Mike Ashby

Department of Engineering, University of Cambridge

**Granta EduPack Exercises: Materials Science and Engineering**

-To accompany Lecture Unit 6

***Exercises with Worked Solutions***

This collection of exercises and solutions has been put together to help you as an instructor choose or develop your own exercises for your students. You may simply want to browse through them for inspiration, or you may use them with your class. We are providing these in Word format, so that you may pick and choose the questions you find suitable for your course this year. We have also included variations on a theme so that you can set different questions for different classes.

Most of the questions come from or are inspired by the exercises in the following books by Professor Mike Ashby of the University of Cambridge Department of Engineering, co-founder of Granta Design.

* **Materials Selection for Mechanical Design (5th ed)** by Michael F. Ashby (ISBN: 978-0-08-100599-6)
* **Materials: Engineering, Science, Processing and Design (4th ed)** by Michael F. Ashby, Hugh Shercliff, and David Cebon (ISBN**:** 978-0-08-102376-1)
* ***Materials and Design: The Art and Science of Material Selection in Product Design*****(3rd ed)** by Michael F. Ashby and Kara Johnson (ISBN: 978-0-08-098205-2)

Most of the questions require the use of Ansys Granta EduPack. Granta EduPack is a materials teaching resource used at 1,000+ Universities and Colleges worldwide. You can find out all about it at: <https://www.ansys.com/products/materials/granta-edupack>

The topic areas of the available Exercises are[[1]](#footnote-1):

|  |  |
| --- | --- |
| **Title** | **Associated Lecture Unit** |
| **Materials: Classification and Properties** | **Lecture Units 1-2** |
| **The Elements** | **Lecture Unit 3** |
| **Materials Science and Engineering** | **Lecture Unit 6** |
| **Material Selection: Translation, Screening, Ranking** | **Lecture Unit 7** |
| **Manufacturing Processes: Classification and Cost** | **Lecture Unit 10** |
| **Eco Properties and Eco Design** | **Lecture Unit 11** |
| **The Eco Audit Tool** | **Lecture Unit 12** |
| **Energy: Power Systems Generation and Storage** | **Lecture Unit: “*Materials for low carbon power”*** |
| **Materials and Sustainable Development** | **Lecture Unit: “*What is a Sustainable development*”** |
| **Bioengineering** | **Lecture Unit: *“Materials for Bioengineering”*** |
| **Design Database for Products, Materials and Processes** | **Lecture Unit: *“The Design database for Products”*** |
| **Introductory Materials (basic excerpts)** | ***Compiled, Lecture Units 1, 2, 3, 7*** |

You can find the other units here: <http://www.ansys.com/education-resources>. If there are suggestions, or if you have questions, please contact the Ansys Education Team at [education@ansys.com](mailto:education@ansys.com). Reproduction and copyright information can be found on the last page. Please make sure to credit Professor Mike Ashby and Ansys if you use these questions.

## Contents

Discovering the Science behind Material Properties with the Granta EduPack

Learning by discovery is more effective (and much more fun) than simply remembering what you’re told. These Granta EduPack-based exercises are designed to guide discovery, provoke thinking and stimulate self-learning. There are relationships between material properties, some easily explained, others so complex that they are not yet fully understood. Exploring relationships between material properties brings a deeper understanding of the physics that underlies the properties themselves. And it brings a “feel” for material property-values, valuable to engineers and designers, giving them a sense of when material property-values should be questioned and an ability to estimate property-values when no direct measurements are available. The exercises are in 4 groups, each group centered on one of the top-level data-tables in the Granta EduPack Materials Science and Engineering (MS&E) database. The table below acts as an index.

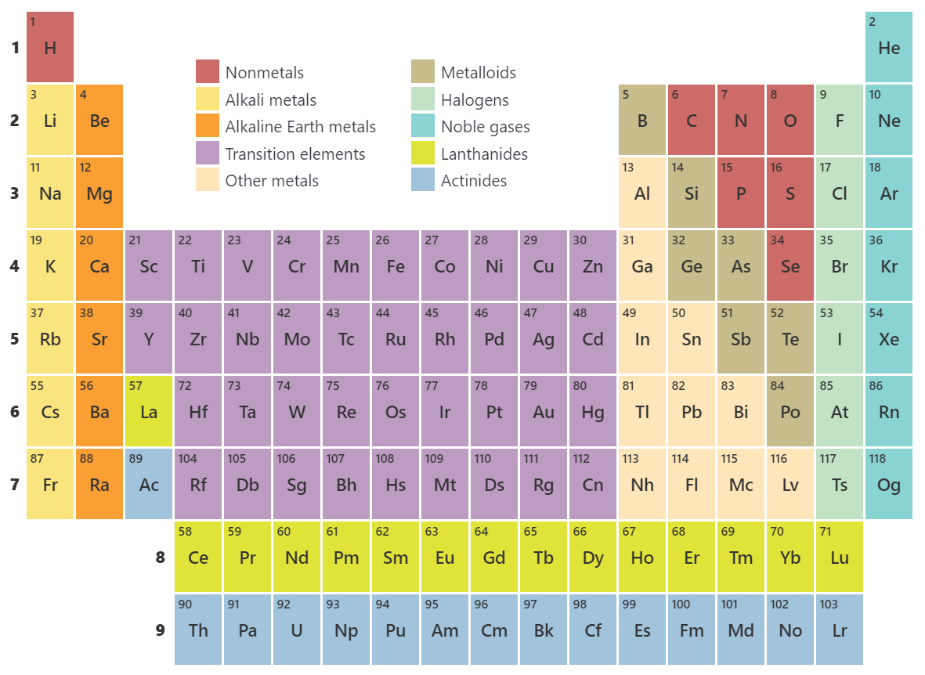
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The properties themselves fall into three broad groups: those most directly related to the atomic nucleus, those related to interatomic bonding and packing, and those relating to microstructure. None are entirely independent on others, so we refer to them as “nucleus-sensitive”, “bonding-sensitive”, “microstructure-sensitive” to suggest the dominant influence. The table below gives examples.

|  |  |  |
| --- | --- | --- |
| **Nucleus-sensitive**  **properties** | **Bonding-sensitive**  **properties** | **Microstructure-sensitive properties** |
| Nuclear stability  Abundance of the elements  Atomic number  Neutron-capture cross section | Crystal structure  Atomic radius  Cohesive energy  Melting point  Latent heats of melting and fusion  Modulus  Specific heat  Expansion coefficient  Electronegativity  Ionization energy  Activation energy for diffusion  Surface energy  Saturation magnetization  Ferroelectric properties | Yield and tensile strength  Hardness  Elongation  Fracture toughness  Thermal conductivity  Electrical resistivity  Coercive field  Energy product |

1. **Discovery with the Elements Data-table**

**Exercise 1: Getting to know the Elements data-table.** The Elements data-table contains records for all the elements of the Periodic table.



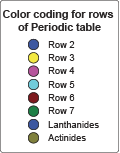
Find the record for Nickel.

1. When was it discovered?
2. What is its crystal structure?
3. What is its abundance in the Earth’s crust?
4. Which two nations produce the most nickel per year?
5. What is the carbon footprint associated with its production?
6. What is its thermal conductivity?
7. Is it magnetic?

**Nucleon-sensitive properties**

**Exercise 2: energy per nucleon.** The protons and neutrons (“nucleons”) that make up the core of a stable atom bind together. The bigger the binding energy per nucleon, the more stable is the atom. Make a chart of Binding energy per nucleon plotted against Atomic number. Use linear scales for both. Which element is the most stable? Approximately how much energy per nucleon is released if Uranium decays to the most stable element in a fission reaction? How much is released if Deuterium (H-2) transmutes to the most stable element in a fusion reaction? Select from *Elements: All Elements*

**Exercise 3: Abundance of the elements in the Earth’s crust.** The Earth formed by the aggregation of the debris of supernovae explosions about 4.6 billion years ago. You might expect that the preponderance of elements in the earth would reflect the nuclear stability – the more stable the nucleus, the greater the occurrence of the element. Test this hypothesis by making a chart of Abundance in the Earth’s crust (use Log scale) against Atomic number (use Linear scale). Is the hypothesis even approximately true? (Ignore the element Promethium)

**Bonding-sensitive properties**

The tell-tail signature of a bonding-sensitive, microstructure-insensitive property is that its value oscillates in a periodic way across the rows of the periodic table. The next five exercises illustrate this, plotting chosen properties against Atomic number. The software automatically color-codes the rows to identify its members. The coding is shown in the adjacent table.

These are followed by a set of exercises that explore the relationships between properties – the dependence of Modulus on Cohesive energy, for example. They are particularly revealing about the ways in which bond strength and character affect properties. They also provide a tool for checking material property values and estimating values when none are available. The section ends with four more advanced questions: estimating Cohesive energies, Surface energies, Activation energies for lattice diffusion and visualizing the Hume-Rothery criteria for solid solution and its applications.

**Exercise 4: Atomic size across the rows of the Periodic table.** Make a chart with Atomic radius on the y-axis and Atomic number on the x-axis. Change the default log scale to linear in the *Chart stage* or by double clicking on the axis name of the chart to reveal the axis-choice dialog box and choose ‘Linear’. Use the “Curve” facility to sketch in the trends. What trends appear? How do you explain them?

**Exercise 5: Melting point across the rows of the Periodic table.** Make a chart of the absolute Melting point for the elements across the Periodic table. To do so, set the temperature scale to Kelvin (Settings > Units > Use Absolute Units for Temperature) and plot Melting temperature on the y-axis against Atomic number. Use linear scales for both. Change the default log scale to linear in the *Chart stage* or by double clicking on the axis name of the chart to reveal the axis-choice dialog box and choose ‘Linear’. Use the “Curve” facility to sketch in the trends. Where are the peaks in the melting point? What does this suggest about the strength of atomic bonding?

**Exercise 6: Expansion coefficient across the rows of the Periodic table.** Make a chart of the Thermal expansion coefficient at 300K plotted against Atomic number. Use linear scales for the X-axis. Change the default log scale to linear in the *Chart stage* or by double clicking on the axis name of the chart to reveal the axis-choice dialog box and choose ‘Linear’ Use the “Curve” facility to sketch in the trends. What trends do you observe?

**Exercise 7: Sound velocity across the rows of the Periodic table.** Make a chart of the sound velocity for the elements. To do so, construct the property-combination on the y-axis using the ‘Advanced’ facility in the axis-choice dialog box, and plot it against Atomic number. Multiply  by 109 to convert GPa to Pa, giving the sound velocity in m/s. Use a linear scale for Atomic number but retain the default log scale for sound velocity. In which element is the velocity greatest? In which is it least?

**Exercise 8: Cohesive energy across the rows of the Periodic table.** What is the “Cohesive energy”? (The Science Notes attached to each property in a datasheet will help here.) Make a chart of Cohesive energy plotted against Atomic number. Use linear scales for Atomic number but retain the log scale for Cohesive energy. Use the “Curve” facility to sketch in the trends. What trends do you observe?

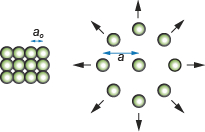
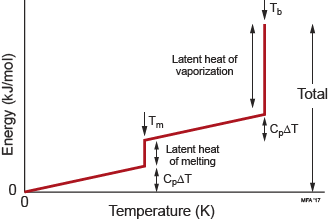
**Exercise 9: Melting point and Cohesive energy.** You might suspect that the melting point and the cohesive energy were at least roughly related. Make a chart to find out if this is so. To do this in a sensible way, plot the thermal energy at the melting point, (3/2)  against the Cohesive energy. To do this use the “Advanced” facility to multiply absolute melting point (K) [set the temperature scale to Kelvin (Settings > Units > Use Absolute Units for Temperature)] by the gas constant  (8.31 J/mol.K), multiply by (3/2) and divide by 1000, to give the thermal energy in the same units (kJ/mol) as the cohesive energy. Use linear scales for both. What is the thermal energy at the melting point in units of cohesive energy?

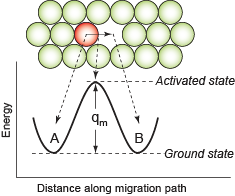
**Exercise 10: Latent heat of melting and energy to raise material to the melting point.** To melt a solid, it must first be raised from an ambient temperature to the melting point, absorbing an energy *CpTmAw* kJ/mol. Here *Cp* is the specific heat (J/kg.K), *Tm* is the melting temperature (K) and *Aw* is the atomic weight (kg/mol). Once it reaches the melting point it absorbs a further Latent heat of fusion, *L* (kg/mol) in the process of melting. Are the two related? What are their relative magnitudes? Make a chart of *L* plotted against *CpTmAw* to find out. Be careful with the units – there is risk of losing a factor of 1000 if mol and kmol are confused, same with J and kJ.

**Exercise 11: Electronegativity of the elements.** What is meant by “electronegativity”? (The Science Notes attached to each property in a CES datasheet will help here.) Make a chart of Electronegativity plotted against Atomic number. Use linear scales for both. Elements that differ in electronegativity by 1.7 or more on the standard Pauling scale will form ionic bonds. Use this criterion to identify elements that will form an ionic bond with Sodium (Na).

**Exercise 12: Electronegativity of the elements.** What is the First ionization energy of an atom? (The Science Notes will help here.) Is it related to the Pauling electronegativity? Make a chart with Electronegativity on one axis and First ionization energy on the other to find out. Use linear scales for both.

**Exercise 13: Heat of vaporization and Cohesive energy.** The Cohesive energy of a solid material is the energy required to separate its atom or ions into neutral atoms at infinity (upper part of the figure). Can it be estimated as the energy to vaporize a material? The lower part of the figure shows that this is the sum of the energy to heat it to the melting point, plus the latent heat of melting  plus the further energy to heat it to the boiling point plus the latent heat of vaporization, . Here  is the specific heat, and are the melting and boiling points and and  are the latent heats of melting and vaporization. In reality  is 15 to 30 times larger than the terms involving the specific heat so a first trial might be to plot Cohesive energy against the sum . Create this chart and form a judgement about the validity of its use to estimate cohesive energies. Use linear scales for both.



**Exercise 14: Activation energy for lattice diffusion and Cohesive energy.** Diffusion is the spontaneous intermixing of atoms over time. The unit diffusive step in a crystal is sketched here. Two things are needed for an atom to switch sites: enough thermal energy for the atom to break at least one of its bonds and an adjacent vacancy. The Maxwell-Boltzmann equation describes the probability  that a given atom has an energy greater than a value  Joules:

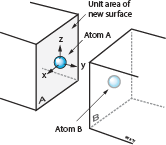


A vacancy has an energy , so the probability  that a given site be vacant is also given by this equation with . To switch sites, the atom marked in red must break away from its original comfortable site at A, its *ground state*, and squeeze between neighbors, passing through an *activated state*, to drop into the vacant site at B where it is once again comfortable. There is an energy barrier, , between the ground state and the activated state to overcome if the atom is to move. The probability  that a given atom has thermal energy this large or larger is our equation again with . The overall probability of an atom changing sites is



where  is called the *activation energy for self-diffusion*.

Bonds are broken when a vacancy forms. Bonds are also broken when an atom jumps from it starting site into an adjacent vacancy. One might, then, expect that the activation energy  was directly related to the Cohesive energy. If this turn out to be the case, the relationship becomes a valuable tool. Cohesive energies are known for almost all the elements and can be estimated when they are not known (see the previous exercise). Activation energies diffusion have been measured in only a few. Make a chart of Activation energy for lattice self-diffusion against Cohesive energy to see if this is a winner.

**Exercise 15: Surface energy and Cohesive energy.** The figure shows a block of material that has been cut in half to create two new surfaces. Creating the surfaces breaks bonds such as the one that previously linked atom A and atom B in the figure. The surface energy  (J/m2) is the sum of the energies of the broken bonds per square meter of new surface. Think of each atom as having 6 bonds, 1 each in the and  directions; in the case of atom A the bond in the +y direction is broken in making surface A. The number of atoms per m2 of surface is



where  is Avogadro’s number (6 x 1023 per mol) and is the molar volume (m3/mol). The cohesive energy per ion is



where  is the Cohesive energy (kJ/mol).

* Use this information to assemble an expression for the surface energy in terms of , and  (values for these and for the surface energy  are contained in the Elements data-table). Watch out for units! is listed in kJ per mol, in m3 per kmol, and  in J per m2.
* Make a chart with this expression as the x-axis and surface energy  as the y-axis.
* Does the expression describe real surface energies well (allowing for the fact that they are difficult to measure, so not very precise)?
* Use the chart to estimate the surface energy of cadmium (= 112 kJ/mol, = 0.013 m3/kmol)

**Exercise 16: Solid solutions and High entropy alloys.** The Hume-Rothery rules set out criteria for the formation of extensive solid solutions:

* Atom size difference less than 15%
* Electronegativity difference less than 0.075
* The components have the same crystal structure
* The components have the same valence within 

Make a chart of Electronegativity against Atomic radius. If you choose a log scale for the Atomic radius and a linear one for Electronegativity you can plot a selection box which meets the first two of these rules. If, in addition, you re-color-code the element-by crystal structure the chart allows the third criterion to be applied. To do this, add a Limit stage, sequentially select; Crystal structure “Cubic: face centered”, “Hexagonal close packed” etc isolating materials of a single structure, high-light the list that appears in the Results window, right-click on high-lighted list and select new “Record color”; finally clear the Limit stage and proceed to the next structure. It is now easy to pick pairs of materials that will form extensive solid solutions. The final valence criterion can be applied if desired by adding another Limit stage.

High entropy alloys are solid solutions with four or more components each with concentrations above 5%. The cumulative entropy of mixing as the components mix reduces the free energy of the alloy, stabilizing the alloy and enhancing mechanical properties. The Hume-Rothery rules give guidance in selecting components to make such alloys. Use your chart to Identify some clusters of elements that might form high entropy alloys.

**Exercise 17: Make yourself a structure table.** There are many other things you can do with the Elements data-table. Here is one that will illustrate the method.

* Open the Elements data-table. Apply a limit stage. Select “Structure – Cubic, face-centered. “Click Apply”.
* A list of all the elements in the Periodic table with the FCC structure appears in the “Results” window.
* Highlight the list and copy and paste into WORD as the first column of a 4-column table.
* Open any one of the selected records. Copy and paste into WORD. Copy and resize the crystal structure image. Paste it into the top of Column 1 of the table
* Clear the limit stage, and repeat the process for Hexagonal close packed, Cubic, body-centered and Cubic, diamond type, thereby filling the remaining 3 columns.

The result: a useful single-sheet look-up table for the elements with the most important crystal structures.

1. **Discovery with the Biological materials Data-table**

The Biological materials data-table gives students access to data for Biological materials (like bone, horn, skin and woods, for example) and to the building blocks of which they are made (collagen, hydroxyapatite, elastin, cellulose and more) in the same format and units as those for the elements, engineering materials and functional materials contained in the database. Uniquely, this allows construction of charts that allow direct comparison of Biological materials with those of engineering, stimulating thinking about man-made substitutes for those of nature and of ways in which nature might inspire advances on the engineering side.

**Exercise 18: Getting to know the Biological materials data-table (1).** What is egg shell? What is the fracture toughness of egg shell? To find out, Browse or use the Search facility to find the record for egg shell.

**Exercise 19: Getting to know the Biological materials data-table (2).** What is Ramie? What is the Tensile strength of Ramie fiber? How does this compare with Low carbon steel? Use the Search facility to find the record for Ramie.

**Exercise 20: Getting to know the Biological materials data-table (3).** What is Resilin? What is the definition of the Mechanical loss coefficient? (The Science Note for Mechanical loss coefficient will help here.) What is the mechanical loss coefficient of Resilin? How does it compare with that for Collagen?

**Exercise 21: Natural and man-made fibers.** It is sometimes claimed that spider drag-line silk is stronger than steel. Patented steel wire (“piano” wire) has a tensile strength  of 3800 MPa, a modulus *E* of 207 GPa and a density of 7900 kg/m3. Make a chart with Tensile strength on the y-axis and Young’s modulus on the x-axis. Limit the materials to Natural fibers (“Custom – Define your own subset – Biological materials - Natural fibers”). Piano wire can be found under man-made fibers or can be added: right click on the chart and select “Add Record”. Enter its values for tensile strength and modulus – it will appear on the chart. Is spider drag-line silk really stronger than steel?

Perhaps the claimants mean “stronger per unit weight” ( ) rather than just “stronger” (just  )? Make a new chart with  on the y-axis and  on the x-axis using the “Advanced” facility on the axis-selection window to find out.

**Exercise 22: Modulus and density of woods.** How does the Young’s modulus *E* for hard and soft woods depend on density ? Make a chart for the relevant materials with *E* on one axis and  on the other. Does the transverse (t) modulus – the one across the grain – depend on density in a different way from the longitudinal (l) modulus parallel to the grain? Fit a power law to each by plotting trial “display” lines onto the chart with slopes of 1 (a linear dependence), 2 (quadratic dependence) and 3 (cubic dependence) to see which best matches the data.

**Exercise 23: Materials for shields.** Imagine yourself to be a 12th century Viking seeking light, tough materials to make shields to protect yourself while you pillage and plunder. “Tough” means high , where  is the fracture toughness and  is Young’s modulus. “Light” means low density, . Use the “Advanced” facility to make a chart of biological materials with  on the y-axis and on the x-axis. Apply a selection line with a slope of 1 describing light, tough materials ( ) and use it to find the best natural materials for shields. Then do a quick web-search to find out if these materials were ever, in the past, used in this way. Use a custom subset of Molecular Building Blocks, Tissues (Mineralized and Soft), and Wood.

**Exercise 24: Bone implant materials.** Badly broken bones are repaired with bio-compatible implants. Stainless steel and Titanium (or one of its alloys) are standard choices. Ideally the implant material should match bone in modulus, strength and density. Do these materials meet or come close to this ideal? Create a subset containing Mineralized tissue, Stainless steel, Titanium and Titanium alloys (“Custom: Define your own subset”). Make a chart with Tensile strength on the y-axis and Young’s modulus on the x-axis. Use it to form a judgement about the suitability of the three metals for implants in cortical bone.

Bone (simplifying a little) is a composite of Hydroxyapatite and Collagen. It has been suggested that a composite of Hydroxyapatite in polyethylene might make a good bone substitute. Add Hydroxyapatite and Polyethylene to your subset (simply edit the subset). Does it look as if a composite of the two has promise as a substitute bone material?

1. **Discovery with the Functional Materials Data-table**

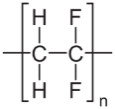
Although there is no standard definition of a functional material, it generally means materials with "interesting" properties that do more than just support loads, conduct heat and electricity. The group includes magnetic materials with piezoelectric, pyroelectric and ferroelectric behavior, and semiconducting materials including thermoelectrics.

**Exercise 25: Getting to know the Functional Materials data-table (1).** What is Terfenol-D? What functional properties does it exhibit? What does “giant magnetostriction” mean? Use the Search function to find the record for Terfenol-D and the science notes attached to Functional Properties to find out.

**Exercise 26: Getting to know the Functional Materials data-table (2).** What is TAGS? What is its composition? What are its Functional Properties? What is the value of its Seebeck coefficient? How is the Seebeck coefficient defined? Use the Search function to find the record for TAGS and the science notes attached to the field for Seebeck coefficient to find out.

**Exercise 27: Fullerenes.** Using Granta EduPack Materials Science and Engineering database, search for the term ‘fullerene’. What is a fullerene? What are examples of fullerenes? What is graphene? How does its tensile strength compare with that of steels? To find out, make a bar-chart of Tensile strength. Use the “Custom - Define your own subset” option in the “Chart/Select” Window to narrow the choice to Graphene and the five steels that are in the database.

**Exercise 28: Piezoelectric materials.** Efficient piezoelectric power generation is characterized by the merit index d33.g33, the product ofthe Piezo electric charge coefficient d33 and voltage coefficient g33. Use the Granta EduPack Materials Science and Engineering database to make a chart with d33 on the y-axis and g33 on the x-axis. Plot contours of the product d33.g33 (they are parallel lines with a slope of -1 on log scales). Use them choose the materials with the highest value of this index, bearing in mind that the use of lead is now restricted by the European Restriction of Hazardous Substances Directive (RoHS) Directive.

**Exercise 29: Piezoelectric polymers.** Polyvinylidene fluoride (PVDF) is unusual because it is a ferroelectric polymer. Its structure is sketched on the right.

(a) What makes it ferroelectric?

(b) Using either EduPack or the internet, find out what it is used for and why.

**Exercise 30: Pyroelectric materials.** Pyroelectric materials are used in thermal detectors and thermal imaging. Incident IR radiation heats up the substance creating a voltage which can trigger a circuit. The merit index for voltage response is:



where  is pyroelectric coefficient, is dielectric constant, and is heat capacity. Make a chart with on the y-axis and  on the x-axis and add contours (lines of slope 1 on log scales) describing the index.

1. Which material has the highest value of the index?
2. Two new pyroelectric materials have been developed recently; they are known as Z1 and Z2. Their properties are listed in the table. Add these temporarily to your database by right-clicking with the curser on your chart and selecting “Add record”. Enter the data for Z1 and Z2, which will then appear on your chart. Are they better than the best of the older materials?

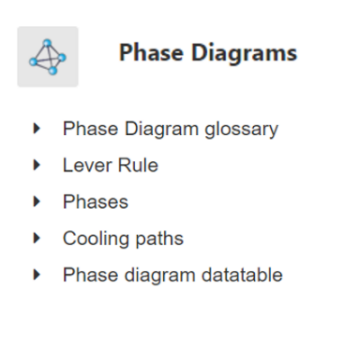
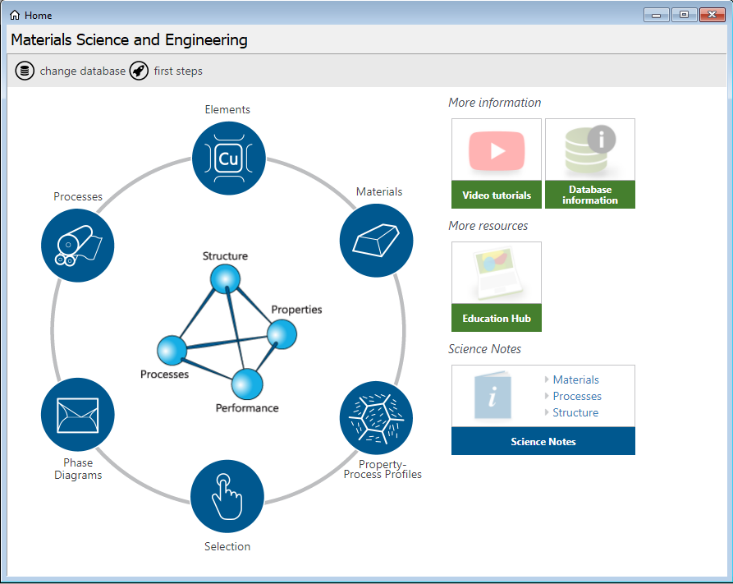
|  |  |  |
| --- | --- | --- |
| Property | Material Z1 | Material Z2 |
| Pyroelectric coefficient/μCm-2K-1 | 250-280 | 190-200 |
| Dielectric constant | 50-60 | 40-45 |
| Specific Heat Capacity/JKg-1K-1 | 300-320 | 150-180 |
| Density/kgm-3 | 7900 | 4800 |

**Exercise 31: Hard magnetic materials.** Hard (permanent) magnets are the key functional materials in efficient DC motors, turbines, and many electronic devices. They require materials with a high remanent induction (determining the strength of the magnetic field) and a high coercive force (determining the resistance to demagnetization). Make a chart with the first of these on the y-axis and the second on the x-axis. Use it to identify the group of alloys that make the best hard magnets.

**Exercise 32: Soft magnetic materials.** Efficient transformers and AC electric motors rely on soft magnets with high saturation induction and high maximum permeability. Make a chart with Saturation induction on the y-axis and Max permeability on the x-axis. Use it to identify the best materials for transformer cores.

1. ***Phase diagram exercises and solutions***

The new Phase diagram tool is located in the MS&E database under “Phase Diagrams” as shown below. Through visual examples, students learn about the phase diagram terminology, the lever rule, different cooling paths and the microstructure and atomic structure of phases. Some common binary phase diagrams with a short description can be found in the phase diagram datatable.



**Exercise 33.** In the ***Phase diagram glossary***, there are three binary diagrams to explore. Explain the terms Liquidus and Solidus. Which important phase points only appear in the Fe-C diagram and what do they mean?

**Exercise 34.** Read and understand the text that comes up when you click on ***Lever rule*** for the first time. Move on to the Lever rule diagram. There are two important concepts: weight fraction and composition. What’s the difference between the two?

**Exercise 35.** By looking at the Cu-Ni phase diagram in ***Phases*** how are the copper and nickel atoms arranged in the solid phase. What does the term solid solution mean?

**Exercise 36.** In ***Cooling paths***,looking at the eutectic phase diagram (Pb-Sn phase diagram), which of the five cooling paths contains the eutectic transformation? This transformation is isothermal, what does that mean?

**Exercise 37.** Which of the three diagrams in ***Cooling paths*** contains a eutectoid point? When you cool eutectoid carbon steel (0.8wt%) what’s the final solid microstructure called? Is this, strictly speaking, a phase?

**Exercise 38.** In the ***Phase diagram datatable***,which one is not a binary metal alloy diagram? What’s special about the components in this diagram?

1. **Discovery with the Property-Process Profiles Data-table**

Most mechanical properties and transport properties depend, to a greater or lesser degree, on microstructure. This means they can be manipulated by thermos-mechanical treatment. The Property-Process Profiles data-table contains a selected set of records for illustrating how properties change when materials are processed by alloying, working and heat treatment. The sets are:

1. Alloying and working: copper alloys
2. Heat treatment: carbon and low alloy
3. Alloying and heat treatment: stainless steels
4. Alloying and heat treatment: aluminum alloys
5. Filling and reinforcement: thermoplastic polymers
6. Powder processing: sintered ceramics
7. Foaming: polymers, metals, ceramics

**Exercise 39: Getting to know the Property-Process Profiles data-table.** Open the Alloying and working: copper alloys folder-level record. Double click on the name to reveal a summary of what the folder contains, what you can do with it and suggestions for projects.

The folder contains 3 sub-folders. Open Copper-Nickel alloys. The records in it illustrate, for 9 different composition of Cu-Ni, the way solid-solution hardening affects all the properties (not just the strength) of these alloys

Find the Thermal conductivity of 4 compositions: 32% Cu, 45% Cu 70% Cu and Pure Copper (the balance is nickel, of course). Which has the lowest Thermal conductivity?

**Exercise 40: Copper alloys: strengthening mechanisms.** Copper can be strengthened by work hardening, solution hardening and precipitation hardening. Explore these using the “Alloying and working copper alloys” module of the Property-Process Profiles data-table. To do so make a chart of Yield strength plotted against Copper content (chose a linear, not log, scale for the copper content). What are the characteristics of each strengthening mechanism? At what copper content is the strength contribution from solution hardening in Cu-Ni alloys a maximum?

**Exercise 41: Copper alloys: trade-off between Conductivity and Strength.** Many applications require high electrical conductivity and strength. How much conductivity is lost when copper, an excellent conductor, is strengthened by work hardening, solution hardening and precipitation hardening? Find out by using the “Alloying and working copper alloys” module of the Property-Process Profiles data-table to make a chart of Electrical resistivity against Yield strength.

**Exercise 42: Relationship between Thermal and Electrical conductivity.** Electrical conductivity is easy to measure; thermal conductivity is much more difficult. If there were a reliable relationship between them the difficult measurement would not be necessary. Make a chart with Thermal conductivity on the x-axis and Electrical conductivity on the y-axis using the “Alloying and working copper alloys” module of the Property-Process Profiles data-table. Make electrical conductivity in S/m by using the “Advanced” function to take the reciprocal of Electrical resistivity in micro-ohm.cm and multiplying it by 108. A new copper alloy has an electrical conductivity of 3x107 S/m. Use the chart to estimate its thermal conductivity?

**Exercise 43: Tempering steel.** The properties of carbon and low alloy steels are manipulated by heating to the austenitizing temperature, quenching and tempering. The “Heat treatment of carbon steels” module of the Property-Process Profile data-table has data for the way in which all the properties of two steels change with tempering temperature (standard tempering time 30 minutes). Explore the trade-off between yield strength and elongation (ductility) for the two steels by making a chart with elongation on the y-axis and yield strength on the x-axis. A steel is sought with a strength above 1000 MPa and at least 10% ductility. Use the chart to select a composition and heat-treatment.

**Exercise 44: Stainless steels: Elongation and Hardness.** Explore the relationship between the elongation (important for metal forming) and the hardness (important as a cause of tool wear) for stainless steels. Use a plot of elongation against hardness using the “Alloying and heat treatment: stainless steels” module of the Property-Process Profiles data-table to select the five stainless steels look most attractive for making a deep-drawn shape from sheet. Which class do they belong to (Austenitic, martensitic, precipitation hardened)?

**Exercise 45: Aluminum alloys: Thermal conductivity and Strength.** Like copper alloys, aluminum alloys can be strengthened by work hardening, solution hardening and precipitation hardening. As always, there are trade-offs. Increasing strength tends to reduce elongation, toughness and thermal and electrical conductivities. An aluminum alloy is sought for the heat-exchanger of a domestic air-conditioning unit. Good thermal conductivity is essential, but since the unit is pressurized, a strength of at least 100 MPa is specified. Use the “Alloy and heat treatment: aluminum alloys” module of the Property-Process Profile data-table to make a chart with Thermal conductivity on the y-axis and Yield strength on the x-axis and use it to select a candidate for the job.

**Exercise 46: Filled polypropylene: Thermal conductivity and Expansion.** Fillers such as talc, calcium carbonate and glass are added to polymers to increase stiffness and strength. But what do fillers do to the thermal properties of polymers? Use the “Filling and reinforcing: thermoplastic polymers” module of the Property-Process Profile data-table to make a chart with Thermal conductivity on the y-axis and Thermal expansion coefficient on the x-axis. Use linear scales for both. What trends are observable?

**Exercise 47: Foams: energy absorption.** Foams crush when compressed, absorbing energy. Two properties are important in choosing protective foams for energy absorption: the energy  absorbed per unit volume

 J/m3,

where *E* is Young’s modulus, and the stress at which the crushing takes place because this determines the forces exerted on object that is being protected. Use the “Foaming: polymers, metals, ceramics” module of the Property-Process Profiles data-table to select a foam with a crushing strength below 0.1 MPa and the largest possible energy absorption. To do so make a chart with Young’s modulus *E* on the x-axis and the Yield strength on the y-axis. Plot parallel lines (contours) of energy absorption *U* onto the chart (they are a family of parallel lines with a slope of 0.5 on a log-log scale). Then select a foam that best meets the design criterion.

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1. Exercise units follow the same numbering of the PowerPoint lectures for the same topic [↑](#footnote-ref-1)