MSE 280: Introduction to Engineering Materials
"Because without materials, there is no engineering."

Instructor: Prof. Duane D. Johnson   Office: 312E MSEB

Scope: Provide an *introduction* to the science and engineering of materials (e.g., metals, ceramics, polymers, and semiconductors).

Objective: Develop an awareness of materials and their properties that, as an engineer, you must rely in the future.

- To introduce basic concepts, nomenclature, and testing of materials.
- To reveal the relationships between
  Processing - Structure - Properties - Performance
- To develop ideas behind materials selection and design.

MSE 280: Introduction to Engineering Materials
"Because without materials, there is no engineering."

Staying Current: see http://web.mse.uiuc.edu/courses/mse280

On the ***website*** students will find:

- *Announcements*: topics, assignments (reading, HW, exams), etc.
- *Grading Policy and Scheme* (HW 10% and 4 Exams each 22.5%).
- *Instructor and TA* locations, phone numbers, email, office hours.
- *Honor Code* is expected (see website).
- *HW and Exam grades* are planned for COMPASS.
- HW: include names, answers must include units or it is wrong.

Text: **Fundamentals of Materials Science & Engineering: an integrated approach**, Callister (Special 2nd edition for MSE280)

Units of Length

1 cm*	⇔	**10^{-2} m**	⇔	**0.01 m**
1 mm	⇔	**10^{-3} m**	⇔	**0.001 m**
1 micron (μm)	⇔	**10^{-6} m**	⇔	**0.000001 m**
1 nanometer (nm)	⇔	**10^{-9} m**	⇔	**0.000000001 m**
1 Angstrom (Å)	⇔	**10^{-10} m**	⇔	**0.0000000001 m**

******nota bene*: **cm are not typically used.**

Metrics Made Easy: UNITS are Important!

Recall the 1999 Mar's lander?

Some Rough Equivalents
- 1 packet of sugar substitute: 1g (gram)
- 1 small apple: 1 N (Newton)
- 1 football running back: 1kN (kilo-Newton)
- 1 card table: $1 m^2$ (meter squared)
- 1 square toothpick end: $1 mm^2$ (millimeter squared)

Visualizing Pressure
1 Pascal (1 Pa, or 1 N/m^2): Imagine applesauce made from an apple and spread thinly enough to cover the card table. (too small)

Experiencing Pressure
1 Mega-Pascal (1 MPa, or 1 MN/m^2): Stick one end of the toothpick into apple and balance the end on your finger.

Six Major Classes of Materials

- Some of these have descriptive subclasses.
- Classes have overlap, so some materials fit into more than one class.

- Metals
  - Iron and Steel
  - Alloys and Superalloys (e.g. aerospace applications)
  - Intermetallic Compounds (high-T structural materials)
- Ceramics
  - Structural Ceramics (high-temperature load bearing)
  - Refractories (corrosion-resistant, insulating)
  - Whitewares (e.g. porcelains)
  - Glass
  - Electrical Ceramics (capacitors, insulators, transducers, etc.)
  - Chemically Bonded Ceramics (e.g. cement and concrete)

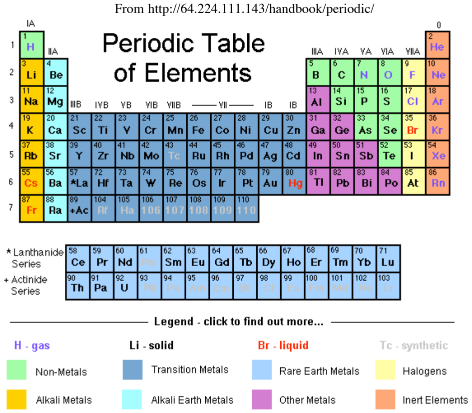
Six Major Classes of Materials

- Polymers
  - Plastics
  - Liquid crystals
  - Adhesives
- Electronic Materials
  - Silicon and Germanium
  - III-V Compounds (e.g. GaAs)
  - Photonic materials (solid-state lasers, LEDs)
- Composites
  - Particulate composites (small particles embedded in a different material)
  - Laminate composites (golf club shafts, tennis rackets, Damaskus swords)
  - Fiber reinforced composites (e.g. fiberglass)
- Biomaterials (really using previous 5, but bio-mimetic)
  - Man-made proteins (cytoskeletal protein rods or “artificial bacterium”)
  - Biosensors (Au-nanoparticles stabilized by encoded DNA for anthrax detection)
  - Drug-delivery colloids (polymer based)

MSE Illinois MSE 280: Introduction to Engineering Materials ©D.D. Johnson 2004, 2006-08

Periodic Table of Elements

From http://64.224.111.143/handbook/periodic/



MSE Illinois MSE 280: Introduction to Engineering Materials ©D.D. Johnson 2004, 2006-08

Properties of Materials

- An alternative to major classes, you may *divide* materials into classification according to properties.
- One goal of materials engineering is to select materials with suitable properties for a given application, so it’s a sensible approach.
- Just as for classes of materials, there is some overlap among the properties, so the divisions are not always clearly defined

Mechanical properties

A. Elasticity and stiffness (recoverable stress vs. strain)
B. Plasticity (non-recoverable stress vs. strain)
C. Strength
D. Brittleness or Toughness
E. Fatigue

MSE Illinois MSE 280: Introduction to Engineering Materials ©D.D. Johnson 2004, 2006-08

Properties of Materials

Electrical properties
A. Electrical conductivity and resistivity

Dielectric properties
A. Polarizability
B. Capacitance
C. Ferroelectric properties
D. Piezoelectric properties
E. Pyroelectric properties

Magnetic properties
A. Paramagnetic properties
B. Diamagnetic properties
C. Ferromagnetic properties

Properties of Materials

Optical properties
A. Refractive index
B. Absorption, reflection, and transmission
C. Birefringence (double refraction)

Corrosion properties

Deteriorative properties

Biological properties
A. Toxicity
B. bio-compatibility

Guided by Properties: Ashby Plots

Why Log(P) vs Log(P)?

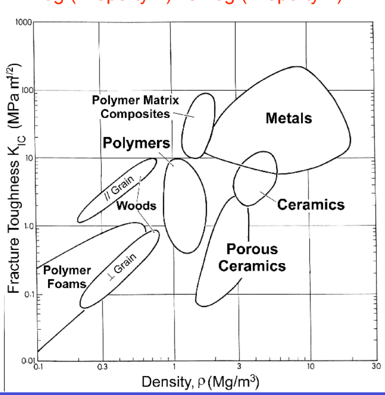
What materials are toughest against fracture?

Does density of materials play a role?

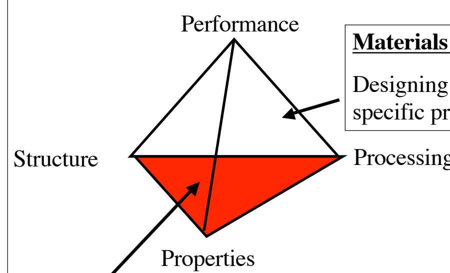
Does this conform to your experience?

We will use these for design!

Log (Property 1) vs Log (Property 2)



Materials Science & Engineering in a Nutshell



Materials Engineering

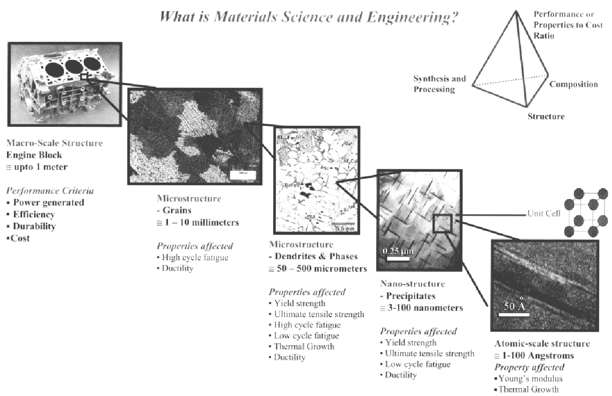
Designing the structure to achieve specific properties of materials.

Materials Science

Investigating the relationship between structure and properties of materials.

- Processing
- Structure
- Properties
- Performance

Multiple Length Scales Critical in Engineering



In Askeland and Phule's book, from J. Allison and W. Donlon (Ford Motor Company)

What is Materials Science & Engineering?

Processing
Texturing, Temperature, Time, Transformations

- Casting
- Forging
- Stamping
- Layer-by-layer growth (nanotechnology)

- Extrusion
- Calcinating
- Sintering

MatSE

characterization
Crystal structure
Defects
Microstructure

- Microscopy: Optical, transmission electron, scanning tunneling
- X-ray, neutron, e- diffraction
- Spectroscopy

Properties
Physical behavior
Response to environment

- Mechanical (e.g., stress-strain)
- Thermal
- Electrical
- Magnetic
- Optical
- Corrosive
- Deteriorative characteristics

Classes and Properties: Metals

Distinguishing features

- Atoms arranged in a regular repeating structure (crystalline - Chpt. 3)
- Relatively good strength (defined later)
- Dense
- Malleable or ductile: high plasticity (defined later)
- Resistant to fracture: tough
- Excellent conductors of electricity and heat
- Opaque to visible light
- Shiny appearance

• Thus, metals can be formed and machined easily, and are usually long-lasting materials.

• They do not react easily with other elements, however, metals such as Fe and Al do form compounds readily (such as ores) so they must be processed to extract base metals.

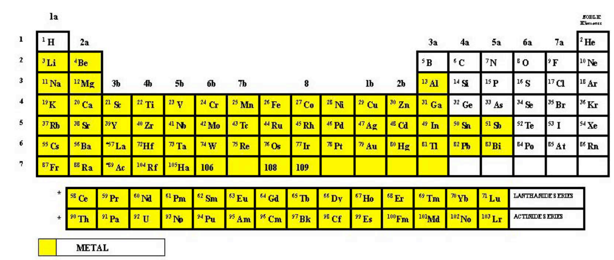
• One of the main drawbacks is that metals do react with chemicals in the environment, such as iron-oxide (rust).

• Many metals do not have high melting points, making them useless for many applications.

Classes and Properties: Metals

Elemental metals are in yellow

- we need to recall and use knowledge from the periodic table



Classes and Properties: Metals

Applications

- Electrical wiring
- Structures: buildings, bridges, etc.
- Automobiles: body, chassis, springs, engine block, etc.
- Airplanes: engine components, fuselage, landing gear assembly, etc.
- Trains: rails, engine components, body, wheels
- Machine tools: drill bits, hammers, screwdrivers, saw blades, etc.
- Shape memory materials: eye glasses
- Magnets
- Catalysts

Examples

- Pure metal elements (Cu, Fe, Zn, Ag, etc.)
- Alloys (Cu-Sn=bronze, Cu-Zn=brass, Fe-C=steel, Pb-Sn=solder, NiTinol)
- Intermetallic compounds (e.g. Ni_3Al)

What's the largest use of shape-memory nitinol?

Classes and Properties: Ceramics

Distinguishing features

- Except for glasses, atoms are regularly arranged (crystalline - Chpt. 12)
- Composed of a mixture of metal and nonmetal atoms
- Lower density than most metals
- Stronger than metals
- Low resistance to fracture: low toughness or brittle
- Low ductility or malleability: low plasticity
- High melting point
- Poor conductors of electricity and heat
- Single crystals are transparent

• Where metals react readily with chemicals in the environment and have low application temperatures in many cases, ceramics do not suffer from these drawbacks.

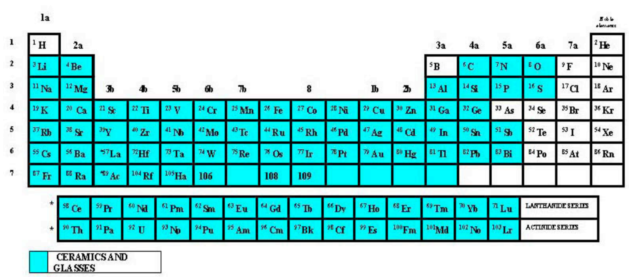
• Ceramics have high-resistance to environment as they are essentially metals that have already reacted with the environment, e.g. Alumina (Al_2O_3) and Silica (SiO_2, Quartz).

• Ceramics are heat resistant. Ceramics form both in crystalline and non-crystalline phases because they can be cooled rapildy from the molten state to form glassy materials.

MSE Illinois MSE 280: Introduction to Engineering Materials ©D.D. Johnson 2004, 2006-08

Classes and Properties: Ceramics

Elemental occurring in ceramics are in blue



MSE Illinois MSE 280: Introduction to Engineering Materials ©D.D. Johnson 2004, 2006-08

Classes and Properties: Ceramics

Applications

- Electrical insulators
- Abrasives
- Thermal insulation and coatings
- Windows, television screens, optical fibers (glass)
- Corrosion resistant applications
- Electrical devices: capacitors, varistors, transducers, etc.
- Highways and roads (concrete)
- Biocompatible coatings (fusion to bone)
- Self-lubricating bearings
- Magnetic materials (audio/video tapes, hard disks, etc.)
- Optical wave guides
- Night-vision

Examples

- Simple oxides (SiO_2, Al_2O_3, Fe_2O_3, MgO)
- Mixed-metal oxides ($SrTiO_3$, $MgAl_2O_4$, $YBa_2Cu_3O_{7-x}$, having vacancy defects.)
- Nitrides (Si_3N_4, AlN, GaN, BN, and TiN, which are used for hard coatings.)

MSE Illinois MSE 280: Introduction to Engineering Materials ©D.D. Johnson 2004, 2006-08

Classes and Properties: Polymers

Distinguishing features
- Composed primarily of C and H (hydrocarbons)
- Low melting temperature.
- Some are crystals, many are not.
- Most are poor conductors of electricity and heat.
- Many have high plasticity.
- A few have good elasticity.
- Some are transparent, some are opaque

• Polymers are attractive because they are usually lightweight and inexpensive to make, and usually very easy to process, either in molds, as sheets, or as coatings.

• Most are very resistant to the environment.

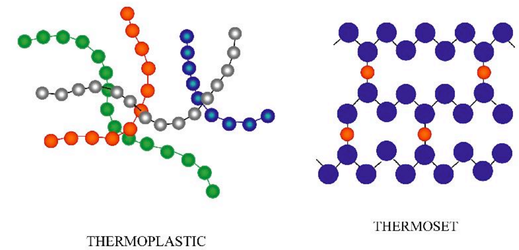
• They are poor conductors of heat and electricity, and tend to be easy to bend, which makes them very useful as insulation for electrical wires. They are also

Classes and Properties: Polymers

Two main types of polymers are thermosets and thermoplastics.

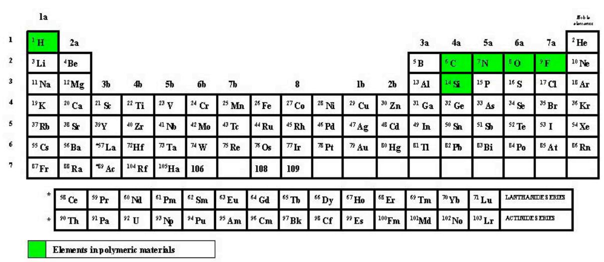
• Thermosets are cross-linked polymers that form 3-D networks, hence are strong and rigid.

• Thermoplastics are long-chain polymers that slide easily past one another when heated, hence, they tend to be easy to form, bend, and break.



Classes and Properties: Polymers

Elements that compose polymers: limited



Classes and Properties: Polymers

Applications and **Examples**
- Adhesives and glues
- Containers
- Moldable products (computer casings, telephone handsets, disposable razors)
- Clothing and upholstery material (vinyls, polyesters, nylon)
- Water-resistant coatings (latex)
- Biodegradable products (corn-starch packing "peanuts")
- Biomaterials (organic/inorganic intefaces)
- Liquid crystals
- Low-friction materials (teflon)
- Synthetic oils and greases
- Gaskets and O-rings (rubber)
- Soaps and surfactants

Classes and Properties: Semiconductors

Distinguishing features

- Made primarily from metalloids
- Regular arrangement of atoms (crystals, but not, e.g., solar cell amorphous Si)
- Extremely controlled chemical purity
- Adjustable conductivity of electricity
- Opaque to visible light
- Shiny appearance
- Some have good plasticity, but others are fairly brittle
- Some have an electrical response to light

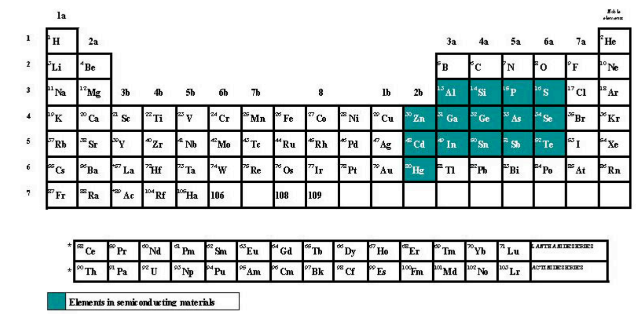
• Semiconductors define the Digital Revolution and Information Age.

• Starting with extremely pure crystalline form, their electrical conductions can be controlled by *impurity doping* (and defect).

• The result is a tiny electrical switching called a "transistor". Transistors (at present) can be packed to about 1 billion in the size of a Lincoln Penny.

Classes and Properties: Semiconductors

Elements occurring in semiconductors



Classes and Properties: Semiconductors

Applications and **Examples**

- Computer CPUs
- Electrical components (transistors, diodes, etc.)
- Solid-state lasers
- Light-emitting diodes (LEDs)
- Flat panel displays
- Solar cells
- Radiation detectors
- Microelectromechanical devices (MEMS)
- Examples: Si, Ge, GaAs, and InSb

Classes and Properties: Composites

Distinguishing features

- Composed of two or more different materials (e.g., metal/ceramic, polymer/polymer, etc.)
- Properties depend on amount and distribution of each type of material.
- Collective properties more desirable than possible with any individual material.

Applications and **Examples**

- Sports equipment (golf club shafts, tennis rackets, bicycle frames)
- Aerospace materials
- Thermal insulation
- Concrete
- "Smart" materials (sensing and responding)
- Brake materials

Examples

- Fiberglass (glass fibers in a polymer)
- Space shuttle heat shields (interwoven ceramic fibers)
- Paints (ceramic particles in latex)
- Tank armor (ceramic particles in metal)

Engineering Materials: controlling Processing - Structure - Properties - Performance

Realistically engineering materials: Trade-off

- Properties (What do we need or want?)
- Deterioration (How long will it last?) *Men's gym shoes last longer! Why?*
- Cost (What's the biggest bang for the buck?)
- Resource depletion (How to find new reserves, develop new environmentally-friendly materials, and increase recycling?)

How to decide what materials to use?

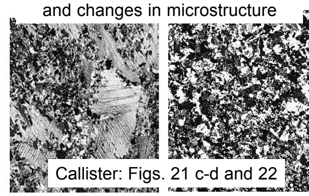
- Pick Application ⇒ Required Properties (mech., electrical, thermal, …)
- Properties ⇒ Required Materials (type, structure, composition)
- Material ⇒ Required Processing (changes to structure and desired shape, via casting, annealing, joining, sintering, mechanical, …)

Structure, Properties & Processing

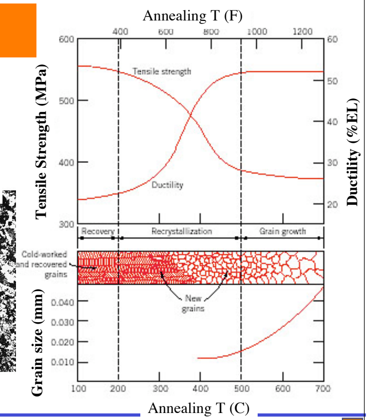
- Properties depend on structure
- Processing for structural changes

Can you correlate structure and strength and ductility?

Strength versus Structure of Brass and changes in microstructure



Callister: Figs. 21 c-d and 22



Electrical: Resistivity of Copper

Increase resistivity of Cu
- by adding impurities
- by mechanical deformation

Resistivity 10^{-8} Ohms-m

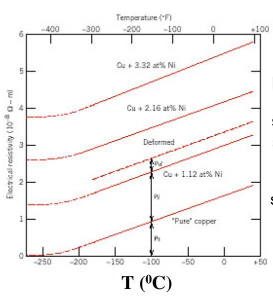
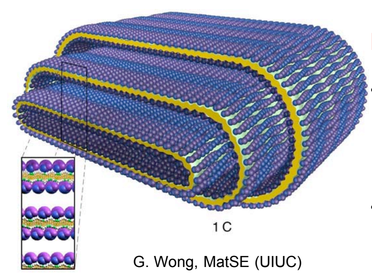


Fig. 19.8 Callister

scattering of e- by microstructure
scattering of e- impurities

scattering of e- by phonons

Biomaterials: Self-Assembled Tubules



G. Wong, MatSE (UIUC)

Potential Nanotechnology

- Self-assembled 'artificial bacterium' comprised of charged membranes and cytoskeletal protein rods.
- These rigid-walled, nano-scale capsules have potential drug delivery applications.

Nanometers: things that span ~10^{-9} m
100 nm ~ 500 atom diameters

Thermal: Conduction of Brass

• low from ceramic oxide (structure and conduction properties)
• changes due to alloying in metals (even though same structure)

Silica (SiO_2) fibres in space shuttle tiles

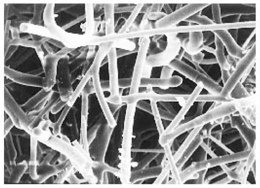
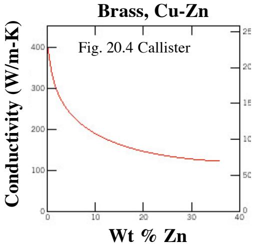


Fig. 23.18 Callister



Optical: transmission of light

e.g., Light transmission of Alumina (Al_2O_3 a.k.a. sapphire). single crystal, polycrystals (low and high porosity)

Which one is single crystal? Why?

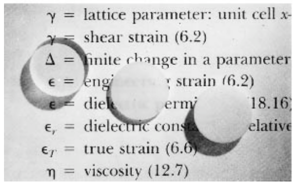
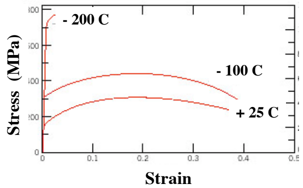


Fig. 1.2 Callister

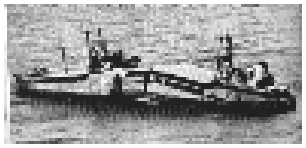
Deterioration and Failure

e.g., Stress, corrosive environments, embrittlement, incorrect structures from improper alloying or heat treatments, …

bcc Fe Fig. 6.14 Callister



USS Esso Manhattan 3/29/43
Fractured at entrance to NY harbor



http://www.uh.edu/liberty/photos/liberty_summary.html

MSE 280 Goals

- Understand the *origin* and *relationship* between "processing, structure, properties, and performance."
- Use "the right material for the right job".
- Help recognize within your discipline the design opportunities offered by "materials selection."

While *nano-, bio-, smart- materials* can make technological revolution, *conservation and re-use methods and policies* can have tremendous environmental and technological impacts!

Hybrid cars in 2004 are as efficient as fuel-cell cars of tomorrow!
Considering reforming, or energy needed to produce hydrogen, or that gasoline has much more energy density than hydrogen.

Motivation: Materials and Failure

Without the right material, a good engineering design is wasted. Need the right material for the right job!

- Materials properties then are responsible for helping achieve engineering advances.
- Failures advance understanding and material's design.
- Some examples to introduce topics we will learn.

The COMET: first jet passenger plane - 1954

- **In 1949, the COMET aircraft** was a newly designed, modern jet aircraft for passenger travel. It had bright cabins due to large, square windows at most seats. It was composed of light-weight aluminum.
- In early 1950's, the planes began falling out of the sky.

These tragedies changed the way aircraft were designed and the materials that were used.

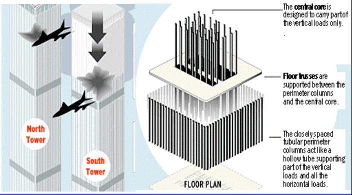
- The square windows were a *"stress concentrator"* and the aluminum alloys used were not *"strong"* enough to withstand the stresses.
- Until then, *material selection for mechanical design* was not really considered in designs.

Concorde Jetliner - August, 2000

- A Concorde aircraft, one of the most reliable aircraft of our time, was taking off from Paris Airport when it burst into flames and crashed killing all on board.
- Amazingly, the pilot knowingly steered the plane toward a less populated point to avoid increased loss of life. Only three people on the ground were killed.
- Investigations determined that a jet that took-off ahead of Concorde had a *fatigue-induced* loss of a metallic component of the aircraft, which was left on runway. During take-off, the Concorde struck the component and catapulted it into the wing containing filled fuel tanks. From video, the tragedy was caused from the spewing fuel catching fire from nearby engine exhaust flames and damaging flight control.

World Trade Center Collapse

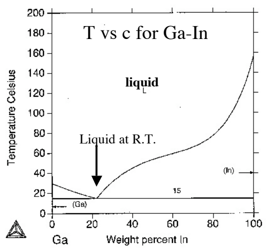
- *Tubular* constructed building.
- Well designed and *strong*.
- Strong but not from *buckling*.
- Supports lost at crash site, and the floor supported inner and outer tubular structures.
- Heat from burning fuel adds to loss of structural support from softening of steel (strength vs. T, stress-strain behavior).
- Building "pancakes" due to enormous buckling loads.



See estimate by Tom Mackie in MIE

Alloying and Diffusion: Advances and Failures

- *Alloying* can lead to new or enhanced properties, e.g. Li, Zr added to Al (advanced *precipitation hardened* 767 aircraft skin).
- It can also be a problem, e.g. *Ga is a fast diffuser at Al grain boundaries* and make Al catastrophically *brittle* (no *plastic behavior* vs. *strain*).
- Need to know *T vs. c phase diagrams* for what alloying does.
- Need to know *T-T-T (temp - time - transition) diagrams* to know treatment.



Bringing an plane out of the sky!

When Ga (in liquid state) is *alloyed to Al it diffuses* rapidly along *grain boundaries* (more volume) making bonds weaker and limiting *plastic response.*

All these are concepts we will tackle.

T.J. Anderson and I. Ansara, J. Phase Equilibria, 12(1), 64-72 (1991).

Precipitation: The Andromeda Galaxy

MSE 280: Introduction to Engineering Materials

"Because without materials, there is no engineering."

- **Engineering Requires Consideration of Materials**
  The right materials for the job - sometimes need a new one.

- We will learn about the fundamentals of
  Processing ⇒ Structure ⇒ Properties ⇒ Performance

- We will learn that **sometime only simple considerations of property requirements chooses materials.**

  Consider in your engineering discipline what materials that are used and why. Could they be better?