Alloying Elements in Detail

This module contains a detailed collection of data about alloy **elements encountered in steel** and in steel making. They are arranged in alphabetical order.
Sources include most major steel books cited in the "book" module, some of the Internet source given there and the odd book or source I ran across. More about alloying and elements can be found in these links

- The periodic table (with details to all elements)
- Short overview of alloying elements
- Science of alloying

- I will also give you some basic background information about the elements. The information given is on occasion contradictory or incomplete. I synthesized what I found to the best of my abilities but that does not guarantee that I didn't get it skewed or plain wrong on occasion. Use at your own risk
- Here is the *basic* information about iron for comparison; detailed information can be found in this link

Basic Properties Iron			
Melting point (K/^{o}C^o/F)	**Lattice type (Trans. T in ^{o}C)**	**Density (g/cm^3)**	**Youngs Modulus (GPa)**
1808 / 1535 / 2795	bcc / fcc / bcc 910 / 1402	7,87	213

Here are quick links to the elements treated:

Al	B	C	Co	Cu	Cr	Mn	Mo	Nb	Ni	N	P	S	Si	Ti	W	V	Zr

Aluminum (Al)

Melting point (K/^{o}C/^{o}F)	Lattice type (Trans. T in ^{o}C)	Density (g/cm^3)	Youngs Modulus (GPa)
934 / 661 / 1222	fcc	2,70	70,5

First of all aluminum is a strong deoxidizer and thus used to kill steel (in competition to silicon (Si) or calcium (Ca)). It also strongly reacts with nitrogen, forming aluminum nitride (AlN). Aluminum, like phosphorous or silicon, is a strong α-stabilizer, producing a "closed γ-field ". It thus opposes austenite formation and there is no hardenability. The transition temperature A_1 decreases by about 40 °C per 0.1% aluminum added.

- Alloying or killing a steel with aluminum also influences the yield strength because the aluminum combines with residual nitrogen to form aluminum nitrides (AlN). The AlN particles formed interfere with grain growth even at high temperatures and keep the grain size small. Removing dissolved nitrogen (N) from solid solution makes dislocation movement easier and thus decreases hardness, look at the old figure. But smaller grains increase hardness, so the total effect is not immediately obvious.
  In any case, additions of aluminum greater than that required to kill the steel and to tie up the nitrogen have little effect.
- Aluminium also improves oxidation resistance, if added in *substantial* amounts. It is used in certain heat resistant alloys because it contributes to corrosion resistance to some gases at high temperatures.

By the way, illustrious Michael *Faraday* believed for a while that it was aluminum in the iron that made wootz steel so great. That was completely wrong, of course.

Boron (B)

Melting point (K / ^{o}C / ^{o}F)	Lattice type (Trans. T in ^{o}C)	Density (g/cm^3)	Young's Modulus (GPa)
2573 / 2300 / 4172	orthorhombic	2,46	440 MPa

- There is a lot of literature about boron (B) as alloying element, and it is, frankly, quite confusing. My major sources are the boron articles in the "key to metals" Internet site.
  First of all, it does not go well with the α - γ -stabilizer philosophy because it brings it its own phases already at very small concentrations. I will thus only give you a number of highlights here - without any guarantees that I got it right.
  The major point about boron is that it "works" very well already for *very small concentrations* of 0.0003 % - 0.005 % or about 3 ppm - 50 ppm.
    - It works because it increases the hardenability of already rather hard steel. It does so because with correct processing, small (2 nm - 3 nm) iron boride (Fe_2B) precipitates form that segregate predominantly at the primary austenite grain boundaries. Even for the small boron amounts used, they retard the $\gamma \rightarrow \alpha$ transformation, thus enhancing the hardenability of the steel.
      Or may be not - the issue is under debate. An alternative view is that boron needs to be atomically dissolved to be beneficial.
      Boron addition beyond the values given deteriorates hardenability because the excess of boron atoms precipitate as cubic $Fe_{23}(CB)_6$ iron-borocarbides, which act as nucleation centers for α phase formation, reversing what was stated above.
    - Boron is most effective in lower carbon steels. The small quantities mentioned above can give the same effect for a hardenability enhancement than other more expensive elements, which must be added in much bigger quantities, too. For example, the addition of 30 ppm B in "SAE" steel replaces approximately 1%Ni, 0,5%C, 0,2%Mn, 0,12%V, 0,3%Mo or 0,4%Cr.
      Another example: An addition of 30 ppm of boron in steel which contains approximately 0.15%C, 1%Mn and 0.9%Cr shows a clear increase in hardness of almost 50% and to a larger hardness depth than in the case of a steel of identical composition, but free of boron.
    - Boron may also be added as an intentional "nitrogen scavenger" in carbon steels instead of aluminum (see above). Boron is easier to work with and has all the other benefits mentioned here.
- Boron steels are used as wear-resistant and high-strength structural steel. Examples include punching tools, spades, knives, saw blades, safety beams in vehicles, etc. Carbon-manganese-boron steels are generally specified as replacements for alloy steels for reasons of cost: C-Mn-B steels are far less expensive than alloy steels of equivalent hardenability. Applications for these steels include earth scraper segments, track links, rollers, drive sprockets, axle components and crankshafts.
    - The boron steel used on Volvo cars has a yield point of about 1.350 MPa -1.400 MPa; an extremely large value, about four times larger than average high-strength steel. Of course, workability suffers.

Carbon (C)

Melting point (K/^{o}C/^{o} F)	Lattice type (Trans. T in ^{o}C)	Density (g/cm^3)	Youngs Modulus (GPa)
3823 / 3550 / 6422	fcc diamond hex graphite	3,51	1220 diamond

- I only offer two short remarks:

  1. Read the Hyperscript if you want to know what carbon does in iron.
  2. Modern steels increasingly do *not* use carbon very much, or in quite different ways than the ancient "plain carbon steels".

Chromium (Cr)

Melting point (K / ºC / ºF)	Lattice type (Trans. T in ºC)	Density (g/cm^3)	Youngs Modulus (GPa)
1808 / 1535	bcc / fcc / bcc 910 / 1402	7,87	213

Chromium belongs to the elements causing closed γ-field systems promoting a ferritic structure, and the elements which tend to form carbides, typically Cr_4C but also mixed iron-chromium carbides (often and wrongly still called "cementite") like $CrFe_3C_2$ $(CrFe)_7$ C_3 or $(CrFe)_4C$.
Most important, however, is that Chromium provides the full **corrosion resistance** of stainless steels. In this case a minimum concentration of 11 % is needed, a kind of magical number that science now can calculate. But concentrations as low as 1,1% already promote an inert passive oxide film on the surface in low-carbon steels, which resists attack by oxidizing reagents and thus already provides some corrosion resistance. It also increases the resistance to oxidation at high temperatures.

- Moreover, chromium is usually used together with nickel (Ni) in austenitic steels because at high concentrations it helps to stabilize the γ-phase, even so it is listed under the "closed γ phase elements". Then nickel provides for strength, ductility and toughness, while chromium prevents corrosion and adds hardness and resistance to wear - without causing much problems, a kind of good-luck anomaly to general rules. This gives us the superior (but very expensive) "18-8" austenitic steels.
  In "normal" Ni-Cr steels the depth of hardening increases substantially. A (just about "high alloy") steel with 4,5 % nickel, 1,25 % chromium and 0,35 % carbon, for example, can be hardened without quenching simply by cooling in air.
- Chromium thus is a very good and useful alloying element. However, it is horribly expensive! You must be prepared to pay 6.000 $ - 3.000 $ per ton.

Cobalt (Co)

Melting point (K / ºC / ºF)	Lattice type (Trans. T in ºC)	Density (g/cm^3)	Youngs Modulus (GPa)
1808 / 1495 / 2723	fcc / hcp 440	8.89	204

Cobalt has a high solubility in alpha- and gamma-iron but a weak carbide-forming tendency. It is a γ-stabilizer, but decreases hardenability. It helps to sustain hardness during tempering, however.

- Cobalt in relatively large concentrations is used in maraging steels or in martensitic steels where it increases the hardness and tempering resistance, especially at higher temperatures. How, exactly, it does that, was not all that clear last time I looked.
  You want to avoid cobalt if you can because it is horribly expensive.

Copper (Cu)

Melting point (K / ºC / ºF)	Lattice type (Trans. T in ºC)	Density (g/cm^3)	Youngs Modulus (GPa)
1357 / 1084 / 1982	fcc	8.92	123

Copper is a γ-stabilizer and thus promotes an austenitic structure. It dissolves in the ferrite to a limited extent - 3,5% at high temperatures and 0,35% at room temperature. It rather has negative effects.

  - However, copper enhances the corrosion resistance to atmospheric corrosion and in certain acids like sulfuric acid when present in amounts exceeding 0.20%. That is the outstanding feature that makes it an integral part of "weathering steels" in concentrations of 0.25 % - 0.55 % and some stainless steel variants.
    It forms intermetallic compounds that can be used for precipitation hardening but, I guess, this can be done more cheaply (copper is expensive!) by other elements.

Manganese (Mn)

Melting point (K / °C / °F)	Lattice type (Trans. T in °C)	Density (g/cm³)	Youngs Modulus (GPa)
1517 / 1244 / 2271	cubic α /cubic β/fcc/bcc 727 /1095 /1133	7.43	198
It should be "cubic weird". While the Bravais lattice is essentially cubic, the α or β phase has 50 or 20 atoms, respectively, in the base!			

- Manganese is arguably the most important alloy element for making steel. First of all it neutralizes sulfur (S) by forming MnS precipitates, preventing sulfur from sitting in the grain boundaries (as iron sulfide), causing deadly "hot shortness".
  Manganese is *always* added to plain "carbon" steel. The Alloy Steels Research Committee, for example, adopted the following definition: “Carbon steels are regarded as steels containing not more than 0,5% manganese and 0,5% silicon, all other steels being regarded as alloy steels”.
  Because manganese is a γ-stabilizer, it gives finer grained ferrite and more finely divided pearlite. This not only increases strength but *reduces* the ductile/brittle transition temperature.
  On top of that, it is also a de-oxidizer, neutralizing oxygen that might still be around from producing steel in the first place.
  - However, if the carbon content is relatively high (greater than 0.15%), a high manganese content may have a detrimental effect on the impact properties of normalized steels because the high hardenability of this steel causes the austenite to transform to the rather brittle upper bainite structure rather than to ferrite / pearlite.
- Manganese is cheap and therefore used to replace more expensive alloy elements, if possible. Steels with 0,3% - 0,4% carbon, 1,3% -1,6% manganese, and 0,3% molybdenum have replaced 3% nickel steel, for example.
  Manganese comes fully into its own if added in *large* concentrations.
  - Good old Hadfield`s steel, for example, contains 12 % - 14% of manganese and 1,0% of carbon. It has an extremely good wear resistance and is therefore used for railway points, rock drills and stone crushers. The new and exciting austenitic TWIP steels also rely on large Mn concentrations.
  - Manganese does many other good things like improving surface quality. It also "works" in stainless steels. I will not go into all of this, however.

Miscellaneous

- **Cerium** (Ce)
  Cerium is one of the rare earth metals. It is used for special heat- resistant steels because it increases the resistance to oxidation and high temperature corrosion. It does so because it improves properties of the protecting oxides and the metal-oxide interface.
- **Arsenic** (As)
  I have not come across arsenic as an alloying element conscientiously used for modern steel, (it's not all that healthy to work with it) but old steel (as in old swords) do contain it. We may assume that its effects on properties are similar to that of phosphorous.
- **Lead**
  Lead is virtually insoluble in liquid or solid steel. However, sometimes it is added to carbon and alloy steels by means of mechanical dispersion during pouring to improve the machinability of a steel.

Molybdenum (Mo)

Melting point (K / °C / °F)	Lattice type (Trans. T in °C)	Density (g/cm^3)	Youngs Modulus (GPa)
2896 / 2623 / 4753 °F	bcc	10.28	329

- Molybdenum belongs to zhe "closed γ-field " group of elements, i.e. it opposes austenite formation. It is a strong carbide former producing, e.g., Mo$_2$C or more complex stuff like (FeMo)$_6$C or Fe$_{21}$Mo $_2$C$_6$. It is frequently used for high-strength steels.
    - Molybdenum is mainly used in combination with other alloying elements. It substantially increases the resistance to both general and localized corrosion, strongly promotes a ferritic structure, and increases the mechanical strength somewhat. It promotes the formation of secondary phases in ferritic, ferritic-austenitic and austenitic steels, i.e. helps nucleation. It also enhances the creep strength of low-alloy steels at elevated temperatures.
    - There are, however, some important exceptions to this generalization. In strongly oxidizing environments such as hot concentrated nitric acid or chromic acid, **molybdenum** is an undesirable alloying addition.

Nickel (Ni)

Melting point (K / °C / °F)	Lattice type (Trans. T in °C)	Density (g/cm^3)	Youngs Modulus (GPa)
1728 /1455 / 2651	fcc	8.91	200

Nickel is the paradigmatic γ-stabilizer, it promotes an open γ- field to the point where austenite is (meta) stable at ambient temperatures. Austenitic steels thus usually rely on high Ni concentrations. Exceptions are the new TWIP steels that rely on manganese; see above. The phase diagrams of nickel or manganese with iron, respectively, are pretty much identical on the iron-rich side.
Nickel does not form carbides but remains in solution.

- The transformation temperature **A$_1$** comes down from its pure iron value of of 914 °C at 0 % Ni to 720 °C for 8% Ni to 600 °C for 15 % Ni. That is already low enough to keep austenite (meta)stable at lower temperatures, too. Nickel (in small amounts) thus increases hardenability.
  But the principal beneficial effect of nickel additions to commercial steels containing about 0.1% carbon results from the substantial grain-size refinement and a reduction of free nitrogen content. It is not much better than manganese in this respect but far more expensive.
  The main uses are therefore in the high-alloy region, especially for stainless austenitic steels or maraging steels. High nickel contents also have a beneficial effect on the oxidation resistance.
- As a speciality, so-called **Invar alloys** or steels with typically 36% nickel, 0,2% carbon, 0,5% manganese show a thermal expansion coefficient that is almost zero! In view of what I have claimed in this context, this is rather amazing! The explanation comes from the fact that Invar is magnetic and that the "magnetostrictive" forces between the atoms, expanding the lattice, decrease with temperature, more or less cancelling the regular thermal lattice expansion. Invar is used extensively in clocks, tapes, wire measures, and so on, where temperature-independent precision counts.
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Niobium

Melting point (K / ^{o}C / ^{o}F)	Lattice type (Trans. T in ^{o}C)	Density (g/cm^3)	Youngs Modulus (GPa)
2750 / 2477 / 4491 °F	bcc	8.57	105

- Niobium, formerly also know as **Columbium**, is an α-stabilizer and a strong carbide / nitride former. It thus provides for precipitation hardening but its main contributions to increased strength is the retardation of austenite recrystallization thus promoting a fine-grain microstructure.
  - In austenitic steels it is added to improve the resistance to intergranular corrosion but it also enhances mechanical properties at high temperatures.
    Niobium as effective element for increasing the recrystallization temperature means that you can "coil" your continuously cast sheet already at relatively high temperatures (e.g. 600°C), saving much space in your plant.
    Cooling down than will be slow and that allows precipitations and thus precipitation hardening
    Keep in mind that with α-stabilizers you pretty much loose hardenability by quenching / fast cooling

Nitrogen (N)

Melting point (K / ^{o}C / ^{o}F)	Lattice type (Trans. T in ^{o}C)	Density (g/cm^3)	Youngs Modulus (GPa)
63.15 / -210 / -346	Gas	-	-

- Nitrogen is a strong γ-stabilizer, expanding the (corresponding) A_1 temperature to a minimum of 595 ^{o}C (pure iron: 911^{o}C, carbon steel: 723 ^{o}C); see the phase diagram.
  - It forms hard nitrides with metals like Al, Ti, Nb and others and thus can be used for precipitation hardening. It is also, together with carbon and phosphorous, one of the the three very strong solution hardeners.
- However, nitrogen is also be a big pain in the (you know where). Like carbon it is dissolved as interstitial, and there are good reasons why there is a growing demand for "interstitial-free (IS) steel". One particular problem results from the small but measurable mobility of nitrogen at room temperature (somewhat larger than that of carbon). That could lead not only to pronounced Lüders band formation but also to aging effects. In contrast to carbon the Fe_4N formation is less effective as a "scavenger" than cementite formation (partially because of the lower A_1 temperature). In other words: while cementite formation pretty much takes out all he carbon from the ferrite, Fe_4N formation may not take out all the nitrogen dissolved in the ferrite. This residual nitrogen then is free to do all kinds of mischief at ambient temperatures.
  - This is the reason why the property "nitrogen scavenger" has been mentioned for several alloy elements. They take out loose nitrogen and thus neutralize it.
- Nitrogen *increases* the corrosion resistance of austenitic stainless steels but *reduces* toughness and corrosion resistance of ferritic stainless steels. Nitrides of aluminium and titanium may inhibit the processes which lead to coarsening of grain size. Nitrogen additions to high-strength steels containing vanadium will enhance precipitation hardening - as long as the nitrogen concentration is limited to 0.005%. .
  And so on.
  - The conclusion is clear: Nitrogen is an interesting (and very cheap) alloying element - but if you want to use it, you better know *exactly* what you are doing!

Oxygen (O)

Melting point (K / °C / °F)	**Lattice type (Trans. T in °C)**	**Density (g/cm^3)**	**Youngs Modulus (GPa)**
54.36 / -218.79 / -361.82	Gas	-	-

- Steel is "killed" to get out the oxygen in there. It is in the steel because that's how steel is made: blow oxygen through the liquid (and very dirty) pig iron.
  It sure looks like oxygen is not an alloying element you want to use. The literature is a bit unclear if oxygen is an interstitial or an substitutional impurity atom in the iron lattice.
  - Oxygen embrittles iron and steel. In alloys with a *high* (!!) oxygen concentration greater than 0.01 %, fracture occurs along "embrittled" grain boundaries. In alloys of lower oxygen content, cracks are nucleated at grain boundaries but then propagate transgranularly.
    So it's a good idea to add de-oxidizing elements such as carbon, manganese, silicon, aluminum or zirconium, which react with the oxygen to form oxide particles. These oxide particles may even be beneficial because they retard the growth of the ferrite grains, producing some grain boundary hardening.

Phosphorus (P)

Melting point (K / °C / °F)	**Lattice type (Trans. T in °C)**	**Density (g/cm^3)**	**Youngs Modulus (GPa)**
Phosphorous is found in many modifications (black, white, red, ...) so no data here.			

- Phosphorous (and sulfur) were the major culprits in early steel engineering. Phosphorous is a strong α-stabilizer, producing a closed γ -field. Phosphorous steel thus has no hardenability and promotes the much dreaded "cold-shortness" .
  It is still a good idea to keep a close eye on phosphorous.
  - On the other hand, phosphorous is just as effective as carbon for solution hardening. It also helps to battle corrosion, the famous "Indian pillar" bears witness to this. Not to forget, it gives steel an attractive silver-white surface, a property quite useful when making show-off composite "damascene" swords.
    I have dedicated a whole sub-chapter to "old" phosphorous steel, so I wont' go into the "old" stuff here any more.
- For *modern* steel, things are different. While phosphorous is
  generaly avoided, it is added intentionally, if carefully, to some special steels, for example to bake-hardening or TRIP steels.
  As with nitrogen: you may use it but you better know exactly what you are doing!

Silicon (Si)

Melting point (K / °C / °F)	**Lattice type (Trans. T in °C)**	**Density (g/cm^3)**	**Youngs Modulus (GPa)**
1687 / 1414 / 2577	fcc	2.33	≈ 150

- Almost every steel (and cast iron) contains Si in a concentration of around 0.5 % or so. Most of the Si produced actually goes in to steel (and aluminum or silicones) and not into chips and solar cells. Its major use is for killing your steel.
  - Silicon, like phosphorous or aluminum, is a strong α-stabilizer, producing a closed γ -field - and here goes the hardenability , if you overdo it. It's uses, besides killing steel, are limited but important. It is essential, for example, in raising the specific resistivity of transformer steel. You may also find it in spring steels or in some stainless steels, where it increases oxidation resistance.
    In low-carbon steels, silicon is generally detrimental to surface quality.

Sulfur (S)

Melting point (K / °C / °F)	Lattice type (Trans. T in °C)	Density (g/cm^3)	Youngs Modulus (GPa)
388.36 / 115.21 / 239.38	Orthorhomic	1.92	-

- Sulfur is just as bad as phosphorous - one of major culprits in early steel engineering. Iron cannot dissolve sulfur and iron sulfides (FeS) are formed, typically at grain boundaries, causing hot shortness, the bane of smiths throughout the millennia. It is still an element you rather avoid. Unfortunately, it is not so easy to get sulfur out of your steel, so you neutralize with manganese as described above.
  - However, if you know what you are doing, you can also use sulfur to your advantage, for example in machining steels. Since there is no such things as a free lunch, you pay for the better machinability with reduced corrosion resistance, ductility and fabrication properties, such as weldability and formability.

Titanium (Ti)

Melting point (K / °C / °F)	Lattice type (Trans. T in °C)	Density (g/cm^3)	Youngs Modulus (GPa)
1941 / 1668 / 3034	hex / bcc 882	4,50	105

- Titanium is a strong α-stabilizer, producing a closed γ -field. Ti alloying thus may impair hardenability. More important, Ti is a strong carbide / nitride former. Most important, however, it does *not* act as a carbide former until it has rounded up and consumed all oxygen, nitrogen and sulphur. It is the most effective oxygen, nitrogen, sulphur and carbon scavenger
  - It is a very good alloying element to have. Small additions of Ti (0.02 %) may already be sufficient to form TiN particles if there is still some nitrogen in the steel or if it is included, e.g., during welding. TiN particles are also very effective in restricting the growth of austenite grains during intercritical annealing.
  - In austenitic steels it increases the resistance to intergranular corrosion and improves mechanical properties at high temperatures. In ferritic stainless steels it improve toughness and corrosion resistance by lowering the amount of interstitials in solid solution, turning the steel into the "interstitial-free" directions. And so on.

Tungsten

Melting point (K / °C / °F)	Lattice type (Trans. T in °C)	Density (g/cm^3)	Youngs Modulus (GPa)
695 / 3422 / 6192	bcc	19.25	411

- Tungsten is a α-stabilizer, producing a closed γ-field. It forms rather hard carbides like WC and W_2C, but in the presence of iron it forms Fe_3W_3C or Fe_4W_2C and intermetallics like Fe_3W_2.
  It is primarily used in tool steel for about the same reasons given above for vanadium
  - As in the case of "Hadfield's steel", **Robert Mushet**, guided by good guessing and luck, produced **Mushet's steel** in 1868. It consisted of 4% -12% tungsten plus 2% – 4% manganese and 1.5% – 2.5% carbon. Mushet steel was harder than standard water quenched steel and was essentially a first tool steel.
  - There is also a bit of mythology around concerning the use of tungsten. Somewhere I read: "The celebrated and ancient *damascus steel* being a form of tungsten-alloy steel" No!

Vanadium (V)

Melting point (K / ºC / ºF)	Lattice type (Trans. T in ºC)	Density (g/cm^3)	Youngs Modulus (GPa)
2183 / 1910 / 3470	bcc	6.11	128

- Vanadium is a α-stabilizer, producing a closed γ-field. It is a scavenger for oxygen and forms a carbide (VC) - but looses against the iron in doing so during regular cooling. The carbon thus ends up mostly as cementite. However, if you heat the steel, the cementite dissolves (making the steel soft) but now VC forms, inducing a secondary precipitation hardening. That's why you find quite a bit of vanadium in tool steel.
    - Vanadium, however, is not so efficient in low carbon steel. But put it in alloy steels relatively rich in chromium, carbon, or manganese, and it works well for increasing the strength, including the the impact strength, of the alloy. It does so by both precipitation hardening and by keeping grains sizes small. Vanadium also improves creep resistance.
Remarkably, steels with vanadium can be quench-hardened and don't loose their hardness easily when they get hot.
Chromium-vanadium steels are well-known and used for,automobile axles, coil springs, torsion bars or tools.

Zirconium

Melting point (K / ºC / ºF)	Lattice type (Trans. T in ºC)	Density (g/cm^3)	Youngs Modulus (GPa)
2128 / 1855 / 3371	hcp	6.52	88

- Zirconium is rather expensive and thus only used for special reasons. Zirconium has an excellent resistance to corrosion and transfers that property to some extent to steel. It is thus used as alloying element for steels exposed to aggressive environments.
    - Zirconium can be added to killed high-strength low-alloy steels to achieve improvements in inclusion characteristics. Zirconium causes sulfide inclusions to be globular rather than elongated thus improving toughness and ductility in transverse bending. Zirconium will also inhibit grain growth and prevent strain aging, although its use for either of these functions is quite limited
    - Zirconium is a major metal for the nuclear industry. Stainless steel–zirconium alloys with 8 5 - 15 % zirconium are developed to safely contain nuclear waste a long time.