Vacuum Science and Technology for Accelerator Vacuum Systems

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  → Aluminum and Alloys
  → Copper and Alloys
  → Other metals

• Non-metals
  → Ceramics and Glasses
  → Polymers
Stainless Steels – Classifications

- Stainless steel is a steel alloy with at least 11% chromium content by weight. It is also called corrosion-resistant steel.

- Austenitic stainless steel (300 series): These are generally non-magnetic steel alloys. They contain a maximum of 0.15% carbon, a minimum of 16% chromium and sufficient nickel and/or manganese to retain an austenitic structure at all temperatures from the cryogenic region to the melting point of the alloy. The low carbon (-L) grades are used when welding is involved. In UHV applications, especially accelerators, 300 stainless steels are commonly used.

- Other less used types of stainless steel alloys are: Martensitic stainless steels (400 series), precipitation-hardening martensitic stainless steels (most common used 17-4PH) and ferritic stainless steels. Martensitic stainless steels are much more machinable, and are magnetic. Those are much less used for accelerators, mainly due to the magnetism.
Austenitic Stainless Steels

- High strength, moderate formability, excellent weldability.
- Can be extruded in simple shapes
- 304L SS, most commonly used in vacuum, but may become magnetized from machining and welding.
- 316L SS, with Mo added, more expensive, resistant to chemical attack, welds are non-magnetic
  316LN SS, a nitrogen-enhanced 316L steel, much more expensive, but excellent strength at very elevated temperatures (as high as 1000°C)
- Wide variety of circular tubes and pipes available (seamless & welded)
- Outgassing rates can be decreased by employing good machining techniques, chemical cleaning and baking (up to 900°C)
- Poor thermal and electrical conductivity
## Mechanical Properties for Stainless Steels

<table>
<thead>
<tr>
<th>Property</th>
<th>304L</th>
<th>316L</th>
<th>316LN</th>
<th>OFE Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength (MPa)</td>
<td>564</td>
<td>560</td>
<td>637</td>
<td>338</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>81.8</td>
<td>81.2</td>
<td>92.4</td>
<td>49.0</td>
</tr>
<tr>
<td>Yield Strength (Mpa)</td>
<td>210</td>
<td>290</td>
<td>&gt;280</td>
<td>217</td>
</tr>
<tr>
<td>Yield Strength (ksi)</td>
<td>30.5</td>
<td>42.1</td>
<td>&gt;41.6</td>
<td>31.5</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>58</td>
<td>50</td>
<td>58</td>
<td>55</td>
</tr>
<tr>
<td>Modulus of Elasticity (Mpa)</td>
<td>197</td>
<td>193</td>
<td>200</td>
<td>115</td>
</tr>
<tr>
<td>Modulus of Elasticity (ksi)</td>
<td>28.6</td>
<td>28.0</td>
<td>29.0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Ref. www.matweb.com
# Physical Properties for Stainless Steels

<table>
<thead>
<tr>
<th>Property</th>
<th>304L</th>
<th>316L</th>
<th>316LN</th>
<th>OFE Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition:</td>
<td>C 0.03% Cr 18-20% Mn 2% Fe Balance Ni 8-12% P 0.045% S 0.03% Si 1%</td>
<td>C &lt;0.03% Cr 17.9% Mn 2.0% Mo 2.5% Fe Balance Ni 11-14% S 0.03% Si 1%</td>
<td>C &lt;0.03% Cr 17.9% Mn 2.0% Mo 2.5% Fe Balance Ni 10.8% N 0.16% S 0.03% Si 1%</td>
<td>Cu 100%</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>1427</td>
<td>1385</td>
<td>1400</td>
<td>1083</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>8.92</td>
</tr>
<tr>
<td>Electrical Resistivity (Ω·cm)</td>
<td>7.2 x 10⁻⁵</td>
<td>7.2 x 10⁻⁵</td>
<td>7.4 x 10⁻⁵</td>
<td>1.71 x 10⁻⁶</td>
</tr>
<tr>
<td>Elect. Conduct. (% IACS*)</td>
<td></td>
<td></td>
<td></td>
<td>101</td>
</tr>
<tr>
<td>Therm. Conduct. (W/m·K)</td>
<td>16.2</td>
<td>16.3</td>
<td>16.0</td>
<td>391</td>
</tr>
<tr>
<td>Coeff. Of Therm. Exp. (°C⁻¹)</td>
<td>17.2 x 10⁻⁶</td>
<td>16.0 x 10⁻⁶</td>
<td>16.0 x 10⁻⁶</td>
<td>17.5 x 10⁻⁶</td>
</tr>
</tbody>
</table>
**Tubing - Seamless and Welded**

- **Seamless (extruded)**: Cleaner to start with and easier to clean.
- **Welded (rolled & welded)**: Rolling can embed dirt in the surface.
Plate/Rod – ESR or Cross-Forged

- **Stainless steels are the most common material for making knife-edge sealing flanges.**

- **For making knife-edge seal flanges, either ESR or cross-forged stainless steels should be used to avoid costly defects on the knife-edge tip.**

*The electroslag remelting (ESR) process is used to remelt and refine steels and various super-alloys, resulting in high-quality ingots.*
Cornell DC Photo-Cathode Electron Gun Chamber

As received stainless steel gun chamber

Air-baked, and assembled to the gun, w/ pumps and gauges
# Aluminum and Alloys

<table>
<thead>
<tr>
<th>Alloy Number</th>
<th>Major Alloy Element(s)</th>
<th>Characteristics and Sample Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>None</td>
<td>Good electric and thermal conductivities, corrosion resistance. Typical applications: electric conductor wires and bus</td>
</tr>
<tr>
<td>2xxx</td>
<td>Copper</td>
<td>High strength, at room and elevated temperatures, Alloys 2011, 2017, and 2117 are widely used for fasteners and screw-machine stock</td>
</tr>
<tr>
<td>3xxx</td>
<td>Manganese</td>
<td>Similar property as 1100, slightly higher strength. Good for sheet works.</td>
</tr>
<tr>
<td>4xxx</td>
<td>Silicon</td>
<td>Excellent flow characteristics. Alloy 4032 for forging, 4043 used for GMAW and TIG 6xxx alloys.</td>
</tr>
<tr>
<td>5xxx</td>
<td>Magnesium</td>
<td>Mostly for structural applications, matching 6xxx extrusions well. 5083 alloy suitable for cryogenic applications.</td>
</tr>
<tr>
<td>6xxx</td>
<td>Magnesium + Silicon</td>
<td>6061-T6 is one of the most commonly used, 6063 is mostly used in extruded shapes</td>
</tr>
<tr>
<td>7xxx</td>
<td>Zinc</td>
<td>Mostly for structural, supporting frames. 7075-T6 is one of the most used 7000 series aluminum, and strongest one.</td>
</tr>
<tr>
<td>8xxx</td>
<td>Sn, Li, etc.</td>
<td>Specialty alloys not cover by other series.</td>
</tr>
</tbody>
</table>
Besides alloy designations (with Nxxx), there are standard temper designations for aluminum alloys, with one letter and a numeral.

For strain-hardened (cold-worked), there are hardness designations.

-F as fabricated;
-H1 Strain hardened without thermal treatment
-H2 Strain hardened and partially annealed
-H3 Strain hardened and stabilized by low temperature heating

For alloys can be heat treated to produce stable tempers (partial list)

-O Full soft (annealed);
-T2 Cooled from hot working, cold-worked, and naturally aged
-T4 Solution heat treated and naturally aged
-T5 Cooled from hot working and artificially aged (at elevated temperature)
   -T51 Stress relieved by stretching
   -T511 Minor straightening after stretching
-T6 Solution heat treated and artificially aged
Aluminum and Alloys – General Characteristics

- Moderate strength, good formability, easy to machine
- 6063-T4 can be extruded in complicated shapes
- 6061-T6 is the most common aluminum alloy for vacuum components
- 5083 is a good alloy for welding
- Aluminum is much cheaper to machine than stainless steel (2x to 3x cheaper)
- Aluminum is much less likely been radiactivated.
- Special care must be taken in the design of welds and the techniques used due to higher thermal conductivity and thermal expansion (30% > SS)
- Surface anodizing degrades outgassing characteristics, but improves chemical resistance
# Typical Mechanical Properties for Aluminum

<table>
<thead>
<tr>
<th>Property</th>
<th>1100-0</th>
<th>5083-H34</th>
<th>6061-T6</th>
<th>OFE Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength (MPa)</td>
<td>165</td>
<td>345</td>
<td>310</td>
<td>338</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>23.9</td>
<td>50.0</td>
<td>45.0</td>
<td>49.0</td>
</tr>
<tr>
<td>Yield Strength (Mpa)</td>
<td>150</td>
<td>280</td>
<td>275</td>
<td>217</td>
</tr>
<tr>
<td>Yield Strength (ksi)</td>
<td>21.8</td>
<td>40.6</td>
<td>39.9</td>
<td>31.5</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>5</td>
<td>9</td>
<td>12</td>
<td>55</td>
</tr>
<tr>
<td>Modulus of Elasticity (Mpa)</td>
<td>69</td>
<td>70.3</td>
<td>69</td>
<td>115</td>
</tr>
<tr>
<td>Modulus of Elasticity (ksi)</td>
<td>10.0</td>
<td>10.2</td>
<td>10.0</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Ref. www.matls.com
## Typical Physical Properties for Aluminum

<table>
<thead>
<tr>
<th>Property</th>
<th>1100-0</th>
<th>5083-H34</th>
<th>6061-T6</th>
<th>OFE Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition:</strong></td>
<td>Al 99%</td>
<td>Al 94.8%</td>
<td>Al 98%</td>
<td>Cu 100%</td>
</tr>
<tr>
<td></td>
<td>Cu 0.05-0.2%</td>
<td>Cr 0.05-0.25%</td>
<td>Cu 0.15-0.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mn 0.05%</td>
<td>Mg 4-4.9%</td>
<td>Cr 0.04-0.35%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Si+Fe 0.95%</td>
<td>Mn 0.4-1%</td>
<td>Mg 0.8-1.2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zn 0.1%</td>
<td>Fe 0.4%</td>
<td>Mn 0.15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Si 0.4%</td>
<td>Fe 0.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ti 0.15%</td>
<td>Si 0.4-0.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zn 0.25%</td>
<td>Ti 0.15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zn 0.25%</td>
<td></td>
</tr>
<tr>
<td><strong>Melting Point (°C)</strong></td>
<td>643</td>
<td>591</td>
<td>582</td>
<td>1083</td>
</tr>
<tr>
<td><strong>Density (g/cc)</strong></td>
<td>2.71</td>
<td>2.66</td>
<td>2.7</td>
<td>8.92</td>
</tr>
<tr>
<td><strong>Electrical Resistivity (Ω-cm)</strong></td>
<td>3x10^-6</td>
<td>5.9x10^-6</td>
<td>3x10^-6</td>
<td>1.7x10^-6</td>
</tr>
<tr>
<td><strong>Heat Capacity (J/g-°C)</strong></td>
<td>0.904</td>
<td>0.9</td>
<td>0.896</td>
<td>0.385</td>
</tr>
<tr>
<td><strong>Therm. Conduct. (W/m-K)</strong></td>
<td>218</td>
<td>117</td>
<td>167</td>
<td>391</td>
</tr>
<tr>
<td><strong>Coeff. Of Therm. Exp. (°C^-1)</strong></td>
<td>25.5x10^-6</td>
<td>26x10^-6</td>
<td>25.2x10^-6</td>
<td>17.5x10^-6</td>
</tr>
</tbody>
</table>

Ref. www.matls.com
Machined Aluminum “Switch-yard” Chamber
Aluminum Electron Beam Stopper

~2.5 m
Extruded Beam Pipes – Complex Shape
Copper and Alloys

- Copper and alloys are designated by a system starting with letter “C”, followed by 5 digits, more copper content with lower numbers.

- Typical copper alloys are C10100 (OFHC), C26800 (Yellow Brass, Zinc alloy), C61400 (Bronze, Silicon alloy), C17200 (Beryllium coppers)

- Low-to-moderate strength, good formability

- Excellent electrical and thermal characteristics

- Difficult to weld (e-beam welding is best)

- May be joined by welding, brazing, and soldering

- Good outgassing characteristics, rates can be decreased by following good machining techniques, chemical and baking (~200°C)
Oxygen-Free High Conductivity (OFHC) Copper

- Oxygen-free high thermal conductivity (OFHC) copper generally refers to a group of wrought high conductivity copper alloys that have been electrolytically refined to reduce the level of oxygen to 0.001% or below.

- OFHC is often used in accelerator vacuum systems, where high heat load is encountered. It is also used to construct normal conducting radio-frequency (RF) cavities.

- **C10100** - This is the purest grade, with 99.99% Cu, <0.0005% (or 5 ppm) oxygen content.

- **C10200** - 99.95% Cu (including Ag), <0.001% (10-ppm) oxygen content.

- **C11000** - Also known as Electrolytic-Tough-Pitch (ETP) copper. It is 99.9% pure and has 0.02% to 0.04% oxygen content (typical).

- Low oxygen content is critical for vacuum assemblies involving welding.
# OFHC Copper Properties

<table>
<thead>
<tr>
<th>Density</th>
<th>Electric Resistivity</th>
<th>Thermal Conductivity</th>
<th>C.T.E.</th>
<th>M.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.9 g/cc</td>
<td>1.71x10^{-6} Ω-cm</td>
<td>383 ~ 391 W/m-K</td>
<td>17.0 µm/m-K</td>
<td>1083°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temper Designation Standard</th>
<th>Tensile Strength (ksi)</th>
<th>Yield Strength (ksi, min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>060 Soft</td>
<td>30</td>
<td>38</td>
</tr>
<tr>
<td>H00 Cold-Rolled, 1/8-hard</td>
<td>32</td>
<td>40</td>
</tr>
<tr>
<td>H01 Cold-rolled, 1/4-hard</td>
<td>34</td>
<td>42</td>
</tr>
<tr>
<td>H02 Half Hard</td>
<td>37</td>
<td>46</td>
</tr>
<tr>
<td>H03 3/4-hard</td>
<td>41</td>
<td>50</td>
</tr>
<tr>
<td>H04 Full hard</td>
<td>43</td>
<td>52</td>
</tr>
</tbody>
</table>
Copper Vacuum Chamber Example

C10100 ½-Hard Cu sheet bend to U-box to form a TiSP pumping plenum

C10100 ½-Hard Cu plates machined to form a beam pipe

SST L-shaped plates added to complete vacuum envelop, with enhance mechanical strength.

(Flanges to be added)
Copper Extrusions

- Cooling Bar Extrusion
- Screen Extrusion
- “Dipole” Chamber Extrusion
Machined Copper Chamber (PEP-II RF Cavities)

- 26 cavities
- $4M total fabrication cost
- Integral cooling channels with electroformed cover
- 5 axis machining
- e-beam welded
- 17 separate manufacturing steps
Glidcop®

Glidcop is pure copper with Al$_2$O$_3$ dispersed throughout.

- **High strength, moderate formability, poor weldability.**
- **Available in sheets, plate, wire, and extruded rounds.**
- **Maintains good mechanical strength after brazing.**
- **Outgassing rates are similar to pure copper.**
- **Thermal and electrical properties are good.**

<table>
<thead>
<tr>
<th>Grade Designations</th>
<th>Copper</th>
<th>Al$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UNS</strong></td>
<td><strong>SCM Metal Prod.</strong></td>
<td>Wt %</td>
</tr>
<tr>
<td>C15715</td>
<td>Glidcop AL-15</td>
<td>99.7</td>
</tr>
<tr>
<td>C15725</td>
<td>Glidcop AL-25</td>
<td>9.5</td>
</tr>
<tr>
<td>C15760</td>
<td>Glidcop AL-60</td>
<td>98.9</td>
</tr>
</tbody>
</table>

Ref. SCM Metal Products
## Glidcop™ Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>C15715</th>
<th>C15725</th>
<th>C15760</th>
<th>OFE Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point (°C)</td>
<td>1083</td>
<td>1083</td>
<td>1083</td>
<td>1083</td>
</tr>
<tr>
<td>Density (lb/in³)</td>
<td>0.321</td>
<td>0.320</td>
<td>0.318</td>
<td>0.323</td>
</tr>
<tr>
<td>Electrical Resistivity (Ω)</td>
<td>11.19</td>
<td>11.91</td>
<td>13.29</td>
<td>10.20</td>
</tr>
<tr>
<td>Elect. Conduct. (% IACS*)</td>
<td>92</td>
<td>87</td>
<td>78</td>
<td>101</td>
</tr>
<tr>
<td>Therm. Conduct. (W/m-K)</td>
<td>365</td>
<td>344</td>
<td>322</td>
<td>391</td>
</tr>
<tr>
<td>Coeff. Of Therm. Exp. (°C⁻¹)</td>
<td>16.6×10⁻⁶</td>
<td>16.6×10⁻⁶</td>
<td>16.6×10⁻⁶</td>
<td>17.7×10⁻⁶</td>
</tr>
<tr>
<td>Mod. Of Elasticity (psi)</td>
<td>19×10⁶</td>
<td>19×10⁶</td>
<td>19×10⁶</td>
<td>19×10⁶</td>
</tr>
</tbody>
</table>

* International Annealed copper Standard

Ref. SCM Metal Products
### Glidcop™ Mechanical Properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>Form</th>
<th>Tensile Strength (ksi)</th>
<th>Yield Strength (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AL-15</strong>&lt;br&gt;(C15715)</td>
<td>Plate</td>
<td>53 ~ 70</td>
<td>37 ~ 66</td>
</tr>
<tr>
<td></td>
<td>Rod</td>
<td>57 ~ 72</td>
<td>47 ~ 66</td>
</tr>
<tr>
<td></td>
<td>Rounds</td>
<td>53</td>
<td>37</td>
</tr>
<tr>
<td><strong>AL-25</strong>&lt;br&gt;(C15725)</td>
<td>Plate</td>
<td>60 ~ 76</td>
<td>43 ~ 68</td>
</tr>
<tr>
<td></td>
<td>Rod</td>
<td>64 ~ 80</td>
<td>52 ~ 77</td>
</tr>
<tr>
<td></td>
<td>Rounds</td>
<td>60</td>
<td>43</td>
</tr>
<tr>
<td><strong>AL-60</strong>&lt;br&gt;(C15760)</td>
<td>Plate</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Rod</td>
<td>72 ~ 90</td>
<td>69 ~ 87</td>
</tr>
<tr>
<td></td>
<td>Rounds</td>
<td>68</td>
<td>48</td>
</tr>
<tr>
<td><strong>C10100</strong></td>
<td></td>
<td>30 ~ 50</td>
<td>20 ~ 35</td>
</tr>
</tbody>
</table>

1. Ref. [http://www.hoganas.com](http://www.hoganas.com)
2. Large spread reflect strength at different tempers
NSLS II Crotch and Absorber Made of Glidcop™

Insertable Crotch

Stick Photon Absorber

Ref: H. Hseuh, NSLS II, BNL
Other Metals – Beryllium

- Beryllium is the lightest metal with good mechanical strength and good thermal conductivity.
- Beryllium is machinable and can be jointed via vacuum braze or e-beam welding.
- Beryllium is hazard mat’l, must be handled by highly trained experts.
Other Metals – Niobium & Titanium

- High purity, small grain niobium is the key material for constructing superconducting RF cavities for many existing and future (such as Jlab, Cornell CESR and ERL, Tesla, ILC, etc.) facilities.

- The grade of the Nb material is usually certified by so-called RRR (Residual-resistance ratio). Hydrogen in the Nb bulk is often degassed for high-Q cavities.

- To match CTE, titanium (grade 1 and grade 5) are used to joint to Nb cavities for flanges and helium vessels.

- E-beam welding is the primary technique for Nb and Ti.
C.T.E. of some metals

![Graph showing linear thermal expansion coefficients of various metals vs. temperature.](image)
Alumina ceramics ($\text{Al}_2\text{O}_3 > 99\%$) are widely used for electric breaks, instrument and electric power feedthroughs, RF windows in the accelerator vacuum systems.

Alumina ceramic beam pipes with thin inner metallic coating are also used as a part of pulsed magnet for beam feedback, injection kickers, etc.

Ceramics are jointed to metal flanges using vacuum furnace braze technique.

Many type of glasses are used mainly as viewports on vacuum systems, for visual inspection of in-vacuum components, for light transmissions (laser entrance, beam profile viewers, etc.)

Machined ceramic parts are UHV compatible. Special diamond-tipped tools are used for ceramic machining. There are also machinable ceramics, such Macor®.
Properties of Some Glasses for Vacuum

<table>
<thead>
<tr>
<th>Property</th>
<th>Fused Silica</th>
<th>Pyrex 7740</th>
<th>7720&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Soda 7052&lt;sup&gt;a&lt;/sup&gt;</th>
<th>0080</th>
<th>Lead 0120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
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<td></td>
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<td>SiO₂</td>
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<td>81</td>
<td>73</td>
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<td>B₂O₃</td>
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<td>Viscosity characteristics</td>
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<td>Strain point °C</td>
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<td>510</td>
<td>484</td>
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<td>560</td>
<td>523</td>
<td>480</td>
<td>514</td>
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<td>Softening point °C</td>
<td>1580</td>
<td>821</td>
<td>755</td>
<td>712</td>
<td>696</td>
<td>630</td>
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<td>Working point °C</td>
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<td>1252</td>
<td>1146</td>
<td>1128</td>
<td>1005</td>
<td>985</td>
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<tr>
<td>Expansion coefficient x10⁻⁷/°C</td>
<td>3.5</td>
<td>35</td>
<td>43</td>
<td>53</td>
<td>105</td>
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<td>Shock temperature, 1/4-in. plate °C</td>
<td>1000</td>
<td>130</td>
<td>130</td>
<td>100</td>
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<td>50</td>
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<td>Specific gravity</td>
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<td>2.23</td>
<td>2.35</td>
<td>2.27</td>
<td>2.47</td>
<td>3.05</td>
</tr>
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</table>

*Source. Reprinted with permission from Corning Glass Works, Corning, NY.*

<sup>a</sup> 7720 glass is used for sealing to tungsten and 7052 glass is used for sealing to Kovar.
## Properties of Some Ceramics for Vacuum

### Table 16.6 Physical Properties of Some Ceramics

<table>
<thead>
<tr>
<th>Ceramic</th>
<th>Main Body Composition</th>
<th>Expansion Coefficient ($\times 10^{-7}$)</th>
<th>Softening Temperature (°C)</th>
<th>Tensile Strength ($10^6$ kg/m²)</th>
<th>Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steatite</td>
<td>MgOSiO₂</td>
<td>70–90</td>
<td>1400</td>
<td>6</td>
<td>2.6</td>
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<td>Forsterite</td>
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<td>90–120</td>
<td>1400</td>
<td>7</td>
<td>2.9</td>
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<tr>
<td>Zircon porcelain</td>
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<td>1500</td>
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<td>1400</td>
<td>14</td>
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<tr>
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<td>18</td>
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<tr>
<td>98% alumina</td>
<td>Al₂O₃</td>
<td>50–70</td>
<td>1700</td>
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<tr>
<td>Pyroceram 9696*</td>
<td>Corderite ceramic</td>
<td>57</td>
<td>1250</td>
<td>14 b</td>
<td>2.6</td>
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<tr>
<td>Macor 9658*</td>
<td>Flurophlogophite</td>
<td>94</td>
<td>800</td>
<td>10 b</td>
<td>2.52</td>
</tr>
</tbody>
</table>


*Reprinted with permission from Corning Glass Works, Corning, NY.

b Modulus of rupture.


*Reprinted with permission from Corning Glass Works, Corning, NY.*

b Modulus of rupture.
Non-Metals – Elastomers and Polymers

- Elastomers, polymers and plastics have also found application in accelerator vacuum systems. Their vacuum properties and radiation resistance must be verified for the applications.

- Elastomers, particularly Viton® (fluorocarbon) are usually used as vacuum seals, often as gate seals for UHV gate valves.

- Though Teflon is UHV compatible, it is easily hardened and break down under radiation. PEEK (Polyether ether ketone) is a type of engineered plastics that is suitable for accelerator UHV applications. PEEK has good formability and machinability. The most uses are in vacuum multi-pin connectors.

- Kapton® (polyimide) films are suitable for accelerator UHV applications.
Dry Lubrications in UHV Systems

- For in-vacuum movement that involves two metallic surfaces in contact, particularly two similar metals, lubrication is between the contacting surfaces is necessary.

- For UHV applications, dry-lubrication is widely used. In a dry lubrication, the process of lubricating relies on a solid film.

- The desirable properties of a dry lubricant are low vapor pressure, low shear strength, and good adhesion to the base metal.

- Commonly used UHV-compatible dry lubricants are silver (electroplated), MoS$_2$, WS$_2$ (Dicronite®) (via PVD). Teflon coating is also a UHV-compatible dry lubricant, however, it is not durable in radiation environment.
However, extreme low vapor pressure may not be good enough in applications where energized desorption may occur.
Stimulated desorption of Krytox

$m/e = 69 \ (CF_3^+)$
Methods of Making Vacuum Joints

Vacuum Joints

Permanent

Non-Metal
- Ceramic-metal
- Ceramic-glass
- Glass-metal
- Ceramic-ceramic
- Glass-glass

Metal
- Brazing
- Soldering
- Diffusion Bonding
- Welding
- Resistance
- Fluxed Consumable Electrode
- MIG
- TIG
- Plasma Arc
- Electron Beam
- Explosive
- Laser

Removable
- Grease Seals
- Elastomer Seals
- Metal Seals

Ceramic-metal
- Permanent
- Welding
- Resistance
- Fluxed Consumable Electrode
- MIG
- TIG
- Plasma Arc
- Electron Beam
- Explosive
- Laser

Ceramic-glass
- Permanent
- Welding
- Resistance
- Fluxed Consumable Electrode
- MIG
- TIG
- Plasma Arc
- Electron Beam
- Explosive
- Laser

Glass-metal
- Permanent
- Welding
- Resistance
- Fluxed Consumable Electrode
- MIG
- TIG
- Plasma Arc
- Electron Beam
- Explosive
- Laser

Ceramic-ceramic
- Permanent
- Welding
- Resistance
- Fluxed Consumable Electrode
- MIG
- TIG
- Plasma Arc
- Electron Beam
- Explosive
- Laser

Glass-glass
- Permanent
- Welding
- Resistance
- Fluxed Consumable Electrode
- MIG
- TIG
- Plasma Arc
- Electron Beam
- Explosive
- Laser
Welding is the process where two materials are joined by fusion.

- Welding is the most common method for joining metals in vacuum systems.

- Inert gas welding is the most common type of welding (TIG, MIG).

- Joint design is critical from vacuum, metallurgical and distorion standpoints.

- Cleanliness is essential.

- Other welding processes to consider are electron beam and laser welding.
TIG – Tungsten Inert Gas Welding

- **TIG welding** is one of most difficult welding, when operating manually.
- Inert gas mixture (Ar and He) form a shield to protect the hot-zone from oxidization. The composition of the gas mixture vary with metal and mass.
- **Arc power** may be direct current or alternate current.
- **Filler rod** is often used, but not needed for some fusion welds.
Welding Stainless Steel

- TIG welding of stainless steels is among easiest, and heat-affected zone (HAZ) is very small.
- In most cases, filler is not needed. However, reinforce stitch welds with filler are added for strengthening the welded joint.
Welding Copper

- The high thermal conductivity of copper makes welding difficult. Heating causes the copper to re-crystalize forming large grain size and annealing. Distortion is also a big problem.

- Copper weldment can be fused via TIG with or without fillers.

- Braze copper to copper, or copper to stainless steel is also done with TIG technique, using CuSil (72%Ag-28%Cu) alloy fillers. (At Cornell, we call this BT-weld, or Braze-TIG.)

- Copper requires:
  1. Very high welding speeds
  2. Excellent material purity (OFE copper) and cleanliness.
  3. Good joint design
  4. Welding coppers must be done in an inert glove-box, or at least purging in-vacuum surfaces.

- Electron beam welding is an excellent process for welding copper.

- Vacuum furnace braze is also a good option for coppers.
Welding Aluminum

- Low melting point, relatively high thermal conductivity, and high rate of thermal expansion make welding aluminum more problematic than stainless steel.

- Aluminum requires:
  - 1. High welding speeds (higher current densities)
  - 2. Good material purity and cleanliness
  - 3. Good joint design

- Aluminum welds have a tendency to crack from excessive shrinkage stresses due to their high rate of thermal contraction. Filler rods (usually 4043 or similar alloys) always needed.

- To keep the aluminum weldment clean from oxidization, AC power is usually used during TIG, with characteristic popping noises.
**Electron Beam Welding (EBW)**

- EBW provides extremely high energy density in its focused beam producing deep, narrow welds.

- This rapid welding process minimizes distortion and the heat affected zone.

- Very good control and reproducibility in weld penetration.

- A disadvantage of EBW is that the process takes place under vacuum ($P = 10^{-5}$ Torr):
  - Extensive fixturing required
  - High initial cost
  - Weld preps are extremely critical, as no filler used.
  - Complexity
  - Welds are not cleanable
Copper chambers EBW

Welding 1-mm thick Copper Cover on CesrTA EC Detector Chamber

RF Cavity

Load into EBW Chamber  E-beam welding
SLAC Electron Beam Welder
Soldering

Soldering is the process where materials are joined together by the flow of a “filler metal” through capillary action.

- Soldering is differentiated from brazing primarily by the melting temperature of the filler metals. Solder alloys melt below 450°C.

- Because of lower working temperature, usually corrosive flux is needed to ensure proper ‘wetting’ of the surfaces.

- All soft solders are unacceptable for UHV systems because:
  - They contain Pb, Sn, Bi, Zn (vapor pressures are too high)
  - System bake-out temperatures typically exceed alloy melting points.
  - Residuals of corrosive flux left on the joints, a long-term reliability issue.

- Most silver solders are unacceptable.
Brazing is the process where two dissimilar materials are joined together by the flow of a “filler metal” through capillary action.

- **There are several different brazing processes:**
  1. Torch
  2. Furnace
  3. Induction
  4. Dip
  5. Resistance

- **Brazing can be used to join many dissimilar metals. The notable exceptions are aluminum and magnesium.**

- **Cleanliness is important in brazing. Cleanliness is maintained by use of a flux or by controlling the atmosphere (vacuum or H₂).**

- **For vacuum furnace brazing, flux is NOT used.**
Brazing (Cont.)

- **Filler metals (brazing alloys) come in the form of wire, foils, or paste.**

- **Brazing alloys are selected to have melting points below that of the base metal.** The brazing alloys must be able to ‘wet’ the base metal(s).

- **Generally, brazing alloys can be categorized into eutectic or non-eutectic.** For eutectic alloy, the transitions between solidus and liquids occur at a very narrow band (within a degree). Eutectic alloys are usually preferable.

- **Multiple braze steps are possible by choosing alloys of differing melting points and proceeding sequentially from highest to lowest temperature.**

- **Braze joints require tight tolerances for a good fit (0.002” to 0.004”) to ensure capillary flow.**
### Some Braze Alloys for UHV Components

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Brazing Temperature</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georo™</td>
<td>361°C</td>
<td>88% Au, 12% Ge</td>
</tr>
<tr>
<td>CuSil™</td>
<td>780°C</td>
<td>72% Ag, 28% Cu</td>
</tr>
<tr>
<td>BAu -2</td>
<td>890°C</td>
<td>80% Au, 20% Cu</td>
</tr>
<tr>
<td>Au-Cu-Ni</td>
<td>925°C</td>
<td>81.5% Au, 16.5% Cu, 2% Ni</td>
</tr>
<tr>
<td>BAu -4</td>
<td>950°C</td>
<td>82% Au, 18% Ni</td>
</tr>
<tr>
<td>50/50 Au-Cu</td>
<td>970°C</td>
<td>50% Au, 50% Cu</td>
</tr>
<tr>
<td>35/65 Au-Cu</td>
<td>1010°C</td>
<td>35% Au, 65% Cu</td>
</tr>
</tbody>
</table>
Diffusion Bonding

- Diffusion bonding is a joining technique where pre-machined components are held together under modest loads at elevated temperatures.
  - The loads are usually well below those producing deformation.
  - Bonding temperatures typically range from 50-80% of melting temperatures of the metals.
  - Processing times vary from 1 minute to over an hour.
  - Most diffusion bonding operations are conducted in vacuum or in an inert gas atmosphere.

- Diffusion bonding requires very clean components with excellent surface finishes.

- Diffusion bonding can also bond dissimilar materials.
Friction Bonding/Welding

Friction welding (FW) is a class of solid-state welding processes that generates heat through mechanical friction between a moving work piece and a stationary component, with the addition of a lateral force called "upset" to plastically displace and fuse the materials.

FW is useful to bond dissimilar materials, such as aluminum to stainless steel, which otherwise difficult to joint.
Explosion Bonding

- Two Plates Are Spaced One Above the Other with Ammonium Nitrate Explosives on top. Thin transitional metal sheet(s) is often used in order to bond dissimilar metals. A progressive charge is detonated and the plates Accelerated to Contact.

- Extreme heat and pressure created at Impact and Ultra Clean Surfaces to fuse the plates to form metallurgical bonding.
A Claim – All Metal Combinations can be bonded

**Atlas Technologies Bonding Matrix**

<table>
<thead>
<tr>
<th>Bonding Capability</th>
<th>Flange Metal Standards</th>
<th>Beam Stop, Absorber Materials</th>
<th>Super-conducting Flange Materials</th>
</tr>
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<tbody>
<tr>
<td>Aluminum</td>
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<tr>
<td>Zirconium</td>
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</table>

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**Aluminum (1)**

**AL. Alloy (2)**

**Chromium (3)**

**Copper (4)**

**CU Alloy (5)**

**Gold (6)**

**GlidCop (7)**

**Hafnium (8)**

**Indium (9)**

**Iron (10)**

**Lead (11)**

**Magnesium (12)**

**Molybdenum (13)**

**Moly. Alloy (14)**

**Nickel, (Invar) (15)**

**Niobium (16)**

**Platinum (17)**

**Rhenium (18)**

**Silver (19)**

**Steel, & Alloys (20)**

**Steel, Mild (21)**

**Stainless Steel (22)**

**Tantalum (23)**

**Tin (24)**

**Titanium (25)**

**Tungsten (26)**

**Vanadium (27)**

**Zinc (28)**

**Zirconium (29)**
Explosion Bonding – Examples

Ref: PA&E Bonded Metals Division

Clad Tubes

- Titanium / Alum
- Cu / SS
- Alum / Steel
- Cu / Nb
SS/AL Bond Interface
Patent# 5836623

- Diffusion Inhibiting Layers: Copper and Titanium Interlayer Enables Bonding AL/SS
- Vacuum: < $1 \times 10^{-10}$ cc He/Sec
- Thermal: Peak 500°C at weld up 0-250°C Operational
- Mechanical: Tensile 38,000 psi

Ref: Atlas Technologies
Applications for bi-metallic joints

Alum/SST transition enable welding instrument feedthroughs to aluminum beampipe

Cu/SST transition used on Cesr-C damping wiggler beampipes
Demountable Metal Sealed Joints

There are a variety of metal seals available for vacuum systems, including:

- ConFlat® flanges: for flanges OD <26”
- HelicoFlex® seals: for customer designed flanges
- Metal wire seal flanges: for large flanges
- VATSEAL® flanges: good RF properties

Metal seals are used for UHV systems, where permeation, as well as radiation damages, are not acceptable.
Conflat® Flanges

- Conflat® style metal seal flanges are the most widely used for UHV vacuum systems.
- During sealing, knife-edges of a pairing stainless steel flanges plastically deform a copper gasket to form a reliable seal.
- The close match of C.T.E. of stainless steel and copper ensure proper sealing force through temperature cycles, up to 450°C.
- Gaskets are usually made of 1/2-hard OFHC. Silver-plated Cu gaskets are used for system baked at temperature higher than 250°C.
- Standard sizes range from 1-1/3” to 16” OD, with fixed and rotatable styles.
Conflat® Flanges Cont.
**Conflat® Flanges Cont.**

<table>
<thead>
<tr>
<th></th>
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Helicoflex® Flanges

- Metal O-ring using an internal spring to maintain the seal force, while outer layer of the gasket deforms to make seal.

- Vacuum rated to $1 \times 10^{-13}$ Torr; Temperature rated to $450^\circ C$.

- Typical size range: 10” - 20” od

Ref: http://www.techneticsgroup.com
Commercial Wire Seal Flanges

- Vacuum rated to $1 \times 10^{-13}$ Torr, Temperature rated to 450°C with copper wire gasket.

- Typical size range: 20” – 27” od with >30” possible

- **Warning** – male and female flanges
As with many X-ray light sources, it is always a challenge to make reliable UHV-compatible seal on a very large lid (often in vertical position) for X-ray optics, as elastomer seal is not acceptable. A reliable, inexpensive and very scalable aluminum wire seal scheme was developed at CHESS, and also adapted by NSLS II.
Large Wire Seal Flanges at CHESS Cont.

How the seal is made:
1. Four aluminum wires are stretched across sealing surfaces, and tensioned with springs.
2. The large lid is placed (with exaggerated bending) over the wires. Tightening from center towards the corners, to ensure that the wires kept stretched.
3. Under cuts at corners may improved sealing reliability.

Features of the seals:
1. No ‘upper-size’ limit.
2. Reproducible and reliable seals
3. Relatively relax seal surface finish, but need to be flat.
4. Only work on flanges with straight sealing edges/
VATSEAL® Flanges

- A style of metal seal for vacuum, cryogenics and high temperature applications.
- Silver-plated or gold-plated copper gaskets
- VATSEAL metal seals make a leak-tight seal and at the same time a reliable, low resistance RF contact

*) 0.6 uncompressed
Elastomer (O-ring) sealed flanges found their uses in accelerators mostly in high-vacuum, or insolation vacuum for cryogenic systems (such as superconducting magnet).

**ISO Flanges**

Flanges come in a variety of fastening styles:
- Kwik-flange
- Rotatable & Non-rotatable
- Double claw clamp
- Banded clamps

**ASA Flanges**

Typical size range: 1” to 12” dia.