5 Projects Using CES EduPack
Projects using CES EduPack

Projects stimulate student interest and create confidence in the use of the methods and software.

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More such projects can be developed using the material contained in the textbook “Material Selection in Mechanical Design” by Prof. Mike Ashby.

*Projects 15, 16, and 17 are courtesy of Dr. Tom Dragone at Orbital Science Corporation,*

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Getting to know CES EduPack software

1. BROWSING materials and process records

Browsing lets you explore records, starting from the content list or “tree”.

Open CES EduPack at Level 1.

1.1 Find the record for the thermoplastic polymer Polycarbonate, PC. What is it used to make? How much does it cost? Is it cheaper than Polypropylene, PP? (Find the record for PP to decide.)

Answer, taken from the record:

Typical uses of polycarbonate, PC
Safety shields and goggles; lenses; glazing panels; business machine housing; instrument casings; lighting fittings; safety helmets; electrical switchgear; laminated sheet for bullet-proof glazing; twin-walled sheets for glazing; kitchenware and tableware; microwave cookware, medical components.

PC is optically transparent, and costs between 3.48 and 3.83$/kg. Polypropylene is cheaper; it costs 1.57 to 1.73 $/kg.

1.2 Find the record for the ferrous metal Stainless steel. What is the value of its thermal conductivity? Is it a better or worse conductor than Aluminum or Copper? (All three are used to make cooking pans.)

Answer, taken from the records:

Thermal conductivity of stainless steel $= 12 – 24$ W/m.K
Thermal conductivity of aluminum $= 76 – 235$ W/m.K
Thermal conductivity of copper $= 160 – 390$ W/m.K

Stainless steel has a much lower thermal conductivity than the other two, so it doesn’t spread the heat as well. You are most likely to burn your cooking in a stainless steel pan. To overcome this, the best stainless steel pans have a copper layer attached to the bottom to spread the heat.
1.3 Find the record for **Borosilicate Glass**, commonly known as Pyrex. What is the value of its “maximum service temperature” (the highest temperature at which it can be used in a product)? What is Pyrex used for?

**Answer**, taken from the record:

Pyrex can be used at temperatures between 230 and 460°C. This makes it suitable for ovenware and cookware.

**Typical uses of Borosilicate glass**
Ovenware, laboratory ware, piping, lenses and mirrors, sealed beam headlights, tungsten sealing, bells.

1.4 Find the records, first for **Titanium alloys** and then for **Aluminum alloys**.
Which has the higher tensile strength? Which has the lower density?

**Answer**, using data read from the records:

Titanium alloys are much stronger than aluminum alloys:

- Tensile strength of titanium alloys: up to 1630 MPa
- Tensile strength of aluminum alloys: up to 550 MPa

(The strength depends on how much it is alloyed and whether it has been worked – rolled or forged.)

Aluminum alloys are much lighter than titanium alloys:

- Density of titanium = 4400 – 4800 kg/m$^3$
- Density of aluminum = 2500 – 2900 kg/m$^3$

(Titanium is also much more expensive, so it is only used when its enormous tensile strength is really needed.)

1.5 Find the records, first for the composite **CFRP** (Carbon-fiber reinforced polymer). It is in the family HYBRIDS, under Composites. What is CFRP used for? Is it denser or less dense than **Magnesium**? Click on the ‘ProcessUniverse’ link at the bottom of the CFRP record to find processes that can shape, join, or finish CFRP. Can CFRP be shaped by Water-jet cutting? (Double click on any name in the list to expand the list and see the records.)

**Answer**, taken from the record:

**Typical uses of CFRP**
Lightweight structural members in aerospace, ground transport and sporting goods; springs; pressure vessels.

The density of CFRP is 1500 – 1600 kg/m$^3$
The density of Magnesium is 1740 – 1950 kg/m$^3$, so it is a little denser than CFRP.

**Processes for CFRP**: yes, water jet cutting is in the list of linked processes. (Shaping ➔ Machining ➔ Non-conventional Machining ➔ Water Jet Cutting)
Now switch from the ‘MaterialUniverse’ to the ‘ProcessUniverse’ by changing the Browse table, using the box below the word Browse.

1.6 Find the Composite shaping record for Filament winding, a way of making high quality composite structures. What are its typical uses?

**Answer**, taken from the record:

**Typical uses of filament winding**
Tanks, pipes, tubes, pressure vessels, drive shafts, wind turbine blades, rocket noses, tubing for lightweight bicycles and space-frames.

1.7 Find the shaping record for Injection molding, one of the most commonly used of all polymer shaping processes. Find materials that can be injection molded by clicking on the LINK button, labelled ‘MaterialUniverse’, at the bottom of the record. Can Polyethylene be injection molded? (Double click on any name in the list to see the record.)

**Answer:**
Yes, polyethylene can be injection molded.

1.8 Find the shaping record for Die casting, one of the most-used ways of shaping metals. What sort of products are made by die casting?

**Answer**, taken from the record:

**Typical uses of Die casting**
Record player and video player chassis, pulleys and drives, motor frames and cases, switch-gear housings, housings for small appliances and power tools, carburettor and distributor housings, housings for gearboxes and clutches.
2. SEARCHING

Searching lets you pull up any record that contains the word or word-string you enter in the search box. It is really useful when you only know the trade name of a material or process, or when you want to search for materials that are used to make a particular product.

2.1 Find the record for Plexiglas by searching. What is its proper name? Can it be injection molded? (Click on the ‘ProcessUniverse’ link at the bottom of the record to find out.)

**Answer:**

The chemical name for Plexiglas is Polymethyl methacrylate (PMMA) or simply Acrylic. It is the stuff of auto tail lights and contact lenses.

Yes, it can be injection molded.

2.2 What is Gore-Tex made of?

**Answer:**

Gore-Tex is Polytetrafluoroethylene, PTFE for short, but also known as Teflon.

2.3 What are spark plugs made of? Search on the name and find out.

**Answer:**

Searching on spark plug gives three records:
- **Alumina** (aluminum oxide) – it is used to make the insulator.
- **Aluminum nitride** – it is used to make the insulator for specialty spark plugs.
- **Tungsten** – it is used for the electrode that makes the spark. It gets very hot, so only metals with high melting points such as tungsten, nickel alloys, and platinum will do.
2.4 Search on cutting tool to find materials that are used to make industrial cutting tools. You will find that some are metals, but others are ceramics – hard ceramics are good because they don’t wear, but they are expensive and hard to make.

**Answer:**
Cutting tools are made from
- high carbon steel or stainless steel (the usual choice for knives and scissors).
- the ceramics: alumina, silicon nitride, zirconia, or tungsten carbide (circular saws often have tungsten carbide cutting teeth, and drills for drilling stone, glass, and masonry have tungsten carbide tips).

2.5 Find what the process RTM is all about by searching on RTM. Since it is a process, not a material, you will have to change the table in which you search from ‘MaterialUniverse’ to ‘ProcessUniverse’, in the box immediately below the search box.

**Answer:**
Three records appear, two of which are for Resin transfer molding, RTM for short. It is a way of making composites by laying glass or carbon fiber in a mold and then squirting in liquid resin and hardener. The third is for Vacuum-assisted resin transfer molding, a variant of RTM in which the mold is evacuated before the resin is let in to stop bubbles of air getting trapped.

2.6 Find what the process SLS is all about by searching on SLS. Since it is a process, not a material, you will have to change the table in which you search from ‘MaterialUniverse’ to ‘ProcessUniverse’, in the box immediately below the search box.

**Answer:**
Four records appear. All are for rapid prototyping processes in which a computer-controlled laser beam is used to sinter (fuse together) a powdered metal, polymer, or ceramic to make a prototype of an object. The letters SLS stand for Selective laser sintering.
3. SELECTING materials and process records

There are three selection tools: GRAPH, LIMIT, and TREE. We will start with the LIMIT STAGE tool. It lets you find materials or processes that meet requirements that you enter in a Limit Stage. To do this, set CES EduPack to select from Level 1 Materials (choose ‘Edu Level 1: Materials’ from the drop-down list). Then click on the Limit button, as shown in the figure.

3.1 Find materials that cost less that $1/kg and are good electrical conductors. Enter the upper limit on Price and the constraint that the material must be a good conductor, as shown in the figure. Then click APPLY at the top of the Limit window. The materials that do not meet the constraints are removed from the RESULTS window on the lower left, leaving those that do.

Answer:

The figure shows how the limits are applied. Only ferrous metals survive. The Results window looks like this:

Results: 6 of 67 pass
- Cast iron, ductile (nodular)
- Cast iron, gray
- High carbon steel
- Low alloy steel
- Low carbon steel
- Medium carbon steel

3.2 The property Fracture toughness is a measure of how well a material resists fracture. A brittle material like glass has a low value of fracture toughness – around 1 in the units you will use (MPa.m$^{1/2}$). Steel used for armour has a very high value – over 100, in the same units. Many engineers, when designing with metals, avoid material with a toughness less than 15. Use a Limit stage to find materials with a fracture toughness greater than 15 and that are good electrical insulators.

Answer:

Not many materials combine these properties. Apply the lower limit on Fracture toughness and then check the box for the electrical property Good insulator. This leaves just one material in the Results window. It is GFRP – glass fiber reinforced plastic.
Now we'll do a GRAPH STAGE. It lets you plot properties and select those materials that lie in a chosen part of the plot.

Delete the Limit stage (right-click on the stage name and select “Delete”).

3.3  If you want to make a high-quality cooking pan to go on the top of a gas stove, you need a material with a high thermal conductivity. The high conductivity is to spread the heat, preventing hot-spots where the flame hits the pan. The material must have enough Elongation to be shaped to a pan (requiring elongation > 15%), and a Maximum service temperature of at least 150°C. First make a Limit stage and put these (lower) limits on elongation and maximum service temperature. Then make a graph with thermal conductivity on the Y-axis. To do this, click on the Graph button, as in the figure. On the Y-axis tab, find Thermal conductivity in the Attribute list and click to select it. When you click OK you get the graph shown. Use a Box selection (the little box icon in the toolbar just above the graph) to select the materials with the highest thermal conductivities.

Answer:

The limits on elongation and maximum service temperature reduce the number of materials in the Results window from 67 to 15 – they are the ones that are still colored in the graph. The ones with the highest thermal conductivity are the ones at the top of the graph – copper and aluminum. They are the best choice. Note that cast iron and stainless steel have conductivities almost a factor 10 lower than copper – they do not spread the heat nearly so well.
Now we'll do a TREE STAGE. A Tree stage is essential if you want to find materials that can be processed in a particular way, or you want to limit the selection to just one class of material – just metals, for instance. To make a Tree stage, click on the Tree button. This gives a window in which you can select the part of the MaterialUniverse or of the ProcessUniverse that you want to explore.

3.4 You want to make a casing for a mobile phone, exotic in color and design. It snaps onto the front of the phone, transforming it from a drab object to one of splendor. Research reveals that the shape is best made by Thermoforming (a very cheap process for shaping polymer sheet into dished and curved shapes) and that the decoration is best applied by In-mold decoration that can be done at the same time as the thermoforming. Find materials that can be processed in this way.

To do this, make two Tree-selection stages. Start in the way shown in the figure. That brings up the Tree Stage wizard. Under the word Trees, half-way down the box, it says ‘MaterialUniverse’. We want to impose constraints on processes, so first click on the down-arrow and change the Tree to ‘ProcessUniverse’. Open Shaping and find Molding – Thermoforming and click ‘Insert’ or double click to make it appear in the box below. The wizard window now looks like the one to the right (we have closed Shaping again for clarity). Click OK and the number of materials in the Results window drops to 17 – these are materials that can be thermoformed. Repeat the job with a second, new, Tree stage, this time opening Surface treatment and choosing Painting and Printing – In mold decorating. The Results window now lists materials that can both be thermoformed and in-mold decorated.

Answer:

The final Results window looks like this. At this stage it would make sense to add another stage to find the cheapest one (a graph of Price would do it).

Results: 9 of 67 pass
Acrylonitrile butadiene styrene (ABS)  Polyoxyymethylene (Acetal, POM)
Cellulose polymers (CA)  Polystyrene (PS)
Polycarbonate (PC)  Polvynil chloride (tpPVC)
Polyetheretherketone (PEEK)  Polyethylene terephalate (PET)
Polymethyl methacrylate (Acrylic, PMMA)
Projects that don’t use indices

Project 1. Filament for a light bulb

Background
A headlight is an essential part of an automobile. Headlights differ in detail, but all have a bulb containing a filament enclosed in a transparent envelope. The filament is exposed to harsh conditions: very high temperature, vibration and a risk of oxidation. The goal of the project is to use CES EduPack to select a material for the filament.

Objective
To select a material that meets the requirements for the filament.

Requirements
- Must be a good electrical conductor
- Must tolerate temperatures up to 850°C
- Must have the highest possible melting point

Set CES EduPack to select ‘Edu Level 2: Materials with durability properties’. Use a Limit stage to apply the first two requirements, then a Graph stage of melting point to find the material with the highest value that also meets the first two requirements.

Remember materials on the graph that do not meet the Limit stage criteria are “grayed-out” by default. You can switch this on and off by clicking the little icon like two intersecting circles in the row of icons along the top of the graph.
Notes for instructors

Open CES EduPack at Level 2. Click on Select. Select from ‘Edu Level 2: Materials with durability properties’. The Results window in the lower left of the screen displays all 98 materials since none have yet been eliminated. Under the Selection Stages heading, click on the Limit button. In the Limit stage select ‘Electrical properties’ and choose the option “Good conductor”, as in the figure on page 8. Click Apply at the top of the window – this eliminates 71 materials from the Results, leaving 27. Now, in the same Limit stage, go to ‘Durability: thermal environments’ and find “Tolerance up to 850 C (1562 F)” – select “Excellent” and Apply. The number of materials in the Results window falls to 3. It now looks like this:

Now make a Graph stage to plot melting point (Under the Selection Stages heading, click on the Graph button). In the Graph Stage Wizard on the Y-axis tab, select Thermal properties / Melting point. A graph with all the materials in the database is displayed, ranking materials by their melting point with the highest at the top left, as in the second figure. Use the Box selection tool (a square box, in the row of icons just above the graph) to select materials near the top of the graph, and drag the box up until only one material is left in the Results window. It is the one that satisfies the first two requirements and has the highest melting point. The result is Tungsten alloys.
Project 2. Automotive headlight lens

Background
The lens of an automobile headlamp protects the bulb and reflector and focuses the light where it is most needed. The project is to use CES EduPack to select materials for the lens.

Objective
To select materials that meet the requirements for the lens.

Requirements
- Must be transparent with optical quality
- Must be able to be molded easily (4 to 5)
- Must have good durability in fresh and salt water
- Must have good durability to UV radiation
- Good abrasion resistance, meaning a high hardness
- Low cost

Set CES EduPack to select ‘Edu Level 2: Materials with durability properties’. Use a Limit stage to apply the first four requirements, selecting Optical properties to apply the first, Processability to apply the second, ‘Durability: water and aqueous solutions’ to apply the third (select both “Acceptable” and “Excellent” to avoid eliminating too many materials), and ‘Durability: Built environments’ the fourth (select both “Good” and “Excellent” to avoid eliminating too many materials). Then make a Graph stage with Price on the X-axis and Hardness on the Y-axis to find the ones that are cheap and have high hardness.

(Remember that you can hide materials on a Graph stage that have failed previous limits by clicking on the two icons that look like this at the top of the graph.)
Notes for instructors

The procedure is the same as that for Project 1. Open CES EduPack at Level 2. Click on Select. Select from ‘Edu Level 2: Materials with durability properties’. The Results window in the lower left of the screen displays all 98 materials since none have yet been eliminated. Under the Selection Stages heading, click on the Limit button. The upper figure shows the first two requirements – that for optical quality transparency and for good moldability – entered in the Limit stage. The next two are Durability properties. They are entered in the same way, checking “Excellent”, and “Good” or “Acceptable”. When these limits have been entered, click Apply. Only three materials survive. The Results window now looks like this:

Now the Graph stage to explore hardness and price. As in Project 1, under the Selection Stages heading, click on the Graph button. In the Graph Stage Wizard on the Y-axis tab, find Hardness - Vickers in the Attribute list, and click on it to put it on the Y-axis. Then switch to the X-axis tab, find Price in the Attribute list and click on it to make it appear in the X-axis. When you click OK the graph shown in the lower figure appears. We have labeled the three materials in the Results box above by clicking on them, and have moved the axes a little to make it more readable – if you want to do that double click on the axis label on the graph (e.g. on Hardness) bringing up a wizard that lets you adjust the axes. The part of the graph we want is the upper left corner, where the selection box is shown. The cheapest and hardest material that meets all the constraints is soda-lime glass – it is used for car headlights. If a polymer is wanted, the cheapest one is PMMA, acrylic – it is used for car tail lights.
Project 3. Novel guitar case (guitar plus amplifier)

Background
Guitars are delicate instruments. They need a case to protect them when moved, and if they are electric, they need an amplifier and speaker and they too have to be moved and protected. The mission is to simplify this protection problem by designing a case that will hold and protect both the guitar and the amplifier plus speaker, using the case itself as the speaker cabinet and amplifier case.

Objective
To select materials and process method to make a case for guitar and amplifier.

Requirements
- Must be tough – the rule of thumb here is that the fracture toughness should be greater than 15 in the usual units (MPa.m$^{1/2}$)
- Must be moldable
- Good durability in fresh and salt water
- Must be light
- Should not cost too much
The procedure is the same as that for Project 1. Open CES EduPack at Level 2. Click on Select. Select from ‘Edu Level 2: Materials with durability properties’. Use a Limit stage to apply the first three requirements, selecting Mechanical properties to apply the first, Processability to apply the second, and Durability: water and aqueous solutions to apply the third. Then make a Graph stage with Price on the Y-axis and Density on the X-axis to find out which of the survivors is the cheapest, and which the lightest.

Remember that you can hide materials on a Graph stage that have failed previous limits by clicking on the two icons that look like this at the top of the graph.

Notes for instructors
The procedure is the same as that for Project 1. The upper figure shows the first two requirements – that for Fracture toughness and for good moldability – entered in the Limit stage. When the requirements of “Excellent” or “Acceptable” durability in fresh and salt water are added (and you click on Apply at the top of the Limit Stage window) the Results window shows just two materials that meet the constraints:

3. Results: 2 of 98 pass
Show: Pass all Stages
Rank by: Alphabetical

Name
- CFRP, epoxy matrix (isotropic)
- GFRP, epoxy matrix (isotropic)

Lightness and cost can be examined simply by opening the record and looking up the density and price (both are under General Properties), or by making a Graph Stage of these two properties, like that shown. It shows that carbon fiber reinforced plastics (CFRPs) are a little less dense, and thus lighter, than glass fiber reinforced plastics (GFRPs), but considerably more expensive. The final decision depends on whether this is to be a cheap case or an up-market, high quality, minimum weight case.
Project 4. Design a CD case that doesn’t crack or scratch CDs

**Background**  The standard CD (“Jewel” case) cracks easily and, if broken, can scratch the CD. Jewel cases are made of injection molded polystyrene, chosen because it is transparent, cheap, and easy to mold.  **The project:** redesign the case and choose a material for it. The redesign might be a minor refinement of the standard 3-part design, a new shape (circular instead of square?), or a single part molding with a natural hinge, linking lid to case.

**Requirements**
- Optical properties: transparent or optically clear
- Fracture toughness better than polystyrene (get data for PS from its record)
- Young’s modulus not too different from polystyrene (to make sure the case is stiff enough)
- Able to be injection molded (use the ‘tree’ selection stage)
- Cost not more than twice that of polystyrene

Applying these using either the Level 1 or Level 2 database gives PMMA (acrylic) and PET as possible alternatives. Both are perfectly sensible choices.

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Project 5. Materials for knife-edges and pivots

**Background**  Precision instruments like clocks, watches, gyroscopes, and scientific equipment often contain moving parts located by knife-edges or pivots. The accuracy of location is limited by the deformation of the knife-edge or pivot and the mating surface. Elastic deformation is minimized by choosing materials with high Young’s modulus; plastic deformation is limited by choosing materials with high hardness.

**Requirements**
- Young’s modulus as large as possible
- Hardness as large as possible

The best way to tackle this using the Level 1 database is to make a Graph stage of Young’s modulus and Hardness and pick the materials with high values of both. The very best are all ceramics: boron carbide, silicon carbide, and tungsten carbide. If the selection box is relaxed so that the first metals appear, the selection picks up high carbon steel and low alloy steel. All are sensible choices: the ceramics when the ultimate precision is required, the steels when robust design able to deal with shock loading is needed.
Project 6. Materials for heat sinks for power electronics

**Background** The power density of present day computer chips is such that removing the heat generated in them is a major consideration. The chip is attached to a heat sink that conducts the heat from the chip to a set of fins cooled by fan-driven airflow. The heat sink must conduct heat well, be able to operate continuously at 150°C, and be electrically insulating.

**Requirements**
- **Electrical properties**: good insulator
- **Maximum service temperature**: > 150°C (423 K)
- **As large a thermal conductivity** as possible

Applying this using the Level 1 database, using a Graph stage to plot thermal conductivity and selecting materials with the largest value gives aluminum nitride – the favored material for heat sinks. (Remember that you can hide materials on a Graph stage that have failed previous limits by clicking on the two icons that look like this \[x\] at the top of the graph.)

Project 7. Materials for a fresh-water heat exchanger

**Background** Heat exchangers, typically, consist of a set of tubes through which one fluid is pumped, immersed in a chamber through which the other fluid flows; heat passes from one fluid to the other. The material of the tubing must conduct heat well, have an maximum operating temperature above the operating temperature of the device, not corrode in the fluid, and – since the tubes have to be bent – have adequate ductility.

**Requirements**
- **Maximum service temperature**: > 150°C (423 K)
- **Elongation**: > 20%
- **Durability in fresh water**: Excellent
- **As large a thermal conductivity** as possible.

Applying this using the Level 2 database (necessary because Level 1 doesn’t have corrosion resistance), using a Graph stage to plot thermal conductivity and selecting materials with the largest value gives copper and non age-hardening wrought aluminum alloys. Both are used for heat exchangers.
Projects that offer greater challenge

Project 8. Cork extractors

Background

Wine improves with age, and deteriorates when exposed to air. This creates for the need for a way of storing it in some sort of protective environment. One solution – now at least 2000 years old – is to store it in glass bottles sealed with a cork. The cork is derived from the bark of an oak tree, common in Mediterranean countries: *Querqus Suber*. Storing it in this way creates a second need – that for a device to extract the cork.

The figure shows one solution. There are three main structural elements.

- A shaft, shaped to a screw at the lower end, with ring-like teeth in the middle and a handle at the top. It carries axial loads.
- A pair of simple levers with toothed ends that engage with the ring-like teeth of the shaft. The levers carry bending moments, and the teeth, contact loads.
- A casing, carrying simple bearings for the levers, but with a complex 3-dimensional hollow shape. It carries small compressive loads.

The project

- Examine cork extractors of this type, choosing more than one if different designs are available (there are several on the market – some work well; one, at least, is a disaster).
- Analyze them, simplifying the mechanics as far as possible, to establish approximate axial loads, bending moments, and contact pressures.
- Select materials and minimum sections for each component, and processes to make them, using the methods developed in the Lectures.
- Compare your selection with the materials and processes used for the real corkscrews, commenting on the criteria (particularly the objectives and constraints) that appear to have been used in selecting them. Remember that these can be purely practical, relating to function and cost, or aesthetic, relating to way in which the consumer perceives the product.
- Present the case for your choice of material and process as a report, using data or charts from CES EduPack and from any other sources you have used to explain your reasoning.
Notes for Instructors: Project 8, Cork extractors

Real corkscrews

- One successful corkscrew of this design uses a zinc alloy die-casting for the casing, lever, and the upper end of the shaft; a machined steel screw, thin at the tip but progressively thicker towards the shaft, is threaded into the lower end of the shaft to give it adequate strength.

- A cheaper model has a molded polypropylene casing and a one-piece die-cast zinc shaft and screw. In our tests the casing flexed alarmingly and the shaft broke part way down the screw the third time the corkscrew was used.

- Still other designs use a bent steel wire screw force-fitted into the lower end of a die cast shaft. The wire screw tended to unwind (by plastic bending) during insertion into the cork.

Design requirements

Here are some orders of magnitude

- A first guess: the stresses are probably small (wrong, as it turns out — they are not huge, but not small). The most important thing may be the ability to make the shapes economically in large batches (100,000 or more). One way to start is to search for processes that can make 3-D shapes with an economic batch size exceeding 100,000. Then use the processes found in this way as constraints on the choice of material (i.e. insist that the material must be capable of being shaped by one of these using the Tree stage facility).

- The axial screw must carry tensile loads as high as 500 N on a cross section of about 10 mm$^2$ in the solid part of the shaft, and 3 mm$^2$ in the screw, giving stresses of order 50 and 150 MPa respectively. These tensile stresses generally exceed the stresses induced by the twisting action when the screw is driven into the cork.

Function

- Shaft — a tensile member

Constraints

- Must have tensile strength > 50 MPa in the solid shaft and > 150 MPa in the screw (it is a good idea to introduce the idea of a safety factor, use a factor of 2)
- Must have adequate toughness ($K_{ic} > 15$ MPa.m$^{1/2}$ is a rule of thumb used by many engineers for structural components)
- Must be able to be shaped to the form shown in the diagram

Objective

- Depends on the market (one could imagine solid silver corkscrews). Try minimizing material cost. Try a graph of material cost and melting point — if the part is to be cast or molded, a lower melting point allows faster, cheaper processing.

Free variables

- Choice of material and process
- Choice of area for cross-section, within limits

Function

- Lever — a beam loaded in bending

Constraints

- Must carry moment of 5 N.m without failure or excessive deflection
- High hardness to withstand wear of teeth (Say $H_v > 100$ Vickers)
- Ability to be shaped (see comments above)

Objective

- Minimize cost: economies are made by using the same process for all parts if possible

Free variables

- Choice of material and process
- Choice of section area and shape
The casing carries compressive loads of 500 N but because of its larger section (50 mm² or more giving stresses of order 10 MPa), strength is not the main problem. The challenge is to find a material compatible with a process that can make the shape.

**Function**
- *Casing – a hollow tube loaded in compression*

**Constraints**
- *Must carry tensile strength $\sigma_{ts} > 10$ MPa*
- *Be compatible with a process that can make 3-D hollow shapes economically at a batch size of 100,000*

**Objective**
- *Minimize cost*

**Free variables**
- *Choice of material and process*

It is instructive, in an advanced project, to create a spreadsheet for the manufacturing cost of the three components, summing them to give a final product cost. The equations necessary to do this are contained in UNIT 4.

**Resources for the student**
- Cork extractors: the type illustrated in the figure can be found with casings made of die-cast zinc alloy, injection molded polypropylene, and with shafts of steel or of zinc alloy
- Corks
- One or more of the documents listed under “Reading”
- The booklet “Useful Approximate Solutions for Standard Problems” that appears as Appendix A of the text “Materials Selection in Mechanical Design” or can be downloaded from the Granta website
- Access to CES EduPack software, set initially to Level 1 or 2

**Reading**

**The Web**
A search on CORKSCREW HISTORY using Google gives interesting returns.
Project 9. Bicycle frames

**Background**  The principal components of the bike are familiar and their function needs no explanation. The largest of these is the frame. Frames can be made from a remarkable diversity of materials: carbon steel, alloy steel, aluminum alloys, magnesium alloys, titanium alloys, GFRP, CFRP, nylon, and even wood. How is it that such diversity can co-exist in a free market in which competition favors the fittest – surely there must be a single “best” material for bicycle frames?

The mistake here is to suppose that all bikes have the same purpose. The specification of a “shopping” bike is very different from that of one for speed or for mountain biking, as are the objectives of the purchaser.

**The project** is to explore materials and process selection for bike frames (illustrated), or for any other component of the bike: handle bars, cranks, wheels...

- Analyze the chosen component, listing its function, the constraints it must meet, and the objectives – this requires a decision about the type of bike you are designing (shopping, speed, mountain, folding, child’s…). Remember to include a lower cut-off constraint on fracture toughness ($K_{IC} > 15 \text{ MPa.m}^{1/2}$ is a good rule of thumb) – a brittle bike would not be a good idea.
- List the requirements as Function, Constraints, Objectives and Free Variables.
- Identify the Material Indices you will use to select materials.
- Use the methods of UNIT 2 to identify promising material for the component.
- Make a choice of material and then use CES EduPack Joining database to select ways of joining the frame.
- Reverse the reasoning to work out the constraints and objectives that were priorities for the designer of (a) a titanium bike and (b) a wooden bike.
- Present the case for your choice of material and process as a report, using data or charts from CES EduPack and from any other sources you have used to explain your reasoning.
Notes for instructors: Project 9, Bicycle frames

This is a project that can be run at many different levels. The simplest is outlined on the accompanying project sheet. It can be extended to include aspects of shape and of trade-off between mass and cost.

Some points to bear in mind:

- The forks and cranks of a bike carry bending moments. The spokes and brake cables carry tension. The tubular frame of a bike carries bending, torsion, and axial loads – the bending moments are usually the most severe.
- The design-load must take account of impact – riding the bike off a curb, for instance – when decelerations of 10G are possible. A lower limit of 15 MPa.m\(^{1/2}\) on fracture toughness is essential.
- A mountain bike is strength-limited, but stiffness is important too – a bike that is too stiff gives a harsh ride. In bikes for sprint events, stiffness can be the most important consideration – excessive flexing of the frame dissipates energy. Stiffness and strength are constraints, not objectives (they must meet specified values). Objectives, usually, are mass and cost (for these a minimum is sought).
- The books by Sharp and by Witt and Wilson are good on bike mechanics. Oliver is good on materials.
- Typical specification for the forks of a cheap street bike. The fork is modeled as a tube loaded in bending.

The selection is made by using the appropriate Material Index. That for a tube of specified bending strength and minimum cost is

\[
M_1 = \frac{C_m \rho}{\sigma_y}
\]

if the outer diameter of the tube is fixed and the wall thickness is the free variable. A Graph stage of elastic limit \(\sigma_y\) against material cost per unit volume \(C_m \rho\) (where \(\rho\) is the density), with a \(K_{IC} > 15 \text{ MPa.m}^{1/2}\) imposed using a Limit stage allows materials with low values of \(M_1\) to be found. The selection using the Level 1 database gives steels and cast iron. Cast iron cannot be drawn to thin-walled tube. It is eliminated if a further constraint on elongation > 40% is added, but common sense is probably enough to suggest that steel is the best choice.

The selection is made by using the appropriate Material Index. That for a tube of specified bending strength and minimum mass is

\[
M_2 = \frac{\rho}{\sigma_y}
\]

if the tube diameter of the tube is fixed and the wall thickness is free. A Graph stage of elastic limit \(\sigma_y\) against material density \(\rho\), with a \(K_{IC} > 15 \text{ MPa.m}^{1/2}\) imposed allows materials with low values of \(M_2\) to be found. The selection using the Level 1 database gives CFRP, Magnesium alloys, and Titanium alloys.

- The dominant constraint for a sprint bike is probably that of stiffness (at minimum mass), found using the indices

\[
M_3 = \frac{\rho}{E}
\]

or

\[
M_4 = \frac{\rho}{E^{1/2}}
\]

depending on whether the tube diameter is fixed and the wall thickness is free, or the other way round.

<table>
<thead>
<tr>
<th>Function</th>
<th>Forks – a hollow tube loaded in compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td>Strength specified</td>
</tr>
<tr>
<td>Fracture toughness &gt; 15 MPa.m(^{1/2})</td>
<td></td>
</tr>
<tr>
<td>Objective</td>
<td>Minimize cost</td>
</tr>
<tr>
<td>Free variables</td>
<td>Tube wall thickness</td>
</tr>
<tr>
<td>Choice of material</td>
<td></td>
</tr>
</tbody>
</table>
That for a toddler’s tricycle might be that of ease of manufacture at minimum cost, favoring a polymer molding method, and requiring a material that can be rotation or compression molded, found using a Tree selection stage.

### Resources for the student

- Access to bicycles and bicycles shops
- One or more of the documents listed under “Reading”
- The booklet “Useful Approximate Solutions for Standard Problems” that appears as Appendix A of the text “Materials Selection in Mechanical Design” or can be downloaded from the Granta website
- Access to CES EduPack software, set to Level 1, 2, or 3, depending on the ambitions of the project

### Reading


Current magazines detailing bicycles.

### The Web

A search on BIKE DESIGN using Google gives interesting returns. Try [http://materials.npl.co.uk/IOP/TheBike.html](http://materials.npl.co.uk/IOP/TheBike.html)
Project 10. Disposable cutlery

Background If you eat at expensive restaurants, the knives have steel blades and ivory handles, and the forks and spoons are made of silver. But if you eat at a local self-service or on an airplane the same function is fulfilled by disposable plastic cutlery. The function is unchanged; but the objectives, clearly, are different: minimizing cost and – you might hope – maximizing recyclability or renewability. Filling the function imposes constraints on material and shape: the plastic fork that snaps in half the first time you use it is only too familiar. Minimizing cost makes choice of process critical, and the material itself must also be cheap.

The project is to investigate the choice of material and process for disposable cutlery.

- Gather as many different sorts of disposable cutlery as possible. Look out for diversity of material – disposable knives and forks come in plastic, metal, and indigenous materials.
- Find out as much as you can about what they are made of and how they were made (look out for recycling marks, parting lines of molds, injection-molding points and the like).
- Design your own knife and fork, and select material and process to make it. Analyze the mechanics of a fork. In use it is loaded in bending. Measure typical use-forces, decide on acceptable deflections, breaking loads and dimensions, and thus calculate the minimum modulus and strength for the material of which it is to be made.
- Use CES EduPack, Level 2, to explore materials and processes for the fork. Aim for a product cost of no more than 3 pence (4.5 cents) per unit.
- Present the case for your choice of material and process as a report, using data or charts from CES EduPack and from any other sources you have used to explain your reasoning.
Notes for instructors: Project 10, Disposable cutlery

Here are some broad indicators and suggestions

• In use the fork is loaded as a cantilever in bending. The use-load is of order 2 N. If an end deflection of 10 mm (!) is acceptable, the required bending stiffness, $S$, is 200 N/m. The deflection of a cantilever of length $L$ (from Ref 1, Appendix A.3 p. 479) is

$$S = \frac{3E I}{L^3}$$

where $E$ is the modulus and $I = b t^3/12$ the second moment of area. Taking length $L = 80$ mm, thickness $t = 3$ mm and width $b = 10$ mm gives $I = 20 \times 10^{-12}$ m$^4$ (using data for prong thickness and width from a typical fork) puts a limit on $E$ of 1.7 GPa. A similar calculation for failure strength uses the expression (from Ref. 1, Appendix A.4, p. 481)

$$F \left( \frac{L}{t/2} \right) \sigma_f$$

where $F$ is the use-load load and $\sigma_f$ is the failure strength of the material of which the fork is made (take it to be the same as the tensile strength). This gives a required tensile strength of 12 MPa. Safe design requires a safety factor – take a value of 2.

• A typical disposable fork weighs about 10 g (students should measure this for themselves). If the material cost exceeds 1 pence (1.5 cents) it will be hard to meet the cost-target. This imposes a material cost limit of around £1 ($1.5) per kg.

• Processing cost is critical. A high-speed net-shape process with no finishing is essential.

• This gives the following approximate design requirements:

<table>
<thead>
<tr>
<th>Function</th>
<th>Disposable fork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td>Modulus $E &gt; 1.7$ GPa</td>
</tr>
<tr>
<td></td>
<td>Tensile strength $&gt; 24$ MPa</td>
</tr>
<tr>
<td></td>
<td>Material cost $&lt; 1.8$/kg</td>
</tr>
</tbody>
</table>

Choosing thermoplastic injection molding as the process gives material selection of Polystyrene (PS), Polyethylene terephthalate (PET), or Polyvinylchloride (PVC), all of which are recyclable.

• Students should be encouraged to explore how shape can be used to increase stiffness and strength without increasing the amount of material that is used (Lectures, UNIT 6).

• Students should be encouraged to explore recyclability issues. (see below).

Resources for the student

• Disposable cutlery

• The booklet “Useful Approximate Solutions for Standard Problems” that appears as Appendix A of the text “Materials Selection in Mechanical Design” or can be downloaded from the Granta website

• Access to CES EduPack software, set to Level 2 so that the process cost model can be used and material Environmental notes are available

References


The Web

A search on DISPOSABLE CUTLERY using Google gives surprisingly rich returns. A perspective on the recycling issues can be found by exploring [http://www.recycle.net/recycle/Plastic/](http://www.recycle.net/recycle/Plastic/)
Project 11. Containers for liquid drinks

Background  A quick scan of a supermarket will reveal drinks packaged in polymers, in glass, in aluminum, or steel cans, and in cartons made of paper laminated with plastic and metal. All are disposable, so they must be cheap (though many cost more than the drink they contain), and since they make up nearly 10% of all household waste, it is desirable that they can be recycled. A container must provide leak free containment, be non-toxic, and allow access to the liquid inside when it is wanted.

One might think that there should be a single, best material and shape for a drink container, yet containers co-exist that are made from at least 6 totally different materials, and in many different shapes. Why is this?

The project is to investigate the choice of material and process for drink containers.

- Gather as many different sorts of container as possible. Identify the difference in the design requirements between them. What constraints are different? What objectives?
- Identify the materials of which they are made and the processes used to make them (look out for recycling marks, parting lines of molds, and the surface process used to decorate them).
- Use CES EduPack to find materials for containers. You can start by simply searching on “Bottle” or any other word you think might be relevant. Then formulate a specification based on the necessary constraints and objectives (remember that ease of shaping is a very important constraint – the material must be compatible with a process suitable for making drink containers).
- Once you have chosen a material and process, explore joining (if this is necessary) and surface finishing – how will the decoration, coloring or printing be done? The Joining and the Surface Treatment data tables in CES EduPack will help here.
- Present the case for your choice of material, process and end-of-life treatment as a report, using data or charts from CES EduPack and from any other sources you have used to explain your reasoning.
Notes for instructors: Project 11, Containers for liquid drinks

Real containers

- Common containers are made of PET, HDPE, aluminum, steel, glass, and various paper-based laminates. CES EduPack has records for all of these except laminated paper at both Levels 1 and 2. ‘Level 2 with Eco properties’ has **Embodied energy, primary production** (the energy consumed in creating 1kg of material from ore or feedstock), **Environmental notes** for materials and processes, and **Recycle marks** for polymers, useful in this project.

- The diversity of materials and arises for a number of reasons:
  - Gassy drinks require that the container can withstand an internal pressure; still drinks do not.
  - Some drinks are acidic (particularly Coca Cola, which is full of phosphoric acid); others are alkaline (milk, for instance).
  - Some containers allow the contents to be seen; others do not.
  - Those with a square or rectangular section can be stacked more closely than those with a circular section; and for some the shape is further constrained by the need to fit the door-shelf of a domestic refrigerator.

- There are several ways to get into this project using CES EduPack. The simplest is to use the SEARCH facility to search on BOTTLE, BEVERAGE, CONTAINER etc. – if that word appears in a record it will be recovered. A second is to identify processes that can make containers (blow molding, for instance), isolate the materials that can be formed in this way (a Tree stage), then make a graph of Strength against Price and select the cheapest materials that can be blow molded and have reasonable strength.

- Once materials and shaping processes have been identified (and – if the student is given a specific goal such as a container for orange juice – a specific choice is made), ways of joining and finishing the container should be explored using CES EduPack Joining and Surface Treatment data tables.

- Finally, an in-depth study of use-pattern, possibility of reuse, recycling issues and other disposal routes should be made. CES EduPack will help you get started here, but further resources (the library, the Reading listed below and the Web) will be needed.

Resources for the student

- Drink containers
- Literature on Green Design (see below)
- The booklet “Useful Approximate Solutions for Standard Problems” that appears as Appendix A of the text “Materials Selection in Mechanical Design” or can be downloaded from the Granta website
- Access to CES EduPack, set to Level 2 so that the process cost model can be used and material **Environmental Notes** are available

Reading


The Web

The Web is a potential source of information for further specialized information on materials, processes, drink containers, and recycling.
Project 12. Storage heaters (again)

Background  The demand for electricity is greater during the day than during the night. It is not economic for electricity companies to reduce output, so they seek instead to smooth demand by charging less for off-peak electricity. Cheap, off-peak electrons can be exploited for home or office heating by using them to heat a large mass of thermal storage material from which heat is later extracted during peak hours by blowing air at a controlled rate over the hot mass.

Storage heaters also fill another role. When testing re-entry vehicles, it is necessary to simulate the conditions they encounter as they enter the atmosphere – hypersonic airflow at temperatures up to 1000°C. The simulation is done in a wind tunnel in which the air stream is rapidly heated to the desired temperature by passing it over a previously heated thermal mass before passing over the test vehicle.

The project is to identify suitable materials for the thermal mass.

- The heater uses a large mass of storage material – if it is to be economic, the material must be cheap. The objective, then, is to store as much heat per unit cost as possible.

- Model the heat storing material by writing an equation for the heat stored per unit mass in a body with specific heat $C_p$ when heated through a temperature interval $\Delta T$. Divide it by the cost per unit mass of the material. Read off the combination of material properties that maximizes the heat stored per unit cost.

- Identify any other constraints that the heat-storing material must meet, and draw up a specification for selecting it.

- Use CES EduPack Level 1 to select a material for the heat-storing component.

- Design a heat-storing unit capable of providing 500 Watts of heat over a period of 3 hours. How much will it weigh if made of the material you have chosen? What shape should it take? How would you control it?

- If, instead, how were asked to design a storage heater for the hypersonic wind tunnel, with an anticipated run time of 10 seconds and a required gas temperature of 500°C, what changes in material and design would be necessary?
Notes for instructors: Project 12, Storage heaters

Approximate modeling

- The energy stored in a mass $m$ of material with a specific heat $C_p$ when heated through a temperature interval $\Delta T$ is

$$Q = m C_p \Delta T$$

The cost of mass $m$ of material with a cost per kg of $C_m$ is

$$C = m C_m$$

Thus the heat stored per unit cost per Kelvin is

$$\frac{Q}{C \Delta T} = \frac{C_p}{C_m}$$

There is one other obvious constraint: the material must be able to tolerate the temperature to which it will be heated – say 300°C (575 K). The basic design requirements for the heat storing unit is:

<table>
<thead>
<tr>
<th>Function</th>
<th>Heat-storing material for storage heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td>Maximum service temperature &gt; 300°C</td>
</tr>
<tr>
<td>Objective</td>
<td>Maximize the index $C_p / C_m$</td>
</tr>
<tr>
<td>Free variables</td>
<td>Choice of material</td>
</tr>
</tbody>
</table>

Imposing the constraint on service temperature with a Limit stage and selecting materials with high $C_p / C_m$ by plotting a bar chart of this quantity using a Graph stage gives the four materials that best meet these requirements: concrete, stone, brick, and cast iron.

- If the unit is to provide a power of 1 kW over 5 hours (roughly 18,000 seconds) it must store 18 MW, requiring a mass $m$ of

$$m = \frac{18 \times 10^6}{C_p \Delta T}$$

Taking $\Delta T = 300°C$ and a typical value of $C_p$ of about 1000 J/kg.K gives the very considerable mass of 60 kg. Clearly minimizing the mass as well as the cost is desirable. It is instructive to make a Graph stage with $C_p / C_m$ on the Y-axis and $m$ (using the equation above) on the X-axis (use the Advanced option in a Graph stage to enter the equation). It reveals that concrete, stone, and brick give a unit that is lighter by about half than cast iron.

- The design of the storage element must balance the time over which heat is to be extracted and the thermal diffusion distance. The distance $x$ that heat diffuses in time $t$ is approximately $x = \sqrt{a t}$ where $a = \lambda / \rho C_p$ is the thermal diffusivity of the material – about $10^{-6}$ m²/s for concrete, stone, and brick. This means that the storage unit in the domestic storage heater can be divided into blocks as large as 0.1 m, but that the unit for the hypersonic wind tunnel must be subdivided into units of 3 mm or less, arranged so that the gas can flow around them.

Resources for the student

- The booklet “Useful Approximate Solutions for Standard Problems” that appears as Appendix A of the text “Materials Selection in Mechanical Design” or can be downloaded from the Granta website

- Access to CES EduPack software, set to Level 1 or 2

The Web

A search on STORAGE HEATERS using Google gives lots of information.
Project 13. Housings for electrical plugs

Background  The electric plug is perhaps the commonest of electrical products. It has a number of components, each performing one or more functions. The most obvious are the casing and the pins, though there are many more (connectors, a cable clamp, fasteners, and, in some plugs, a fuse). Power plugs have two or three pins and are robust construction. System plugs, like that of the parallel port on a computer, have 25 or more pins and are miniaturized and delicate, placing more importance on the mechanical as well as the electrical properties of the materials.

The project is to investigate materials and processes for the casing of plugs.

- Examining existing plugs, noting the materials and the way they are made.
- Formulate the design requirements for the casing, and list the constraints each must meet. What are the functions of the casing? What properties must the material for them have if the plug is to work properly and safely? If the plug is to be cheap, what limits are imposed on the materials and processes? List these to give a specification for the material, organizing them under the headings Function, Constraints and Objectives.
- Use CES EduPack software to select materials for casings.
- Present the case for your choice of material and process as a report, using data or charts from CES EduPack and from any other sources you have used to explain your reasoning.
Notes for instructors: Project 13, Housings for electrical plugs

At the elementary level the student might be guided towards a material specification such as that listed below.

- The shape for a casing is complicated, and the part will be made in very large numbers. Start by imposing the essential constraints, listed below. The most important are that the material be an insulator and that it is compatible with processes that can make the complex 3-dimensional shape at an economic batch size of \(10^5 \text{ – } 10^6\). The limit on modulus is set at the boundary between rigid polymers and elastomers (1 GPa). It will help to run two investigations in parallel, one selecting the material and one the process, using the results of the one as constraints on the other.

<table>
<thead>
<tr>
<th>Function</th>
<th>Casing for electric power plug</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Good electrical insulator</td>
</tr>
<tr>
<td></td>
<td>Sufficiently stiff (modulus (E &gt; 1) GPa)</td>
</tr>
<tr>
<td></td>
<td>Sufficiently strong (strength (\sigma &gt; 10) MPa)</td>
</tr>
<tr>
<td></td>
<td>Sufficient ductility for fasteners to be screwed in ((\varepsilon_f &gt; 2%))</td>
</tr>
<tr>
<td></td>
<td>Able to be injection molded</td>
</tr>
<tr>
<td>Objective</td>
<td>Minimize part cost</td>
</tr>
<tr>
<td>Free variables</td>
<td>Choice of material (dimensions are not free because the plug must meet certain standards)</td>
</tr>
</tbody>
</table>

What standards must be met in the design of plugs? The Web can help here.

The project can be run at a more advanced level. Here are the real design requirements for the casing of a 25-pin parallel port plug. The Level 3 database allows selection to meet these constraints, giving a list of candidates that can be explored in further depth by searching for them by name (using the SEARCH option) in the CAMPUS database that is available at Level 3.

<table>
<thead>
<tr>
<th>Function</th>
<th>Electrical encapsulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High resistivity: (\rho_c &gt; 10^{19} \mu\Omega\text{cm})</td>
</tr>
<tr>
<td></td>
<td>Tensile strength &gt; 100 MPa</td>
</tr>
<tr>
<td></td>
<td>Tensile elongation &gt; 2%</td>
</tr>
<tr>
<td></td>
<td>Heat deflection temperature &gt; 225°C</td>
</tr>
<tr>
<td></td>
<td>Moisture absorption &lt; 0.35% in 24 hours</td>
</tr>
<tr>
<td></td>
<td>Filler content &gt; 35%</td>
</tr>
<tr>
<td></td>
<td>Able to be injection molded</td>
</tr>
<tr>
<td>Objective</td>
<td>Minimize part cost</td>
</tr>
<tr>
<td>Free variables</td>
<td>Choice of material (dimensions are not free because the plug must meet certain standards)</td>
</tr>
</tbody>
</table>

Resources for the student
- Examples of plugs

The Web
For pure entertainment, try http://www.maztravel.com/maz/explain/plugs.html
Project 14. Microwave dishes

Background What do fast food, airline meals, and instant coffee have in common? That they are all heated by microwaves. To do this they have to be held in a container that must meet certain criteria. It must not absorb microwaves strongly – if it does, it will get hot and the contents (where you would like the heat to be generated) will stay cold. It must be stiff and strong enough to allow the food or drink to be carried and consumed. And, if the container is to be disposable, it must be very cheap.

The coupling of microwaves to materials depends on their dielectric constant $\varepsilon$; and the degree to which this coupling is dissipative is measured by the power factor $Z$. Thus microwave absorption scales as the product of the two. If the wall of the container is thick it will absorb more than if it is thin so that a second requirement is that the material be stiff and strong enough to carry the contents but also be thin.

The project is to investigate materials for containers for microwave cooking.

• Collect and examine real containers, identifying materials if possible.
• Formulate a specification for selecting materials for microwave dishes. Clearly we want materials with low values of $\varepsilon Z$. But the dish must be stiff and strong enough to cope with ordinary handling loads. The deflection $\delta$ of a flat square plate made of a material of modulus $E$, of width $w$ and thickness $t$, held on two opposite edges and carrying a distributed load $F$, is

$$\delta = \frac{Fw^3}{384Et} \text{ with } I = \frac{wI^3}{12}$$

and the maximum stress is

$$\sigma = \frac{Ftw}{16I} = \frac{3F}{4t^2}$$

Make sensible estimates for $t$, $w$, $F$, and the acceptable $\delta$, and thereby arrive at approximate lower limits for the modulus and strength for the dish. Finally, remember it will get hot – you will need a constraint on service temperature.

• Consider how stiffness and strength could be improved by modifying the shape from a simple flat plate.
• Use CES EduPack Level 2 to explore the choice of materials for disposable microwave dishes (very cheap) and for reusable dishes (cost less critical) for microwave cooking.
• Remember to consider the chemical composition of possible food products which the microwave dish is going to be used for – acidic, salty etc.
• Present the case for your choice of material and process as a report, using data or charts from CES EduPack and from any other sources you have used to explain your reasoning.
Notes for instructors: Project 14, Microwave dishes

The approximate dimensions of the dish shown in the picture are $w = 200$ mm, $t = 2$ mm (but note the ribs, increasing $l$ for a given $t$). A reasonable design load might be $F = 10$ N (equivalent to a 1 kg mass) and a maximum acceptable deflection might be $\delta = 10$ mm. These plus the limit on service temperature and the need for low dielectric loss lead to the following specification:

<table>
<thead>
<tr>
<th>Function</th>
<th>Microwave dish – low dielectric loss container</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td>Low dielectric loss (dissipation factor $&lt;0.005$)</td>
</tr>
<tr>
<td></td>
<td>Young’s modulus $E &gt; 0.16$ GPa</td>
</tr>
<tr>
<td></td>
<td>Elastic limit $&gt; 1.9$ MPa</td>
</tr>
<tr>
<td></td>
<td>Maximum service temperature $&gt; 100^\circ$C</td>
</tr>
<tr>
<td></td>
<td>Durability in fresh water and salt water = Acceptable / Excellent</td>
</tr>
<tr>
<td></td>
<td>Durability in dilute acids (Acetic acid (10%), Citric acid (10%)) = Acceptable / Excellent</td>
</tr>
</tbody>
</table>

Objective

Minimize unit cost

Free variables

Plate thickness and shape – the shape can be chosen to increase the bending stiffness

Choice of material

This leads to the selection POLYETHYLENE and POLYPROPYLENE. ALUMINA, POLYTETRAFLUOROETHYLENE and SILICA GLASS, have good properties but are expensive – options, perhaps, for reusable dishes.

A Web search turns up the information that PET, PP, PVC, and polyester are all approved by the US Food and Drug Administration for microwave cooking.

Resources for the student

- Access to microwave dishes
- The booklet “Useful Approximate Solutions for Standard Problems” that appears as Appendix A of the text “Materials Selection in Mechanical Design” or can be downloaded from the Granta website
- Access to CES EduPack software, set to Level 2

The Web

Project 15. A fan blade for an aircraft turbine engine

Most of the thrust for propulsion in a modern commercial jet engine comes from a large diameter fan at the front of the engine, which is driven by the low-pressure turbine at the rear of the engine. The fan, similar to a room fan, consists of multiple blades that rotate about the fan axis at high speed, and push the air backward past the engine. The power to the fan is transmitted through a long shaft down the centerline of the engine and then into a large disk into which the fan blades are inserted. The mass of the blades rotating at high speed not only creates high stresses in the blades themselves, it also requires that the fan disk be strong enough to hold the blades, further increasing the weight of the system. Since increased engine weight increases the takeoff weight and reduces the payload, it is desired to minimize the weight of the fan blade, subject to other limitations.

To perform its aerodynamic function (pump air) the fan blade has to have a specified size and shape. The size to be considered here is 460 mm long x 150 mm wide by a maximum thickness of 10 mm. The shape is typically a complex airfoil with twist and taper along the radial axis, and may be hollow for weight reduction. For this problem, assume the blade to be rectangular in outer cross section with internal cavities per your description.

The blade is to withstand a tensile stress $\sigma$ caused by centrifugal loading. For a given angular velocity, this stress scales with the density $\rho$ of the material of the blade:

$$\sigma = 0.11 \rho \ (\sigma \text{ in MPa, } \rho \text{ in kg/m}^3)$$

and must withstand these loads for at least 10,000 engine flights (1 start-stop cycle per flight). You may simplify your fatigue criterion by assuming that a material will last 10,000 cycles if the stresses are held below one half of the ultimate tensile strength $\sigma_{u}$.

Tolerance to damage (dents, cracks) from impact of foreign objects (rocks, birds) is also important. A 0.5 mm deep impact-induced crack should not propagate under the cyclic loads imposed by centrifugal force. Fast fracture will occur if the fracture toughness $K_{IC} = \sigma \sqrt{\pi a}$; use this criterion to set a lower limit for the allowable fracture toughness of your material.

In addition to the centrifugal loads, blades are subjected to lateral vibrational loads due to air turbulence, system excitation, etc. The method used to reduce vibrational fatigue is to keep the natural frequency (first flex) as high as possible. Natural frequencies scale as $\sqrt{E/\rho}$, so the answer is to make this as large as possible. In practice, torsional stiffness is important too: to prevent torsional modes from developing, torsion (shear) stiffness must be at least 25% of longitudinal stiffness.

The temperature of the fan blade will reach a maximum of 100°C during operation.

Cost is always a constraint in jet engines, particularly commercial ones, and it is desired (though not essential) to keep blade cost below $2000. Cost is not only a function of starting material, but also fabrication. To consider fabrication costs, calculate the surface area, internal and well as external, and multiply by $6000/m^2$. For composite systems, count each ply interface as a surface (e.g. if there are 10 plies per thickness in a solid rectangle, then to the outer surface area add the surface area of the internal 9 ply interfaces.)

Describe the principal risks in the material selection approach you have adopted, and what actions you would take to reduce these risks.

This Project is based on one provided by Dr. Ken Wright at General Electric Aero Engines. I wish to thank him and Professor Kevin Hemker of the Engineering Department, Johns Hopkins University who brought it to my attention.
Solution

There are several ways to tackle this problem. Here is one, using the Level 2 database.

The fatigue strength requirement can be expressed as

\[ \frac{\sigma_{ts}}{\rho} > 2 \times 0.11 = 0.22 \text{ MPa/} (\text{kg/m}^3) \]

The damage-tolerance requirement imposes a limit on \( K_{lc} \) of

\[ K_{lc} > \sigma \sqrt{\pi a} = 0.11 \rho \sqrt{\pi} \times 0.55 \times 10^{-3} = 4.6 \times 10^{-3} \rho \]

or

\[ \frac{K_{lc}}{\rho} > 4.6 \times 10^{-3} \quad (\rho \text{ in kg/m}^3) \]

The first figure shows these two quantities, constructed using the “Advanced” facility in the dialog box that lets you set the X and Y axes. The two limits listed above are applied with a box selection – only the materials within the box are retained. The temperature requirement is a simple limit, imposed with a Limit stage (not shown).

Maximizing natural vibration frequency requires that

\[ M = \frac{E}{\sqrt{\rho}} \]

be as large as possible. The quantity \( E/\rho \) is plotted against material cost in the second figure. The materials that have failed the earlier stages are hidden.

The clear winner is CFRP, but it is also the most expensive. All the other materials have nearly the same value of \( E/\rho \). Titanium alloys, which did particularly well in the first chart, remain a good, but expensive choice. Aluminum and magnesium alloys, which only just made the grade in the first chart, are much cheaper, but the safety margin with these is less.
Project 16. Design of a spacecraft antenna boom structure

**Background**  As a spacecraft structural designer, you are to specify the material and shape of a boom structure to support a communications antenna from a small satellite. Consider the following points:

- The quality and coverage of the communications signal depend on the antenna boom’s ability to maintain its pointing accuracy despite environmental disturbances (attitude changes, propulsion system firings, micrometeoroid impingement, etc.). In particular, the boom must minimize the deflection under thermal loads, and accommodate a thermal gradient across the depth of the boom due to the solar flux of 1000 BTU/hr with a minimum tip deflection.

- In addition, the communication signal is particularly susceptible to low frequency vibrations, so the natural frequency in the bending mode should be maximized. A high internal damping, or loss factor ( > 0.0005), is desired so that the boom will quickly return to its equilibrium state if it is disturbed.

- Since the spacecraft has a strict weight budget, a minimum mass is desired for the structure.

- The antenna boom must survive particularly severe shock and vibration loads during launch, so the material chosen must have reasonably good tensile strength ( > 30 ksi) and fracture toughness ( > 10 ksi-in$^{1/2}$).

- Magnetic materials, such as steels and nickel alloys would interfere with the antenna pattern and are not allowed for the design.

- Low cost (< $500/lbm) is also desirable, but not required.

The antenna is shown on the spacecraft in the accompanying figure, and may be idealized as a cantilevered beam. The antenna is 10 ft in length, and its tip should deflect no more than 0.5" under thermal loads. Because the antenna boom must be folded and stowed within the spacecraft for launch, its depth is limited to 0.5". In order to fit within the electrical elements, the boom must be no wider than 4".

**The project**  You are to derive material indices to determine a subset of materials that would be best for this application. Apply the other design constraints to narrow your selection of materials. Choose the best material for the antenna boom. What shape should the boom have? If the boom must also have a high torsional natural frequency, what shape should it be? What process or processes can be used to make this boom? What thickness can you specify to meet the design requirements? For the thickness you specify, what is the maximum thermal deflection of the boom? What is the natural frequency of the boom? What is its mass?
Notes for instructors: Project 16, Design of a spacecraft antenna boom structure

The design requirements are summarized in the table.

<table>
<thead>
<tr>
<th>Function</th>
<th>Spacecraft antenna boom structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td>Non-magnetic to prevent interference with antenna pattern</td>
</tr>
<tr>
<td></td>
<td>High damping</td>
</tr>
<tr>
<td></td>
<td>Reasonable strength to survive launch loads ( \ (&gt; \sim 30 ksi))</td>
</tr>
<tr>
<td></td>
<td>Reasonable fracture resistance (K_{tc} &gt; \sim 10 ksi-in^{1/2})</td>
</tr>
<tr>
<td></td>
<td>Reasonable cost (\ (&lt; $500/lbm)</td>
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<tr>
<td>Objectives</td>
<td>Minimize thermal distortion under solar heat flux</td>
</tr>
<tr>
<td></td>
<td>Maximize bending frequency</td>
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<td>Free variables</td>
<td>Choice of material</td>
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<tr>
<td></td>
<td>Choice of dimension</td>
</tr>
<tr>
<td></td>
<td>Choice of shape</td>
</tr>
</tbody>
</table>

Derivation of critical equations

There are two critical equations in this materials selection problem: 1) the thermal distortion of the beam as a function of applied solar heat flux, and 2) the natural frequency of the boom in bending.

The conduction through the depth of the beam is governed by the standard heat conduction law (See Ref 1, Chapter 11):

\[ \dot{q} = \lambda \frac{\Delta T}{\Delta x} = \lambda L t_w \frac{\Delta T}{h} \]  \hspace{1cm} (1)

where \( \dot{q} \) is the flux (BTU/hr), \( \lambda \) is the thermal conductivity (BTU-in/in^2-hr-\°F), \( L \) is the length of the beam (in), \( \Delta T \) is the temperature differential (\°F), \( h \) is the depth of the beam (in), and \( t_w \) is the thickness along the width of the beam (in). Note that \( t_w \) is equal to the width of the beam only for a solid section beam.

The equation that describes thermal distortion can be derived by noting that under the solar flux on one side for the beam, the exposed side will expand more than the non-exposed side.

\[ L_{\text{hot}} = L_{\text{cold}} (1 + \alpha \Delta T) \]  \hspace{1cm} (2)

The differential expansion will cause the beam to distort along a circular arc as shown below:

From the geometry, relate \( L \) to \( R \) and substitute in (2):

\[ L_{\text{cold}} = \theta R \hspace{1cm} L_{\text{hot}} = \theta (R + h) = \theta (1 + \frac{h}{R}) = L_{\text{cold}} (1 + \frac{h}{R}) \]  \hspace{1cm} (3)

\[ L_{\text{cold}} (1 + \alpha \Delta T) = L_{\text{cold}} (1 + \frac{h}{R}) \Rightarrow \alpha \Delta T = \frac{h}{R} \Rightarrow R = \frac{h}{\alpha \Delta T} \]  \hspace{1cm} (4)

Also from geometry:

\[ \delta = R [1 - \cos \theta] \cong R [1 - (1 - \frac{\theta^2}{2})] \]  \hspace{1cm} for small angles \( \Rightarrow \delta \cong \frac{R \theta^2}{2} \]  \hspace{1cm} (5)
Substituting (3) into (5) and then (4) into the new equation gives:

\[
\delta = \frac{L^2}{2R} = \frac{L^2}{2} \alpha \frac{\Delta T}{h}
\]  

(6)

where \( \delta \) is the tip deflection (in), and \( \alpha \) is the thermal expansion coefficient (°F⁻¹).

The mass of the beam is:

\[ m = \rho A L \]  

(7)

The bending frequency can be found in Appendix A.12 of Ref 1 as:

\[ f = \frac{3.52}{2\pi} \sqrt{\frac{EI}{\rho mL^3}} \]  

(8)

Substituting (7) into (8) gives:

\[ f = \frac{3.52}{2\pi} \sqrt{\frac{EI}{\rho A L^4}} \]  

(9)

Using the definition of shape factor and substituting gives:

\[ \phi_B = 4\pi \frac{I}{A^2} \Rightarrow \frac{I}{A} = \frac{\phi_B A}{4\pi} \]  

(10)

\[
f = \frac{3.52}{2\pi} \sqrt{\frac{E\phi_B}{\rho} \frac{A}{4\pi L^4}}
\]  

(11)

where \( f \) is the natural frequency (Hz), \( E \) is Young’s Modulus (psi), and \( I \) is the bending moment of inertia (in⁴) and \( m \) is the mass of the beam (lbm), \( \phi_B \) is the bending shape factor and \( A \) is the beam cross sectional area (in²). Note that for this formula to work you must account for the difference between lbf and lbm using the conversion 1 lbf = 386.4 lbm-in/s² or 1 lbf = 32.2 lbm-ft/s².

**Consideration of shape factors**

In addition to selecting the appropriate material for this application, you are to also consider what the appropriate shape for this application might be. See Reference 1, Chapter 11 and especially Table 11.3 for a description of shape factors. Make your materials selection based on solid cross-sections and then optimize the performance of your antenna by considering various shapes.

*Given these design criteria, use CES EduPack software, Level 3, to narrow the list of possible materials.*

**References**


*This Project is courtesy of Dr. Tom Dragone at Orbital Science Corporation and Professor Kevin Hemker of the Engineering Department, Johns Hopkins University.*
Solution

Under the solar flux, a temperature gradient is set up through the depth of the beam. The flux is related to the temperature gradient by equation (1) above. The temperature gradient causes the beam to deflect into a circular arc. The tip deflection is given by equation (6)

Combining equations (1) and (6) to eliminate the temperature gradient yields:

\[
\delta = \frac{\alpha L}{\lambda} \frac{\dot{q}}{t_w} \quad (12)
\]

The best materials will be those with maximum values of

\[
M_1 = \frac{\lambda}{\alpha}
\]

This material index is shown in the first stage results opposite.

The best materials to maximize the frequency of the beam will be those with maximum values of

\[
M_2 = \frac{E\phi_B}{\rho} \quad (14)
\]

Note that this index will also minimize the mass of the beam. This index is shown in the second stage results shown below for only those materials passing the first stage.

In a multiple objective optimization such as this one, it is beneficial to set both material index lines relatively low and “creep” up to the optimum corner (upper left in this case) until a reasonable number of materials are left for further evaluation.

The damping, strength, fracture toughness, and cost constraints should be straightforward, implemented in a Limit stage, leaving a short list of materials shown in the table. Of these, beryllium has the best stiffness performance, but aluminum matrix composites have the best performance balance for both stiffness and thermal distortion.
The shape factor can be considered separately in this problem. Clearly, equation (11) indicates that the best design is one where the shape factor is maximized. Table 11.3 in Ref. 1 indicates that hollow sections have much better shape factors than solid sections. This implies that hollow sections are much more efficient at resisting bending than a solid section of the same mass. Since the depth of the beam is limited to 0.5", the best sections are either an elliptical tube, a rectangular box, or a short I-beam. Both the box and the I-beam are marginally better than the elliptical tube in bending, but the closed-section box beam is much more efficient than the open I-beam in torsion, so the box beam is preferred. Such shapes can typically be extruded or built up from bent sheet and bonded, brazed, or welded together. Typical minimum gage for these sections is in the range of 0.020".

Since both the height and the width of the beam are constrained, the thickness of the box beam is the only design parameter to be specified. Interestingly, the natural frequency of the boom is independent of the thickness. This is because the inertia, $I$, and the mass, $m$, of the box beam both scale linearly with thickness. The thickness does affect the thermal distortion, however.

The following table lists typical properties, thicknesses, and performance of the materials listed above.

<table>
<thead>
<tr>
<th>Material</th>
<th>$M_1$ $10^6$ BTU/hr-ft</th>
<th>$M_2$ Msi/pcf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al/C</td>
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<td>0.24</td>
</tr>
<tr>
<td>Al/SiC</td>
<td>9.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Ep/Gr</td>
<td>1.5</td>
<td>0.23</td>
</tr>
<tr>
<td>Mg/C</td>
<td>7.3</td>
<td>0.12</td>
</tr>
<tr>
<td>Be</td>
<td>18.1</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Note that all but the graphite/epoxy boom meet the thermal distortion and frequency criteria at the minimum gage.

The actual material used on the ORBCOMM spacecraft was Graphite/Epoxy composite for the first few launches and an Aluminum-Beryllium alloy for the subsequent missions. Aluminum matrix composites were not seriously considered because they had no significant flight heritage and were deemed too risky. Pure beryllium alloys are hazardous to deal with, so were not considered. The aluminum-beryllium alloy has similar properties as beryllium without the health hazard.

References


This project is courtesy of Dr. Tom Dragone at Orbital Science Corporation and Professor Kevin Hemker of the Engineering Department, Johns Hopkins University.
Project 17. Design of a heat-shield for a Mars airplane probe

It has been proposed to explore the Martian landscape from an unmanned airplane flying in the Mars atmosphere. The airplane would be folded and carried to Mars in a spacecraft protected from the heat of re-entry in the Martian atmosphere by a heat-shield. Once within the atmosphere, the heat-shield would be jettisoned, and the airplane would unfold, be released, and would fly free. The task is to design the structure for the heat-shield.

The carrier spacecraft can hold a probe with a maximum diameter of 30 in. The heat-shield is shaped as a spherical cap with a radius of curvature of 36 in. The heat-shield structure is covered with ceramic tiles (similar to the tiles on the Space Shuttle) to insulate it from the surface temperature of 2500°F and keep the structure temperature below 350°F.

The peak loading on the heat-shield occurs during Martian entry when aerodynamic drag forces slow the probe from 23,000 ft/sec (15,600 mph) to 300 ft/sec in order to deploy the airplane. The maximum pressure $P$ encountered is about 6 psi on the heat-shield surface, as shown in the figure on the next page.

Under this peak aerodynamic loading, the heat-shield must not deflect more than 0.010 in. Any deflection greater than this risks popping a tile off the surface and losing the insulation they provide. In addition, under this loading, the stresses within the heat-shield must be less than the elastic limit of the material. As a standard practice for the aerospace industry, a factor of safety $S_f$ of 1.5 should be applied to this calculation.

The stress and deflection of a spherical cap can be found in any standard reference book (e.g. Roark, Table 28, Case 3f) as:

$$
\delta = \frac{PR^2}{2Et} \quad \text{and} \quad \sigma = \frac{PR}{2t}
$$

where $R$ is the radius of curvature, $P$ the pressure, $t$ the shield thickness and $E$ its modulus. The heat-shield must survive only one cycle of this loading, so fatigue endurance is not a design driver.

The cap is in compression under the aerodynamic load, so buckling is a concern. The critical pressure at which the heat-shield will buckle is given by:

$$
P_{\text{Crit}} = 0.17 \frac{Et^2}{R^2}
$$

Damage tolerance is also important. Non-destructive inspection of the heat-shield can detect flaws down to 0.050" in size. Damage smaller than this should not result in fracture of the material under the design load condition (including the factor of safety above). Use the criterion for a simple crack, $K_{IC} = (a)^{1/2}$, to set a limit for the allowable fracture toughness of the material.
Cost is also a concern, and total fabrication cost for the heat-shield must be below $20,000. In addition to raw material costs, fabrication and tooling costs must be included. Fabrication and tooling costs can be estimated by calculating the surface area, internal and well as external, and multiplying by $1000/ft^2 to account for fabrication, labor and tooling costs. For composite systems, count each ply interface as a surface (e.g. if there are 10 plies per thickness in a solid rectangle, then to the outer surface area add the surface area of the internal 9 ply interfaces).

Because launching a spacecraft to Mars is so costly both in energy and dollars, the total mass allocation for the airplane, the heat-shield and all associated electronic equipment is only 80 lbm. Most of this must be reserved for the airplane and the cameras to gather the flight data, so the mass of the heat-shield must be as small as possible, subject to other mission constraints.

What is the best material for this heat-shield application? What is the driving design constraint? What is the minimum thickness that satisfies all the design criteria? What is the minimum mass of the heat-shield? What is the total cost of the heat-shield?

One of the members of the design team has suggested replacing the spherical heat-shield with a flat heat-shield to allow more internal volume and better packaging for the airplane. The equations governing deflection and stress for this configuration are found in Reference 1 on p. 487. Why is the form of these equations different from the equations given above? What is different about the way the heat-shield in this configuration would support the load? Does the choice of material change for this configuration? How much would a flat heat-shield weigh, given the same requirements described above? Is a flat heat-shield a good idea?

References


This Project is courtesy of Dr. Tom Dragone at Orbital Science Corporation and Professor Kevin Hemker of the Engineering Department, Johns Hopkins University.
Solution

(1) The deflection constraint requires that \( \delta < \delta_{\text{max}} \) with \( \delta_{\text{max}} = 0.01 \text{ in} \):

\[
\delta = \frac{PR^2}{2Et} \leq \delta_{\text{max}} \quad \Rightarrow \quad t \geq \frac{PR^2}{2E\delta_{\text{max}}} \tag{1}
\]

For a spherical cap, the mass \( m \) depends on the thickness and the surface area:

\[
m = 2\pi R^2 (1 - \cos \theta) \, t \, \rho \tag{2}
\]

where \( R \) is the radius of curvature and \( \theta \) is the included angle.

Substituting for \( t \) and rearranging in terms of Functional, Geometric, and Material requirements gives the mass \( m_1 \) of the shield required to meet the deflection constraint:

\[
m_1 \geq \pi \frac{P}{\delta_{\text{max}}} \frac{R^4}{1 - \cos \theta} \frac{\rho}{E} \tag{3}
\]

This suggests mass is minimized by maximizing \( E/\rho \), shown as one axis of the figure opposite.

(2) The buckling criterion can be re-stated as:

\[
S_f \times P \leq P_{\text{Crit}} = 0.17E \frac{t^2}{R^2} \quad \Rightarrow \quad t \geq \sqrt[3]{\frac{P}{0.11E}} \cdot R \tag{4}
\]

(with \( S_f = 1.5 \)). The mass is still given by equation (2). Thus the mass \( m_2 \) required to resist buckling is:

\[
m_2 = 2\pi R^2 (1 - \cos \theta) \rho \tag{5}
\]

Substituting for \( t \) and rearranging gives:

\[
m_2 \geq \frac{2\pi}{\sqrt{0.11}} \sqrt{P} \frac{R^3}{(1 - \cos \theta)} \frac{\rho}{\sqrt{E}} \tag{6}
\]

This suggests mass is minimized by maximizing \( E^{1/2}/\rho \), shown as the other axis of the figure.

The figure is best used by employing the coupling line construction described in Reference 1, Section 9.2, pp. 241 – 245. Setting \( m_1 = m_2 \) gives the equation for the coupling line:

\[
\sqrt[3]{\frac{E}{\rho}} = \frac{2}{\sqrt[3]{0.11}} \frac{\delta_{\text{max}}}{R} \frac{E}{\rho} \quad \Rightarrow \quad \sqrt[3]{\frac{E}{\rho}} = 0.68 \frac{E}{\rho}
\]

(using the data given in the question, and remembering that the units of stress and pressure are \( 10^6 \text{ psi} \)). Slide the box up the line until a small subset of materials is left.
(3) The **strength criterion** can be restated as:

\[ S_f \times \sigma = \frac{S_f \cdot PR}{2t} \leq \sigma_{\text{Limit}} \quad \Rightarrow \quad t \geq \frac{3 \cdot PR}{4 \sigma_{\text{Limit}}} \]  

(7)

Substituting for \( t \) into the mass equation (2) above gives the mass \( m_3 \) required to give sufficient strength:

\[ m_3 \geq \frac{3}{2} \pi P R^3 (1 - \cos \theta) \frac{\rho}{\sigma_{\text{Limit}}} \]  

(8)

The mass \( m_3 \) is minimized by maximizing \( \frac{\sigma_{\text{Limit}}}{\rho} \). It appears as one axis of the figure opposite.

(4) The **damage criterion** can be restated as:

\[ K_I = \sigma \sqrt{\pi a} = \frac{S_f \cdot PR}{\sqrt{\pi a}} \leq K_{IC} \quad \Rightarrow \quad t \geq \frac{3 \cdot PR}{4 K_{IC}} \]  

(9)

Substituting for \( t \) into the mass equation (2) above and rearranging:

\[ m_4 \geq \frac{3}{2} \pi^{3/2} P \sqrt{a} R^3 (1 - \cos \theta) \frac{\rho}{K_{IC}} \]  

(10)

This suggests mass is minimized by maximizing \( K_{IC} / \rho \), shown as the other axis of the figure.

The figure is used in the same way as the previous one. Setting \( m_3 = m_4 \) gives the equation for the coupling line:

\[ \frac{K_{IC}}{\rho} = \sqrt{\pi a} \frac{\sigma_{\text{Limit}}}{\rho} \quad \Rightarrow \quad \frac{K_{IC}}{\rho} = 0.4 \frac{\sigma_{\text{Limit}}}{\rho} \]

using the limiting crack size of 0.05 in. This line is plotted on the figure. A selection box with its corner on the line, as shown, correctly balances the constraint on strength and that on damage tolerance. Sliding this up the line, and exploring the intersection between the two selection stages gives the materials that best meet the four criteria.
(5) The temperature criterion is easily applied using a Limit stage (not shown).

(6) The cost constraints are not easily separable, but are not very stringent. Manufacturing and tooling costs amount to ~$5000 for an isotropic material, leaving ~$15,000 for the heat-shield that weighs on the order of 1 lbm. Therefore, all materials are allowed in terms of cost. Note that this is a common occurrence for unique, high performance aerospace products: raw material costs usually do not factor heavily into the overall design equation.

Material selection The “short list” of best materials and their properties are shown below. Note that the minimum performance and maximum mass and cost values have been used. Also shown are calculations of the minimum thicknesses based on the deflection constraint, the buckling constraint, the strength constraint, and the fracture toughness constraint using the equations derived above. In all cases, buckling is the limiting design constraint. Finally, the calculation of minimum mass and cost for the driving design constraint is shown.

### Material Properties

<table>
<thead>
<tr>
<th>Database</th>
<th>Material</th>
<th>Modulus Msi</th>
<th>Strength ksi</th>
<th>Density pcf</th>
<th>Toughness ksi</th>
<th>Price /lbm</th>
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### Thickness Calculation

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<th>tTough in</th>
<th>tmin in</th>
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### Mass and Cost Calculation

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<tr>
<td></td>
<td>Mg-Graph</td>
<td>3.62</td>
<td>$217</td>
<td>1</td>
<td>$5,143</td>
<td>$2,680</td>
<td>$8,040</td>
</tr>
</tbody>
</table>
Clearly, the best choice based on this table is beryllium, giving the thinnest section (0.042") and lowest mass (2.1 lbm) with a low total fabrication cost ($8800). The driving constraint is buckling as stated above.

Note that CFRPUni has been eliminated from consideration because the heat-shield must have bidirectional strength. If CFRPUni was used and oriented in one direction, it would be very stiff and strong in that direction, but in the transverse direction, it would be compliant and weak, resulting in failure.

Flat heat-shield alternative

The equations for the flat panel deflection and strength are different because of the way the structure physically supports the load. For the spherical cap, even though it is very shallow, the loads are supported by membrane forces within the shell. The slight bit of curvature prevents much bending in the shell. In the flat panel configuration, the load must be supported in bending, which in general, is less efficient. Also, in the flat panel configuration, buckling is not a concern since the panel is not placed into global compression.

Although the slope of the guidance lines would change on the modulus-density plot and the elastic limit-density plot for this configuration, the same set of materials would be selected as good performers. However, because of the inefficiency of thin shells in bending, the minimum thickness and mass of a beryllium heat-shield would be on the order of 0.8" and 40 lbm respectively! Clearly, the flat heat-shield is NOT a good structural idea.

Final note

Both the spherical shell and the flat plate heat-shield design can be improved (in terms of mass) by considering sandwich construction. Just separating the shell thickness with a ¼" core can increase the bending stiffness (and buckling resistance) of these thin shells by two orders of magnitude. This would reduce the amount of material required for the facesheets accordingly. However, then there would be concerns about the weight and stiffness of the core as well as the minimum gage limits on facesheet thickness from a manufacturing and cost standpoint.

This Project is courtesy of Dr. Tom Dragone at Orbital Science Corporation and Professor Kevin Hemker of the Engineering Department, Johns Hopkins University.
**Project 18. CO₂ eco-audit for patio heater.**

Use the Eco Audit Tool to conduct a CO₂ eco-audit for the patio heater shown here. It is manufactured in SE Asia and transported using sea freight 8,000 km to the US where it is sold and used.

*It weighs 24 kg, of which 17 kg is rolled stainless steel, 6 kg is rolled medium carbon steel, 0.6 kg is cast brass and 0.4 kg is unidentified injection-molded polypropylene.*

In use it delivers 14 kW of heat (“enough to keep 8 people warm”) while consuming 0.9 kg of propane gas (LPG) per hour. The heater is used in an open patio for 3 hours per day for 30 days per year, over 5 years, at which time the owner tires of it and takes it to the recycling depot (only 6 miles / 10 km away, so neglect the transport CO₂) where the stainless steel, carbon steel and brass are sent for recycling.
Solution

The bar chart below shows that the total energy consumed (and hence CO₂ footprint) by the usage phase of the life-cycle dominates the other phases.

---

**Static Mode Usage Inputs**

<table>
<thead>
<tr>
<th>Energy Input/Output Type</th>
<th>Fossil fuel to thermal, vented system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Efficiency</td>
<td>0.7</td>
</tr>
<tr>
<td>Use Location</td>
<td>United States</td>
</tr>
<tr>
<td>Energy Equivalence, Source (MJ/MJ)</td>
<td>1</td>
</tr>
<tr>
<td>Power Rating (kW)</td>
<td>14</td>
</tr>
<tr>
<td>Usage (hours per day)</td>
<td>3</td>
</tr>
<tr>
<td>Usage (days per year)</td>
<td>30</td>
</tr>
<tr>
<td>Product Life (years)</td>
<td>5</td>
</tr>
<tr>
<td>Total Life Usage (hours)</td>
<td>450</td>
</tr>
</tbody>
</table>

The use of the heater over its entire life, delivering 14 kW, or 50.4 MJ/hour with the release of 0.071 kg CO₂/MJ, emits 2300 kg of CO₂. (note efficiency of 70%)

Sea transport over 8000km, consuming 0.011 kg CO₂/tonne.km, releases 2.2 kg of CO₂ per unit, so small as to be invisible on the bar chart.

---

**Table of CO₂ data for material and manufacturing phases**

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg)</th>
<th>Material CO₂ (kg/kg)</th>
<th>Material CO₂ per unit (kg)</th>
<th>Process CO₂ (kg/kg)</th>
<th>Process CO₂ per unit (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, rolled</td>
<td>17</td>
<td>5.109</td>
<td>86.847</td>
<td>0.268</td>
<td>4.558</td>
</tr>
<tr>
<td>Carbon steel, rolled</td>
<td>6</td>
<td>2.482</td>
<td>14.892</td>
<td>0.236</td>
<td>1.418</td>
</tr>
<tr>
<td>Brass, cast</td>
<td>0.6</td>
<td>6.252</td>
<td>3.751</td>
<td>0.143</td>
<td>0.086</td>
</tr>
<tr>
<td>Polypropylene, thermoplastic polymer molded</td>
<td>0.4</td>
<td>2.698</td>
<td>1.079</td>
<td>1.494</td>
<td>0.598</td>
</tr>
</tbody>
</table>

**Totals**  
24  
106.569  
6.659

**Table of Potential End-of-life ‘savings’ of CO₂ through recycling**

<table>
<thead>
<tr>
<th>Recycled material</th>
<th>Mass (kg)</th>
<th>Difference between material CO₂ and recycling CO₂ (kg/kg)</th>
<th>CO₂ saved by recycling per unit (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel, rolled</td>
<td>17</td>
<td>3.678</td>
<td>61.816</td>
</tr>
<tr>
<td>Carbon steel, rolled</td>
<td>6</td>
<td>1.787</td>
<td>10.470</td>
</tr>
<tr>
<td>Brass, cast</td>
<td>0.6</td>
<td>4.689</td>
<td>2.788</td>
</tr>
<tr>
<td>Polypropylene, thermoplastic polymer molded</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Totals**  
24  
75.069
Recycling saves the difference between the carbon footprint of virgin and that of recycled material. The above table lists these differences. However, the CO₂ saved is only 75.1kg, much less than the CO₂ given off in usage.

### Summary of Energy and CO₂ consumption

<table>
<thead>
<tr>
<th>Phase</th>
<th>Energy (MJ)</th>
<th>Energy (%)</th>
<th>CO₂ (kg)</th>
<th>CO₂ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>1651.7429</td>
<td>5.00</td>
<td>106.5692</td>
<td>4.55</td>
</tr>
<tr>
<td>Manufacture</td>
<td>83.6008</td>
<td>0.25</td>
<td>6.6594</td>
<td>0.28</td>
</tr>
<tr>
<td>Transport</td>
<td>30.7200</td>
<td>0.09</td>
<td>2.1811</td>
<td>0.09</td>
</tr>
<tr>
<td>Use</td>
<td>32400.0000</td>
<td>98.12</td>
<td>2300.4000</td>
<td>98.28</td>
</tr>
<tr>
<td>End of life</td>
<td>-1146.7449</td>
<td>-3.47</td>
<td>-75.0693</td>
<td>-3.21</td>
</tr>
<tr>
<td>Total</td>
<td>33019.3188</td>
<td>100</td>
<td>2340.7404</td>
<td>100</td>
</tr>
</tbody>
</table>

Therefore, the only way to effectively reduce the carbon footprint of a device like this is to **turn it off**.
### Product Definition

#### Eco Audit Project

**1. Material, manufacture and end of life**

<table>
<thead>
<tr>
<th>Qty</th>
<th>Component name</th>
<th>Material</th>
<th>Recycle content</th>
<th>Primary process</th>
<th>Mass (kg)</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Medium carbon steel</td>
<td></td>
<td>Forging, rolling</td>
<td>6</td>
<td>Recycle</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Stainless steel</td>
<td></td>
<td>Forging, rolling</td>
<td>17</td>
<td>Recycle</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Brass</td>
<td></td>
<td>Casting</td>
<td>0.6</td>
<td>Recycle</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>Polypropylene (PP)</td>
<td></td>
<td>Plastic molding</td>
<td>0.4</td>
<td>Landfill</td>
</tr>
</tbody>
</table>

#### 2. Transport

<table>
<thead>
<tr>
<th>Stage name</th>
<th>Transport type</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sea freight</td>
<td>1000</td>
</tr>
</tbody>
</table>

#### 3. Use

- **Product life:** 5 years
- **Country electricity mix:** United States

**Static mode**

- **Product uses the following energy**

**Mobile mode**

- **Product is part of a vehicle**

<table>
<thead>
<tr>
<th>Energy input and output</th>
<th>Fuel and mobility type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating: 14 kW</td>
<td>Usage: 1000 days per year</td>
</tr>
<tr>
<td>Usage: 30 days per year</td>
<td>Distance: 0 km per day</td>
</tr>
</tbody>
</table>
Open-ended projects

Here is a list of a few of the many projects arising from real industrial problems that have been explored in teaching programs on Material Selection at Cambridge and Grenoble.

- **Finding new applications for metal foams.** An exploration of the problem of finding viable applications for new materials.
- **Wood – material of the future.** A study of the potential for the wider use of wood as a sustainable structural material.
- **Light structures for balloon capsule flooring.** A contribution to the redesign of a multi-person capsule for a low-level, tethered hot air balloon to allow an aerial view of a city. The balloon has a fixed lift, so the payload (meaning the number of people in the capsule) can only be increased by making the structure lighter.
- **Thermal connectors for a space detector.** The need here was for a flexible connector to act as a heat sink for a movable detector to be maintained below 4 K.
- **Springs for extreme conditions.** An investigation of steel springs, polymer springs, and springs for racing cars.
- **Novel energy absorbing unit for automobile A-pillars.** A study of the replacement of the conventional A-pillar head-impact absorber by one made of metal foam.
- **Polishing of dental components.** The choice of material for polishing needles in a device for polishing artificial teeth.
- **Materials selection in Industrial Design.** A study of the material attributes and selection methods required by industrial designers.
### Physical constants and conversion of units

<table>
<thead>
<tr>
<th>Physical constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute zero temperature</td>
<td>-273.2°C</td>
</tr>
<tr>
<td>Acceleration due to gravity, g</td>
<td>9.807 m/s²</td>
</tr>
<tr>
<td>Avogadro’s number, Nₐ</td>
<td>6.022 x 10²³</td>
</tr>
<tr>
<td>Base of natural logarithms, e</td>
<td>2.718</td>
</tr>
<tr>
<td>Boltzmann’s constant, k</td>
<td>1.381 x 10⁻²³ J/K</td>
</tr>
<tr>
<td>Faraday’s constant, F</td>
<td>9.648 x 10⁴ C/mol</td>
</tr>
<tr>
<td>Gas constant, ( \bar{R} )</td>
<td>8.314 J/mol/K</td>
</tr>
<tr>
<td>Planck’s constant, h</td>
<td>6.626 x 10⁻³⁴ J/s</td>
</tr>
<tr>
<td>Velocity of light in vacuum, c</td>
<td>2.998 x 10⁸ m/s</td>
</tr>
<tr>
<td>Volume of perfect gas at STP</td>
<td>22.41 x 10⁻³ m³/mol</td>
</tr>
<tr>
<td>Angle, ( \theta )</td>
<td>1 rad 57.30°</td>
</tr>
<tr>
<td>Density, ( \rho )</td>
<td>1 lb/ft³ 16.03 kg/m³</td>
</tr>
<tr>
<td>Diffusion Coefficient, ( D )</td>
<td>1 cm³/s 1.0 x 10⁻⁹ m³/s</td>
</tr>
<tr>
<td>Energy, ( U )</td>
<td>See opposite</td>
</tr>
<tr>
<td>Force, ( F )</td>
<td>1 kgf 1 lb 4.448 N</td>
</tr>
<tr>
<td></td>
<td>1 dyne 1.0 x 10⁻⁹ N</td>
</tr>
<tr>
<td>Length, ( l )</td>
<td>1 ft 304.8 mm</td>
</tr>
<tr>
<td></td>
<td>1 inch 25.40 mm</td>
</tr>
<tr>
<td></td>
<td>1 Å 0.1 nm</td>
</tr>
<tr>
<td>Mass, ( M )</td>
<td>1 tonne 1000 kg</td>
</tr>
<tr>
<td></td>
<td>1 short ton 908 kg</td>
</tr>
<tr>
<td></td>
<td>1 long ton 1107 kg</td>
</tr>
<tr>
<td></td>
<td>1 lb mass 0.454 kg</td>
</tr>
<tr>
<td>Power, ( P )</td>
<td>See opposite</td>
</tr>
<tr>
<td>Stress, ( \sigma )</td>
<td>See opposite</td>
</tr>
<tr>
<td>Specific Heat, ( C_p )</td>
<td>1 cal/gal.°C 4.188 kJ/kg.°C</td>
</tr>
<tr>
<td></td>
<td>1 Btu/lb.°F 4.187 kJ/kg.°C</td>
</tr>
<tr>
<td>Stress Intensity, ( K_{\text{IC}} )</td>
<td>1 ksi ( \text{√in} ) 1.10 MN/m²²</td>
</tr>
<tr>
<td>Surface Energy, ( \gamma )</td>
<td>1 erg/cm² 1 mJ/m²²</td>
</tr>
<tr>
<td>Temperature, ( T )</td>
<td>1°F 0.556°C</td>
</tr>
<tr>
<td>Thermal Conductivity, ( \lambda )</td>
<td>1 cal/s.cm.°C 418.8 Wm.°C</td>
</tr>
<tr>
<td></td>
<td>1 Btu/h.ft.°F 1.731 Wm.°C</td>
</tr>
<tr>
<td>Volume, ( V )</td>
<td>1 Imperial gall 4.546 x 10⁻³ m³</td>
</tr>
<tr>
<td></td>
<td>1 US gall 3.785 x 10⁻³ m³</td>
</tr>
<tr>
<td>Viscosity, ( \eta )</td>
<td>1 poise 0.1 N.s/m²</td>
</tr>
<tr>
<td></td>
<td>1 lb ft.s 0.1517 N.s/m²</td>
</tr>
</tbody>
</table>

### Conversion of units – stress and pressure*

<table>
<thead>
<tr>
<th>Unit (MPa)</th>
<th>dyn/cm²</th>
<th>lb.in²</th>
<th>kgf/mm²</th>
<th>bar</th>
<th>long ton/in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPa</td>
<td>1</td>
<td>10⁷</td>
<td>1.45 x 10²</td>
<td>0.102</td>
<td>10</td>
</tr>
<tr>
<td>dyn/cm²</td>
<td>10⁻⁷</td>
<td>1</td>
<td>1.45 x 10⁻⁵</td>
<td>1.02 x 10⁻⁶</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td>lb/in²</td>
<td>6.89 x 10⁻³</td>
<td>6.89 x 10⁶</td>
<td>1</td>
<td>703 x 10⁻⁴</td>
<td>6.89 x 10⁻²</td>
</tr>
<tr>
<td>kgf/mm²</td>
<td>9.81</td>
<td>9.81 x 10⁷</td>
<td>1.42 x 10⁵</td>
<td>1</td>
<td>98.1</td>
</tr>
<tr>
<td>bar</td>
<td>0.10</td>
<td>10⁶</td>
<td>14.48</td>
<td>1.02 x 10⁻²</td>
<td>1</td>
</tr>
<tr>
<td>long ton/in²</td>
<td>15.44</td>
<td>1.54 x 10⁶</td>
<td>2.24 x 10⁵</td>
<td>1.54</td>
<td>1.54 x 10²</td>
</tr>
</tbody>
</table>

### Conversion of units – energy*

<table>
<thead>
<tr>
<th>Energy Unit</th>
<th>J</th>
<th>erg</th>
<th>cal</th>
<th>eV</th>
<th>Btu</th>
<th>ft lbf</th>
</tr>
</thead>
<tbody>
<tr>
<td>J</td>
<td>1</td>
<td>10⁷</td>
<td>0.239</td>
<td>6.24 x 10⁻⁸</td>
<td>9.48 x 10⁻⁴</td>
<td>0.738</td>
</tr>
<tr>
<td>erg</td>
<td>10⁻⁷</td>
<td>1</td>
<td>2.39 x 10⁻⁹</td>
<td>6.24 x 10⁻¹¹</td>
<td>9.48 x 10⁻¹⁸</td>
<td>7.38 x 10⁻⁸</td>
</tr>
<tr>
<td>cal</td>
<td>4.19</td>
<td>4.19 x 10⁷</td>
<td>1</td>
<td>2.61 x 10⁻⁹</td>
<td>3.97 x 10⁻⁸</td>
<td>3.09</td>
</tr>
<tr>
<td>eV</td>
<td>1.60 x 10⁻¹⁹</td>
<td>1.60 x 10⁻¹²</td>
<td>3.38 x 10⁻²⁰</td>
<td>1</td>
<td>1.52 x 10⁻²²</td>
<td>1.18 x 10⁻¹⁹</td>
</tr>
<tr>
<td>Btu</td>
<td>1.06 x 10³</td>
<td>1.06 x 10⁶</td>
<td>2.52 x 10⁵</td>
<td>6.59 x 10⁻¹⁰</td>
<td>1</td>
<td>7.78 x 10⁷</td>
</tr>
<tr>
<td>ft lbf</td>
<td>1.36</td>
<td>1.36 x 10⁷</td>
<td>0.324</td>
<td>8.46 x 10⁻¹⁸</td>
<td>1.29 x 10⁻³</td>
<td>1</td>
</tr>
</tbody>
</table>

### Conversion of units – power*

<table>
<thead>
<tr>
<th>Power Unit</th>
<th>kW (kJ/s)</th>
<th>erg/s</th>
<th>hp</th>
<th>ft lbf/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW (kJ/s)</td>
<td>1</td>
<td>10⁻¹⁰</td>
<td>1.34</td>
<td>7.38 x 10⁻²</td>
</tr>
<tr>
<td>erg/s</td>
<td>10⁻¹⁰</td>
<td>1</td>
<td>1.34 x 10⁻¹⁰</td>
<td>7.38 x 10⁻⁸</td>
</tr>
<tr>
<td>hp</td>
<td>7.46 x 10⁻¹</td>
<td>7.46 x 10⁹</td>
<td>1</td>
<td>15.50 x 10²</td>
</tr>
<tr>
<td>Ft lbf/s</td>
<td>1.36 x 10⁻³</td>
<td>1.36 x 10⁷</td>
<td>1.82 x 10⁻³</td>
<td>1</td>
</tr>
</tbody>
</table>

* To convert row unit to column unit, multiply by the number at the column row intersection, thus 1 MPa = 1 bar.
This is one of six CES EduPack teaching resource books. All are available free of charge to users with a maintained CES EduPack license.

**Book 1:** Getting Started with CES EduPack

**Book 2:** Material and Process Selection Charts

**Book 3:** Useful Approximate Solutions for Standard Problems

**Book 4:** PowerPoint Lectures

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