsed or oscillating magnetic fields i.e. booster synchrotrons in order to reduce eddy currents, since its electric conductivity is smaller than stainless steel and the walls can be made thinner due to higher mechanical strength [26].

A titanium alloy, Ti Al(6),V(4), is used for an undulator chamber at the SRS [27]. It can be machined as easily as aluminium and has a considerably high yield strength (three times higher than stainless steel) allowing to design vacuum chambers with thin walls.

Martensitic stainless steel, AM350 Fe Ni(17)Ni(4)Mo(3), is magnetic but has higher strength than austenitic steel. It is used for bellows in regions were a significant relative permeability is allowed i.e. bellows in photon beam lines.

For the LHC beam duct a relative permeability of less than 1.003 was needed at 10 to 20 K. This could be obtained by using an iron-mangan alloy [5].

4. BONDING

Explosion bonding, roll bonding and inertia bonding are processes by which dissimilar materials that cannot be welded together are joined. Bringing dissimilar materials together enables one to benefit from the different properties of both materials. A thin, electrically-high-conducting material for surface currents can be combined with a low-conducting material for the envelope to reduce eddy currents. Thermal high-conducting material (copper) can be joined to stainless steel in order to disperse a heat load on the copper with the benefit of stainless steel for the vacuum system. Extruded aluminium or copper tubes can be joined to stainless steel to permit use of the more reliable CF stainless flanges.

For explosion bonding [28], schematically shown in Fig. 17, the two materials are positioned at a defined distance. The upper material is covered by an explosive which is detonated from one end. During a controlled explosion a plasma jet is formed at the impact zone of the two materials which scrubs off several layers of both materials leaving virgin material at the interface. The bond line usually has a wavy form that increases the strength of the joint. The quality of the bonding depends on the amount of explosive and the initial distance of the materials. In some cases (aluminium to stainless steel) an interlayer has to be used to get good results [29].

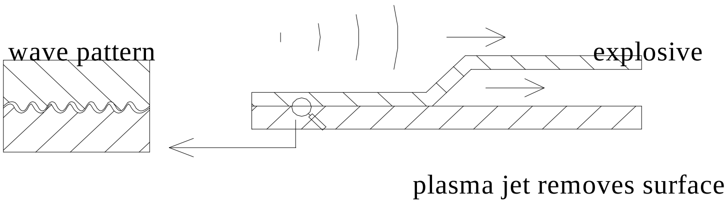


Fig.17 Explosion bonding.

Inertia bonding can be applied for joining cylindrical parts of different materials together. One part is rotated at high speed then the other non-rotating part is moved against it. Due to the high friction heat the materials are melted at the interface. With additional pressure the rotating part is decelerated and the two materials fuse.

5. CORROSION

A summary article about corrosion in vacuum systems can be found in Ref. [30]. Corrosion is an electrochemical process between an electrolyte and the metal surface. Thin walls, bellows, bimetallic contacts, brazings and welds and feedthroughs are mostly at danger. Atmospheric corrosion is the most usual and normally a relative humidity of more than 60% is needed. It should be noted that close to a cooling line the relative humidity can be considerably higher than in the remaining building. Furthermore the presence of radioactivity enhances corrosion considerably due to the formation of free radicals in the air. Ozone, nitrogen oxides, and subsequently acids, are formed with the moisture films on the surfaces.

Another source of corrosion is caused by spurious free chlorine ions from irradiated halogen-containing products (cable, tapes) or residuals from cleaning processes or brazing flux. Thus vacuum components should be thoroughly rinsed. Nitrogen oxides can also be formed by spurious discharges of high electric fields (i.e. feedthroughs for ion pumps, DESY has developed a specially designed plug to avoid this problem). Corrosion also occurs when materials with different electro-chemical potentials are connected (copper water pipe to an aluminium vacuum chamber). The corrosion is also enhanced by the speed of the water and impurities.

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APPENDIX

Table 3

Material properties of selected materials [1].

Material	Density 10^3kg/m^3	Melt pt °C	Therm. cond. W/(mK)	Elect. cond. $10^6/(\Omega m)$	exp. coeff. $^{10-6}$/K	E-modul 10^9 Pa	Yield strength 10^6Pa	Tensile strength 10^6Pa	Elonga-tion %
Al6063	2.8	507	192	29	23	72	250	300	12
Alumina	4.0	2050	30	$10^{-12}/(\Omega m)$	8	393	-	270	0.1
Aluminium	2.7	659	231	36	24	69	17	55	25
Beryllium	1.9	1280	216	24	12	303	270	350	3
Brass Cu-Zn	8.5	915	120	16	20	110	75	303	68
Bronze Cu-Sn	8.8	880	62	8	18	110	152	380	70
Diamond	3.5		2000		1	1000	-	800	0.1
Copper	8.9	1083	398	58	17	110	152	220	45
GlidCop-15	8.9	1083	365	54	17	130	330	420	25
Fused silica	2.2		1.3	$10^{-12}/(\Omega m)$	0.5	75	-	110	0.1
Iron	7.9	1558	12	10	12	207	130	260	45
304	7.8	1370	16	1.4	16	193	207	552	60
AM350	7.7	1500	25	2	10	210	1000	1500	
Magnesium	1.7	650	122	17	27	45	41	41	14
Molybdenum	10.2	2610	142	19	4.9	324	565	655	35
Nickel	8.9	1454	80	12	13	207	138	483	40
Inconel	8.4	1400	15	1	11	157		1200	
Pyrex	2.2		1.4	$10^{-12}/(\Omega m)$	3.3	69		70	0.1
Silver	10.5	961	418	56	19	76	55	125	48
Titanium	4.5	1670	17	2	9	107	240	330	30
TiAl(6) V(4)	4.4	1600	6	0.6	8	110	900	1000	14

Table 4
Vapour pressure as a function of the temperature for different elements [23].

Element	**Melting pt**	**10^{-9} Torr**	**10^{-7} Torr**	**10^{-5} Torr**	**10^{-3} Torr**
Ag	1234	800	899	1030	1195
Al	932	906	1015	1155	1355
Au	1336	1020	1150	1260	1365
Ba	983	510	583	690	810
Be	1556	925	1035	1175	1365
C	-	1845	2030	2250	2520
Ca	1123	524	590	675	790
Cd	594	328	368	422	494
Ce	1077	1175	1325		
Co	1768	1130	1265	1435	1650
Cr	2176	1055	1175	1335	1540
Cs	302	241	273	319	383
Cu	1357	945	1060	1215	1415
Fe	1809	1105	1230	1380	1595
Ge	1210	1030	1150		
Hg	234	190	214	245	289
In	429	716	812	943	1110
Ir	2727	1755	1960	2070	2380
K	336	276	315	364	435
La	1193	1220	1375		
Mg	923	432	487	560	655
Mn	1517	734	827	970	1125
Mo	2890	1770	1975	2260	2650
Na	371	328	370	431	511
Ni	1725	1145	1270	1415	1660
Pb	601	580	656	760	900
Pd	1823	1050	1185	1430	1660
Pt	2043	1480	1655	1875	2180
Re	3453	2100	2350		
Rh	2239	1470	1640		
Sb	903	526	582		
Se	490	317	356		
Sn	505	900	1020	1155	1365
Sr	1043	483	546	615	729
Ta	3270	2120	2370	2470	3080
Th	1968	1610	1815	1959	2272
Ti	1940	1265	1410		
W	3650	2270	2520	2872	3280
Zn	963	374	421	481	563
Zr	2128	1665	1855	2110	2460