INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 224281/2/3/4/5/6
CABLE: CENTRATOM - TELEX 460392 - I

SMR/388 - 19

SPRING COLLEGE IN MATERIALS SCIENCE
ON
"CERAMICS AND COMPOSITE MATERIALS"
(17 April - 26 May 1989)

APPLICATIONS OF ADVANCED CERAMIC MATERIALS

XI-REN FU
Shanghai Institute of Ceramics
Academia Sinica
865 Chang-Ning Road
Shanghai 20050
People's Republic of China

SPRING COLLEGE IN MATERIALS SCIENCE

ON "CERAMICS AND COMPOSITE MATERIALS"

APPLICATIONS OF ADVANCED CERAMIC MATERIALS

Xi-Ren Fu

Shanghai Institute of Ceramics, Academia Sinica

1) Applications of Advanced Structural Ceramics

2) Applications of Advanced Functional Ceramics

3) Applications of Ceramic Matrix Composite Materials

INDUSTRIAL MATERIALS

* Metallic Materials
* Organic Materials
* Inorganic Nonmetallic Materials
  -- CERAMICS

INORGANIC NONMETALLIC MATERIALS

* Monolithic crystals
* Glasses and crystallized glasses
* Polycrystals
  -- combination of small crystals -- CERAMICS

CERAMICS

* Traditional -- pottery, porcelain etc.
* Advanced -- oxides, nitrides, borides etc.

ADVANCED CERAMICS

- made from extremely pure, ultrafine, inorganic particles
- the composition of which is very carefully controlled
- the particles are formed, agglomerated, and heat-treated under tightly monitored conditions
- results in superior and more reproducible performance characteristics

MAIN ADVANCED STRUCTURAL CERAMICS INTERESTED

1) Oxide ceramics

* Alumina and aluminates
* Magnesia
* Zirconia and zirconates
* Beryllia

2) Silicon nitride-based ceramics

3) Silicon carbide-based ceramics

4) Transformation toughened ceramics

* Partially stabilized zirconia (PSZ)
* Tetragonal zirconia polycrystalline (TZP)
* Zirconia toughened alumina (ZTA)
* Zirconia toughened mullite (ZTM)

5) Cermets

-- Ceràmics/metal composites

UNIQUE PROPERTIES OF ADVANCED STRUCTURAL CERAMICS

* High strength
* Strength retention at elevated temperatures
* High hardness
* High elastic modulus
* Dimensional stability
* High corrosion and erosion resistance
* High oxidation resistance
* High wear resistance
* High radiation resistance
* High thermal stability
* Low mass density
* Low coefficient of friction
* Low coefficient of thermal expansion
* Low ablation rate

MAIN APPLICATIONS OF ADVANCED STRUCTURAL CERAMICS

1) Mechanical applications
2) Metallurgical applications
3) Automotive applications
4) Paper and board production
5) Textile machinery parts
6) Thermal applications
7) Chemical applications
8) Nuclear applications
9) Biological applications
10) Military applications
11) Daily life applications
12) Others

1) MECHANICAL APPLICATIONS

* Ceramics for Machining

* Mechanical Seals

* Ceramic Bearings

* Sandblast Nozzle

* Ceramic Coiled Springs

CERAMIC CUTTING TOOLS

Materials

1) Alumina-based cutting tools

* Sintered or hot-pressed α-Al_2O_3 ceramics

* Al_2O_3-TiC composites

* Zirconia toughened alumina ceramics (ZTA)

* SiC whisker reinforced Al_2O_3 composites

2) Silicon-nitride based cutting tools

* Sintered or hot-pressed silicon nitride

* Sialons -- solid solution of Si_3N_4 and Al_2O_3

* Si_3N_4-Y_2O_3-TiC composites

* SiC whisker reinforced Si_3N_4 composites

3) Superhard materials

* Cubic boron nitride (CBN)

* Synthetic diamond

4) Ceramic-coated cutting tools

* TiC, TiN, HfC, HfN single layers coated on WC-Co

* TiC/TiN, TiC/Al_2O_3, TiC/Al_2O_3/TiN etc. laminates coated on WC-Co

* TiC or Ti(C, N) coatings on Si_3N_4-TiC composites

Features:

* High machining speed
* Increased productivity
* Reduced production cost
* Improved dimensional accuracy
* Improved finish of workpiece
* Longer tool life
* Extremely hard materials can be machined

Market:

1977	$ 58 million
1986	$ 433 million
1991	$ 885 million
1995	$ 1625 million

(Souce: The Freedonia Group, Inc.)

MECHANICAL SEALS

Materials:

* Alumina-based ceramics and cermets
* Silicon nitride-based ceramics
* Silicon carbide-based ceramics
* Toughened zirconia and other oxides
* Graphite

Features:

* High hardness
* Low friction
* High resistance to corrosion
* Low thermal expansion
* High thermal conductivity
* Excellent thermal shock resistance
* Higher temperature capability

Application examples:

1) Face seals

* Sand slurry pumps (pump ~ 35% solids)
* Fuel pumps
* Chemical processing and handling
* Washing machines and dishwashers
* Garbage disposals
* Automotive water pump seal faces

2) Ceramic seal discs

* Single and twin-lever mixers
* Thermostat mixers or valves

- Guarantee that water-borne solids like sand, rust or lime fail to damage the seal discs.
- The dimensional stability keeps discs level and tight even under conditions of strongly fluctuating pressure and extreme temperature differences of flowing water.

3) Water pump seal faces

Materials:

* Sintered alpha-silicon carbide ceramics

Features:

* A greater resistance to both wear & thermal shock
* Used to replace alumina seal faces for automotive water pumps
* Meet the performance needs of European cars, such as Volkswagen/Audi, Porsche 959S, Fiat turbodiesels etc.
* Annual production of 3-4 million seals is projected for 1989
* The ultimate goal is to produce a pump that lasts the lifetime of the automobile without leaking

- This time frame translates into 200,000 km or 120,000 miles

CERAMIC BEARINGS

Materials:

* Sintered silicon nitride ceramics
  - Low friction coefficient
  - High wear resistance
  - High compressive strength
  - Extremely long fatigue life
  - Failure mode of rolling elements is not catastrophic

Types:

* All ceramic - both rolling elements and race are made of ceramics
* Hybrid - ceramic rolling elements in steel race

Features:

* Increased corrosion resistance with less lubrication
* Can withstand temperatures as high as 1100°C
* Higher speeds revolution than steel bearings
* Ligher weight
* Insulation effect
* Anti-magnetic
* Can work in vacuum environment

Major application areas:

* High-temperature & high speedes - all-ceramic
* Low-temperature & high speeds - hybrid
* High acceleration conditions - all-ceramic or hybrid
* Corrosive/hostile environments - ceramic or hybrid
* Ultraprecision conditions - all-ceramic or hybrid

Market:

Worldwide sales of ceramic bearings are currently in the range of $3 to 5 million.

By the mid-1990's the market could reach $75 to 150 million in the U.S. and $ 300 to 500 million worldwide

- Aerospace
- Defence
- Machine tool
- Biotechnology
- Automotive industries
- General industry

SANDBLAST NOZZLE

Materials:

* Sintered alumina ceramics
* Hot-pressed boron carbide
* Cobalt-bonded WC cermet

Features:

* High wear resistance
* Low cost

Functions:

* For cleaning metal surface prior to finishing
* For removing the ceramic molds from metal castings
* For cleaning ceramic parts after sintering
* For applying inscriptions to memorials

Particles of SiO_2, Al_2O_3, or other abrasives are carried by room-temperature high-pressure air through the sandblast nozzle to do the cleanings.

CERAMIC COILED SPRINGS

Material:

Partially stabilized zirconia

Properties:

* Modulus of transverse elasticity is virtually identical to that of steel springs
* Have no permanent set in fatigue when used in high temperature environments

Advantages:

* Lighter than steel springs
* Superior resistance to corrosion
* Can be used at high temperatures
* Electrically insulated
* Will not draw magnetism

2) METALLURGICAL APPLICATIONS

BREAK RINGS
FOR HORIZONTAL CONTINUOUS CASTING OF STEEL

Materials:

* Boron nitride ceramics
* Reaction sintered Sialon-10% BN composite
* Hot-pressed Si_3N_4-BN composite

Features:

* Can be easily machined to close toleraces
* Excellent thermal shock resistance
* High thermal conductivity
* Not wet by molten steel and other metals
* Resistant to corrosion of molten steel
* Long service life
* Non-toxic

CERAMIC PARTS FOR METAL FORMING

Materials:

* Toughened zirconia ceramics
* Silicon nitride ceramics
* TiC-TiN cermets

Features:

* High strength
* High wear resistance
* Outstanding friction behavior
* High temperature stability
* No tendency to weld
* Excellent surface quality of the products
* Trouble-free and cost-effective
* Long service life

Application examples:

* Forming tools for tube bending and expanding
* Mandrels for the drawing of pipe and tube
* Rollers in the steel rolling process
* Dies for extrusion of metal parts

CERAMIC ROLLERS FOR THIN METAL PLATES

Materials:

* Sialon-based ceramics

Features:

* Excellent wear resistance
* High durability
* Extremely smooth surface
* Lower elastic modulus - 300 GPa vs 500 GPa for the superhard alloy rollers

Application examples:

* Cold rolling of stainless steel into thin plates
- To produce mirror finishes on plates
- Have a service life 10 times that of steel rollers
- Much lighter abd easier to use
* Warm rolling (450^{o}C) of W, Ti & other rare metals
- Can last up to 500 h with continuous operation vs only 2 h for superhard alloy rollers
- Yield a more precise product
* Cold rolling of aluminum and copper
- Never stick to rollers due to chemical reactions

CERAMIC WIRE DRAWING PARTS

Materials:

* Alumina ceramics
* Zirconia ceramics

Types of wire drawing parts:

* Drawing cones
* Rings
* Pulleys
* Guide rollers

Features:

* Extremely wear resistant
* Suitable for manufacturing all types of wire
* High surface quality of wire
* Cost-effective

CERAMIC WELDING PARTS

Materials:

* Silicon nitride ceramics
* Chromium oxide doped alumina ceramics

Types:

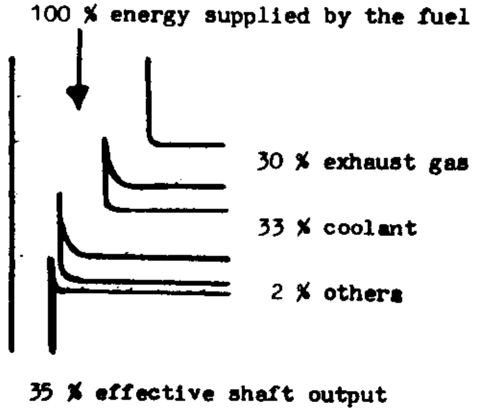
* Welding cups (gas shrouds)
* Location pins

Features

* Excellent thermal shock resistance
* High-temperature resistance
* Electrical insulation
* Wear resistance
* High strength
* Resistance to molten metal spatter

3) AUTOMOTIVE APPLICATIONS

- Ceramic Precombustion Chamber
- Ceramic Glow Plug
- Ceramic Turbocharger Rotor
- Ceramic Valve
- Ceramic Rocker Arm Pad
- Ceramic Valve Guide
- Ceramic Exhaust Portliner & Manifold
- Ceramic Piston Pin
- Ceramic Fuel Needle Valves
- Ceramic Tappet Shim
- Ceramic Roller Cam



Energy balance of a conventional diesel engine

CERAMIC PRECOMBUSTION CHAMBER

(SWIRL CHAMBER HOT PLUG)

Material:

Sintered silicon nitride ceramics

Features:

* Fast engine start-ability
* Improved combustion characteristics
  -- under low-load condition
* Higher combustion chamber temperature
* Lower noise level
* Lower particulate level in exhaust gas
* Higher engine output

CERAMIC GLOW PLUG

Materials:

Tungsten alloy heating element embedded
in sintered silicon nitride body
-- replaced Mg-Ni-Cr wire previously used

Features:

* Fast engine start-ability
  -- especially in cold regions
* Longer after-glow life
* Higher combustion stability
  -- during idling and low-load operation
* Better fuel economy
* Greater plug durability

CERAMIC TURBOCHARGER ROTOR

Materials:

* Silicon nitride-based ceramics
* Silicon carbide-based ceramics

Features:

* 40% ligher in weight than metal rotor
* Moment of inertia is reduced by ~35%
* Reduced turbo lag
* Improved acceleration response
* Increased performance at all speed
* Handles increased exhaust temperatures
  ~1,000°C
* Improved fuel efficiency
* Reduced emissions

CERAMIC VALVE

Material: Sintered silicon nitride ceramics

Features:

* Reduced inertia weight due to lighter weight
* Improved response in high rpm range
  -- Increased output as a result of higher rpm.
* Mated to an aggressive, high lift cam
  -- Offers improved intake and exhaust efficiency.
* Reduced load on valve spring reduces mechanical loss
  -- Improves acceleration response, increase torque at low speed, improves fuel economy.
* Higher heat resistance than super alloy
* Higher thermal conductivity than titanium alloy.

- During the June, 1988 Mileage Competition held in Silverstone, U.K., a vehicle powered by an engine equipped with ceramic valves won first place by setting the world record of 6409 mpg.
- Ceramic valves are being road tested by Norton/TRW Ceramics. Since November 1987 the test vehicle has logged several miles of city and highway operation, including long-distance trips.

CERAMIC ROCKER ARM PAD

Materials:

Silicon nitride ceramic pad inserted in the aluminum rocker arm

Features:

* Improved wear resistance
* Compatibility with mating materials
* Reduced friction
* Maintenance free operation for long period

CERAMIC VALVE GUIDE

Materials:

* Silicon nitride ceramics
* Toughened zirconia ceramics

Features:

* Outstanding wear resistance
* Non-scaling at ~1,000°C
* 90% less wear of composite valve guide-valve stems

CERAMIC EXHAUST PORTLINERS AND MANIFOLD

Material:

* Aluminium titanate

Features:

* Low thermal conductivity
* castable into aluminum and cast iron
* durability under all operating conditions
* low specific weight
* low thermal expansion coefficient
* high thermal shock resistance

Advantages:

* lower heat flow into the cooling system
* elevated exhaust gas temperatures
* lower temperature of the cylinder head
* lower emissions

CERAMIC PISTON PIN

Material:

* Sintered silicon nitride ceramics

Potential advantages:

* 50% mass reduction
* 70% reduction in reciprocating mass of cylinder
* Reduced bearing loads and stresses
* 7% reduction in secondary shaking forces of a four cylinder engine
* Specific fuel consumption will be reduced by $\leq$1%

Problems:

* Increased cost
* Catastropic failure mode inherent to pistons
* Sealing problem due to high elastic modulus

Market prediction:

- may reach 5% market penetration as soon as 1995

4) PAPER AND BOARD PRODUCTION

Materials:

* Alumina ceramics
* Silicon carbide ceramics

Papermaking machine parts:

* Perforated and felt suction boxes
* Covers
* Cleaner cones
* Other paper related parts

Features:

* extreme hardness
* good wear resistance
* high chemical stability
* long service life

5) TEXTILE MACHINERY PARTS

Materials:

* Alumina ceramics (white color)
* Alumina ceramics doped with chromia (pink color)

Parts:

* Friction discs
* Doffing tube and doffing tube inserts
* Tension elements
* Thread guides

Features:

* High mechanical strength
* High hardness
* Excellent heat and wear resistance
* Superior electrical insulation
* Low coefficient of kinetic friction
* Very beautiful lustrous surfaces

6) THERMAL APPLICATIONS

HIGH TEMPERATURE HEAT EXCHANGER

Materials:

* Silicon carbide-based ceramics
* Silicon nitride ceramics
* Lithium aluminum silicate (LAS)
* Magnesium aluminum silicate (MAS)
* Mullite

Features:

* High temperature capability
* Corrosion resistance
* Good thermal shock resistance
* High thermal conductivity

Application examples:

* Steel slot forge furnace recuperator
* Aluminum remelt furnace recuperator
* Solar-thermal systems
* Domestic hot water heating systems
* Indirect fired gas turbine

HEAT EXCHANGER FOR SOLAR ENERGY UTILIZATION

- For gas-cooled solar tower generating station

Materials:

* Reaction-bonded silicon carbide infiltrated with Si

Features:

* High thermal stability
* Excellent resistance to corrosion
* Outstanding resistance to oxidation beyond 1300°C
* High thermal conductivity
* Good resistance to thermal shock
* Gas tightness

- The strength of the material must be sufficiently high up to 1200°C.
- The air heated in the receiver is pressurized to about 10 bars.
- The material has to be stable in air in the range from 25° - 1200°C because of the periodic sun rise and sunset.
- The material has to have a good thermal conductivity to minimize the existing thermal tensions in tubes.

CERAMIC REFRACTORY TUBES AND OTHER WARES

Materials:

* Mullite ceramics
* Alumina ceramics
* Stabilized zircomia ceramics
* Magnesia ceramics
* Silicon nitride ceramics
* Silicon carbide ceramics
* Aluminium silicate ceramics

Main applications:

* Ceramic refractory tubes
- for combustion, calcination, sintering, heating in the range of 1450° to 2000°C.
* Nonmetallic pyrometer tubes
- for protecting thermocouples in lab or plant
* Insulating tubes for thermocouples
* Combustion crucibles
- for making quick analysis of C and S in steel
* Combustion boats
- for quantitative analysis

7) CHEMICAL APPLICATIONS

HONEYCOMB CATALYST SUBSTRATE

Material:

* Cordierite ceramics

Features:

* Large surface area per unit weight
* Small fluid resistance
* Good flow-velocity distribution
* Small thermal shock resistance
* Can be used at high temperatures
* Small thermal expansion coefficient

Main applications:

* Purification of internal combustion engines
* Cleaning and deodorization of plant exhaustic gases
* Cleaning of organic gases by oxidation
* Energy saving as heat-exchangers, heat-catalyzers, burners, flame holders etc.

CERAMIC VALVES AND TUBE LINER

Materials:

* Alumina ceramics
* Reaction bonded silicon nitride ceramics
* Reaction bonded silicon carbide ceramics
* Toughened zirconia ceramics

Features:

* Great mechanical strength
* Excellent resistance to various chemical reagents
* Good wear resistance
* High dimensional accuracy
* Long service life.

8) NUCLEAR APPLICATIONS

I. Ceramics in Nuclear Fission Power Generation

NUCLEAR FUELS

Materials:

* Oxides: UO_2, $(U-Pu)O_2$, $(U, Th)O_2$
* Carbides: $(U, Pu)C$, UC_2
* Nitrides: $(U, Pu)N$, $(Th, U)N$

Forms of fuels:

* Pellets - a solid right circular cylinder with a diameter of ~ 6 mm & l/d of 0.9 to 1.2
* Microspheres - usually 40 to 60 µm, loaded into cladding tubes.
* Coated particles - up to 1 mm in diameter, fuel kernel coated with C and SiC

Features:

* Higher melting points than metal fuel materials
* Dimensional stability under neutron irradiation
* Chemical inertness
* Stability against corrosion
* Ability to withstand the fissioning of a large part of fissile atoms without deterioration

CONTROL MATERIALS (NEUTRON POISONS ABSORBERS)

Materials:

* Oxides: UO_2-Gd_2O_3, Gd_2O_3-Al_2O_3, Eu_2O_3
* Carbides: B_4C
* Mixtures: B_4C-Al_2O_3, B_4C-Al_2O_3, B_4C-SiO_2

Forms:

* Mixed with the fuels
* As discrete control rods

Features:

* B_4C contained in steel tubes is the most reliable and economical material as control rods
* Gd_2O_3 possesses the isotops Gd-155 and Gd-157
- they are highly absorbent to neutrons in the thermal energy range
- they are burnable poisons
- increase the operating period of reactor core
- improve core performance(better power distribution)
- increase safty and a reduction in mechanical control
* Eu_2O_3 has high cross section and long lifetime

II. Ceramics in Nuclear Fusion Power Generation

FIRST WALL AND BLANKET REGION MATERIALS

Materials:

* Isotropic graphites and CVD carbon
* Silicon carbide ceramics

Features:

* Low gamma absorption
* Low attenuation of X-rays
* High oxidation resistance for SiC
* Low electrical conductivity
* Extensive histories in fission reactor applications (particularly graphite)
* Low permeability to tritium
* High fatigue and thermal shock resistance
* Displacement damage nearly simulated in fission reactor irradiations

Advantages:

* Very high temperature resistance
* Relatively good radiation damage resistance
* Extensive native resources
* A well established industrial manufacturing base

9) BIOLOGICAL APPLICATIONS

CERAMIC DENTAL IMPLANT

Materials:

* Single-crystal alumina
* Alumina ceramics

- Single-crystal alumina root is set into the alveolar bone with a softer polycrystalline alumina crown.

Features:

* Exhibits hard and soft tissue biocompatibility
* To function under the occlusive stresses and alterations
* Exhibit an elastic modulus 20 times greater than that of cortical bone.

- Over 60,000 successful dental implants were performed over the past 10 years.

* Alumina ceramics are available for all tooth areas for molars and incisors, as anchors for bridges and dentures.

ARTIFICIAL HEART VALVES

Materials:

* Low-temperature isotropic carbon (LTI)

- This pyrolitic carbon is formed in a fluidized bed from the pyrolysis of a hydrocarbon such as methane at 1000^o to 2400^{o}C.

* Ultralow-temperature isotropic carbon (ULTI)

- This vapor-deposited carbon is produced by any number of vacuum heating processes to form an impermeable isotropic coating.

Features:

* Biocompatible - not associated with thrombotic complications and don't produce hemolysis
* Stable and nonreactive as tissue implants
* Outstanding wear resistance - carbon heart valves are able to withstand the rigors of millions of openings and closings

Literally hundreds of thousands of these devices have been made since their introduction 15 years ago.

KNEE AND HIP JOINT PROSTHESES

Materials:

* Pure alumina ceramics
* Toughened alumina and zirconia ceramics
* Ceramic matrix composites

Configulation:

* Acetabular cup - alumina or zirconia ceramics
* Femoral head (ball) - alumina or zirconia
* Stem insert - ceramic composites or metal

Features:

* Higher mechanical strength under load
* Greater fracture toughness
* Greater surface fineness
* Excellent biocompatibility
* Low wear rate
* Lower risk of failure

The alumina ball to alumina cup combination seems to be the most desirable to date.

10) MILITARY APPLICATIONS

ARMOR

- Helicopter armor
- Infantry armor
- Ground vehicles armor

Materials:

* Boron carbide / Kevlar or fiberglass
* Silicon carbide / Kevlar or fiberglass
- Hot-pressed B_4C or Sintered SiC plates backed with Kevlar or fiberglass and covered with a fabric spall shield
- One-piece SiC armored helicopter seat bottom

Features:

* High hardness
* High dynamic strength
* High elastic properties
* Low theoretical density

Properties of hot-pressed B_4C ceramics:

- Hardness: ~3500 kg/mm^2
- Density: 2.4 to 2.5 g/cm^3

Properties of sintered SiC ceramics:

- Hardness: $\sim$2[illegible]00 kg/mm^2
- Density: 3.10 g/cm^3

One-piece SiC seat bottom is $\sim$ 30% lighter than antiballistic steel.

Advantages:

A plate of B_4C about 6.4 cm thick with a similar backing of fiberglass can stop a 0.3 caliber armor-piercing projectile. A much heavier layer of steel would be required to defeat the same projectiles.

STELLITE LINERS IN GUN BARRELS

Materials:

* Sintered silicon carbide tube

Features:

* Increased wear resistance
* Increased erosion resistance
* Higher temperature operation
* Lighter weight
* Potentially lower cost

11) DAILY LIFE APPLICATIONS

1) Ceramic scissors

Toughened alumina, toughened zirconia

* Next to diamond in hardness
* Chemically resistant to acid and alkali
* Never rust
* Not affected by magnetism

2) Ceramic knives

Silicon nitride, toughened zirconia

* Never rust in water
* Not corroded by salt
* Do not leave a metallic taste in foods
* Long service life

3) Bottle opener

Toughened zirconia

* Durable, hard and non-rusted

4) Ceramic ball point pens

Toughened alumina and zirconia

* Extreme durability and smooth writing
* Resistant to abrasion
* Maintain a non-varying line width

5) Ceramic Tweezers

* Alumina ceramics
* Zirconia ceramics
* Ceramic tweezer tips supported by coated stainless steel spring bodies
- Highly resistant to chemicals
- Anti-magnetic & electrically insulating
- Less prone to static electricity than plastic
- Higher abrasion resistance than metal
- Can be used in precision engineering, surface-mount electronics, silicon-waferindustries & microscope work etc.

6) Wrist watch cases

* Silicon nitride ceramics
* Black zirconia ceramics
- Exhibits a beautiful glossy scratch-proof surface

7) Golf and baseball shoe spikes

* Toughened zirconia ceramics
- Light in weight
- Considerably increased degree of grip
- 20 times stronger than metal spikes

8) Ceramic nail files

* Toughened zirconia and alumina ceramics
- Non-rust and comfortable

9) Ceramic golf putters

* Toughened zirconia ceramics
* Graphite fiber reinforced composite shaft
- Does not chip, break, scar or dimble
- Help to keep the blade square and on-line during take-away, impact and follow-through
- Allows the golfer to reduce tension in the grip and stroke
- Putter sales in 1987 totaled $40 million

10) Ceramic ornaments

* Alumina ceramics
* Zirconia ceramics
* Other ceramics
- Different kinds of advanced ceramics can be fashioned into fine accessories

11) Ceramic screw drivers

* Toughened alumina ceramics
- Electrically insulating
- Non-magnetic
- High wear resistance
- Can be used in TVs manufacturing

2) Applications of Advanced Functional Ceramics

ADVANCED STRUCTURAL CERAMICS

-- Mechanical properties

-- Thermal properties

-- Chemical properties

-- Biological properties

-- Nuclear properties

ADVANCED FUNCTIONAL CERAMICS

-- Optical properties

-- Electrical properties

-- Magnetic properties

MAIN ADVANCED FUNCTIONAL CERAMIC MATERIALS

1) Optical ceramics

* Light and infra-red transmitting ceramics
* Electro-optic ceramics
* Laser materials

2) Electronic ceramics

* Electrical insulation ceramics
* Electrical conductor materials
* Semiconductor materials
* Ion conducting materials
* Superconductors
* Capacitor dielectrics
* Piezoelectric ceramic materials

3) Magnetic ceramics

* Hard ferrites
* Soft ferrites

OPTICAL APPLICATIONS

ARC TUBES FOR HIGH PRESSURE SODIUM VAPOR LAMPS

Materials:

* Translucent alumina ceramics
* Yttria, Calcia, Spinel etc.

Features:

* Superior resistance to corrosion of sodium vapor
* High optical transmission at visible wavelength
* High stability at temperatures as high as 1,800 K
* A dependable life of more than 10,000 hours
* Much higher luminous efficiency than that of conventional lamps

RADOMES

- a protective covering and window
- for electronic guidance & detection equipment
- used on missile, aircraft and spacecraft

Materials:

* MgO, Al_2O_3, and Fused SiO_2
* MgF_2, ZnS, ZnSe, and CdTe
* Si_3N_4

Features:

* Transparent to the wavelength of electromagnetic radiation used by the equipment
* Resistant to high-velocity impact
  - by rain and other atmospheric particulates
* Resistant to thermal shock
* Low theoretical density

THERMAL/FLASH PROTECTIVE GOGGLES

Materials:

* Hot-pressed transparent PLZT ceramics

(PLZT - lead lanthanum zirconate titanate)

- The best composition is 9.5/65/35 PLZT

(65% $PbZrO_3$, 35% $PbTiO_3$ with 9.5% Pb replaced by La)

* An interdigitally-electroded PLZT wafer properly aligned and sandwiched between polarizers

Features:

* To provide protection from temporary flashblindness and permanent retinal burns caused by the brilliant flash of nuclear explosions.
* Very fast switching is possible to an optical density of 3.0 within 150 μs.
* Open-state transmittance is about 20%.

Other applications:

* Image storage
* Other electro-optic modulating devices
* New simple numeric and bar graph color displays

ELECTRICAL APPLICATIONS

CERAMIC HEATERS

Materials:

* Alumina ceramics + tungsten or molybdenum

- W or Mo are printed and embedded in the given pattern in alumina ceramics and are sintered into an integral unit.

Features:

* Acid-proof
* No wire breaking and degradation with time
* Uniform temperature distribution
  - due to the good thermal conductivity of Al_2O_3
* High capacity
  - due to high electric insulation of Al_2O_3
* Can be used at temperatures up to 900°C
* Smaller in size
* Lighter in weight

RESISTOR-CERAMICS

Materials:

* Mullite ceramics, forsterite ceramics
* Alumina ceramics with different contents of Al_2O_3
* Cordierite ceramics, zircon ceramics

Types of resistors:

* Carbon-film resistors
* Metal-film resistors
* Metal-oxide-film resistors

Features:

* High flexural strength
* High thermal conductivity
* Large insulation resistance
* Low thermal expansion coefficient
* Smooth surface

THICK FILM CHIP RESISTORS

* Produced by printing resistors on tiny ceramic substrates and offer highly accurate resistivity
* Can reduce the size and optimize the performance of VCRs, TVs, communication equipment etc.

CERAMIC SUBSTRATE MATERIALS

(CERAMIC PACKAGING MATERIALS)

* Mainly used to form Integrated Circuit Packages
* IC packages provide protection for IC chips from air and other elements
* Tens of thousands of circuit elements are integrated onto a tiny silicon chip for high performance

- Ceramic dual-in-line packages (CERDIP Type)
- Multilayer ceramic IC packages (MLC)
- Hybrid IC Subassembly substrates
- Chip carriers

Materials:

* Alumina ceramics

- For high performance packages such as multilayer chip carriers & substrates for hybrid circuits
- A low dielectric constant & dielectric loss
- Nonreactive and dimensionally s abl.
- Easy to form and relatively inexpensive
- Accounts for > 90% of current substrates sales
- Lower thermal conductivity than we'd like
- Higher thermal expansion coefficient than we'd like

* Beryllia ceramics
- High thermal conductivity at room temperature
- Used in military & some automotive applications
- High thermal expansion coefficient & toxicity prevent its significant increase in market

* Beryllia-doped silicon carbide ceramics
- Thermal expansion coefficient near that of Si
- High thermal conductivity
- Has already been applied as laser diode heat sinks and in forming single- & multichip pin-grid arrays

* Aluminum nitride ceramics
- Thermal conductivity is 10 times higher than Al_2O_3
- Good thermal expansion match with silicon
- Have excellent electrical resistivity
- Dielectrical constant is similar to those of Al_2O_3
- Mechanically stronger than either Al_2O_3 or BeO
- AlN substrates can be used to replace Al_2O_3 in power transistor modules, laser diode heat sinks, power hybrid circuits, and LSI & VLSI circuit packages

* Glass ceramics
- Can be made by the addition of glass to ceramics or by controlled crystallization of glass
- With a low dielectric constant of ~5
- Cosinterability with copper or gold
- Used for high-speed computer packages

* Cubic boron nitride and diamond
- Thermal conductivity is hundred time better
- Thin diamond films have been grown on a Silicon substrate using microwave plasma and methane and hydrohen gases
- Diamond films have even higher thermal conductivitiy
- Under development

Integrated ceramics

* Dielectric capacitors, resistors or inductors are incorporated in the substrate by the addition of various functional layers or surface patterns.

Monolithic multi-component ceramic substrates(MMC)

* The substrate is fabricated entirely from a functional material.

PTC THERMISTORS

(PTC - Positive Temperature Coefficient)

- The resistivity of PTC thermistors increases rapidly as the Curie temperature is reached

Materials:

* $BaTiO_3$-based ceramics with various additives
- Donor additives - La, Ce, Nb, Sb, Sm, Nd etc.
- Accepter additives - Mn, Cu etc.
- Additives to shift Curie temperatures - Sr, Sn, Pb

Features:

* Resistivity can be increased by several powers of 10 as the Curie temperature is reached
- Curie temperature can be shifted by additives by as much as 250°C
* Simple and reliable

Thermal applications:

* Mainly used as self-regulating heating elements
- Fuel evaporator for diesel engines
- Intake air heater & automatic choking heater
- To produce a warm air current for warming the hands while driving in winter
- Auto-stabilizing foot warmer & rice warmer
- Hair and clothes dryer
- Space heater, coffee makers & baby bottle warmers

Electrical application:

* Control elements in circuits
* To surge stabilization in the degaussing girdles for color TV sets

NTC THERMISTORS

(NTC - Negative Temperature Coefficient)

- The resistivity of NTC thermistors displays a drop at the Curie temperature

Materials:

* A combination of transition metal oxides
- Mn_3O_4, NiO, CuO, Co_3O_4 etc.
- Mn-Ni system, Mn-Co system, Mn-Co-Ni system etc.

Applications:

* A temperature sensor to measure relatively low temperatures such as that of cooling water or intake air.

* A fuel level sensor installed inside the fuel tank

- When the thermistor circuit is exposed to air, its temperature rises, triggering a warning light on the vehicle's dashboard

HIGH TEMPERATURE THERMISTORS

Materials:

* Stabilized zirconia
* Spinel oxide, such as $CoAl_2O_4$

Application:

As an exhaust-gas-temperature sensor in overheating warning systems in automobiles

DEWDROP SENSOR

Materials:

* Aluminum phosphate ceramics
* Zinc phosphate ceramics

- These ceramic semiconductors are built into the rear window glass. The sensor activates heater wires printed on the glass, which keep it from fogging over.

GAS SENSORS

To identify the individual gaseous species in the environment

- for warning against possible hazadous conditions
- for detection & determination of potential hazards

1) Tin oxide ceramics - porous sintered block, films

* A n-type semiconductor
* Conductivity increases when reducing gases exposed exposed to the sensor
* High sensitivity at medium temperatures
* Using a Pd dopant to generate sensitivity
* Using both Pt-black & Pd-black as catalysts for the detection of hydrocarbon

2) Zinc oxide ceramics

* A n-type semiconductor
* The sensitivity varies with different gases and catalysts - high selectivity

3) Ferric oxide ceramics - γ-Fe_2O_3, α-Fe_2O_3 etc.

* Porous sintered block with a grain size of 0.05-0.2 um and a porosity of 65%
* Sensitive to liquefied petroleum gas such as methane, butane etc. and ethanol

4) $LnMBO_3$ system ceramics

* Ln - La, Pr, Sm, Gd etc.
* M - Ca, Sr, Ba etc.
* B - Fe, Ni, Co etc.
* Examples: $LaNiO_3$, $La_{1-x}Sr_xCoO_3$
* Resistivity rapidly increases or decreases with the partial pressure in environments
* Used to detectethanol, CO and smoke etc.

5) $Ag_{0.04}V_2O_3$ thick film

* Produced by V_2O_3 doped with Ag
* Very sensitive to N_xO, even as low as 1 ppm
* Not influenced by H_2, CO, Butane and NH_3 etc.

ZINC OXIDE VARISTORS

Materials:

* ZnO-based highly multicomponent oxide ceramics
- A typical composition contains 97 mol% ZnO, 1 mol% Sb_2O_3 & 1/2 mol% each of Bi_2O_3, CoO, MnO, & Cr_2O_3

Features:

* With highly nonlinear current-voltage characteristics
- At a critical voltage the device shows a rapid increase in current flow.
* A simple, cost-effective way to protect electrical systems from transient pulse.
* Can be fabricated into a variety of sizes & shapes, this feature facilitates a high degree of flexibility for the users.
* Inherently able to absorb more energy than single junction protective devices.
- Energy absorption capability in 100's of J/cm^3 are now routinely available.
* Another application is for the protection of electric power distribution and transmission. ZnO varistor disks, each $\geq$ 100 cm^3 in volume are available.

HUMIDITY SENSORS

Materials:

* $MgCr_2O_4-TiO_2$ ceramics

Features:

* This ceramic sensor is porous - 85% dense.
* It is a p-type semiconductor for TiO_2 additions of up to 40%, for higher TiO_2 content the material is an n-type semiconductor.
* Adsorbed water molecules on the surface of ceramics dissociate into hydroxyl and hydronium ions, which alter the electrical resistivity.
* The water molecules formed on the materials are easily desorbed by either decreased pressure or temperatures slightly higher than room temperature.
* Response times are on the order of 12s with resistance decreasing and increasing as the relative humidity increases and decreases.
* These relative humidity sensors are designed for applications in microwave ovens, dryers, refrigeration units and air conditioners.

SODIUM-SULPHUR BATTERY

Materials:

* β''-alumina ceramics, $Na_{1.67}Mg_{0.67}Al_{10.33}O_{17}$

Features:

* A secondary high energy battery.
* The battery is operated at about 300°C, both the sodium anode and the sulphur cathode are molten.
* High electrical conductivity - $2\sim3\times10^{-1}\Omega^{-1}\ cm^{-1}$ (300-350°C).
* The theoretical energy density(~750 Wh/kg) is much higher than that of lead-acid battery(~170 Wh/kg).
* The practical energy density reaches ~ 200 Wh/kg, for lead-acid battery it is only 30 Wh/kg.
* Long cycle life - 2000~3000 cycles in laboratory
  >1000 cycles in practical use
* The structure is not complex and easy to fabricate.

Applications:

* Electric vehicle traction
* Electric energy conservation systems
* Nautical or aviation power systems

OXYGEN SENSORS

STOICHIOMETRIC AIR-FUEL-RATIO SENSORS

Types of sensors:

* Zirconia sensor - uses oxygen-ion conductivity
* Titania sensor - uses semiconductor properties

Zirconia sensors:

* Tube-shaped and laminate-shaped
* Made with Y_2O_3 partially stabilized ZrO_2
* A porous Pt functions as inside & outside electrodes to form an oxygen concentration cell.
* The sudden change in electric potential that occurs at the stoichiometric air-fuel ratio turns the sensor on and off.
* The size of this change varies depending on the temperature, it enables the sensor to detect the stoichiometric ratio.
* The laminated construction improves the output characteristics of the sensor at low exhaust gas temperatures and it is cost-effective.

CERAMIC SUPERCONDUCTORS

Materials:

* Oxides of yttrium, barium and copper, $YBa_2Cu_3O_7$
* A perovskite-type structure similar to $BaTiO_3$
* This material can be made superconductive at temperatures above that of liquid N_2 ($-196^{o}C$)
* Prices: liquid N_2 - ~$0.25/gal.
  liquid He - ~$11/gal.

Possible applications:

* Frictionless generators, motors & high speed trains;
* Levitating toys & gimmickes;
* Electronic Josephson junctions & resistaceless interconnects;
* Large magnetic fields for NMR medical diagnosis, nuclear accelerators & hydrogen fusion;
* Power transmission lines & closed-loop energy storage for load leveling;
* Radiation detectors for astronomy, oil exploration, and brain-wave research.

CERAMIC DIELECTRIC CAPACITORS (CONDENSERS)

* The devices, which store an electric charge, consist of conductive metal plates separated by ceramics.
* Used in tuning circuits and to protect logic and memory chips from damaging voltage levels.

Materials:

* Barium titanate ($BaTiO_3$) based ceramic materials

Features:

* A high dielectric constant. $BaTiO_3$ packs maximum capacity into minimum space.
* Additives can be used to alter both position and shape of the Curie peak to maximize flexibility.
* The dielectric constant (K) and its relationship to temperature can also be tailored to give:

- a uniform K within a special temperature range
- a linear variation of K with temperature to compensate for variations in other circuit components.

* $BaTiO_3$ can be cast into dense films less than 10 um
* The multilayer ceramic chip capacitors (MLC) are produced by precision-stacking of $BaTiO_3$ layers and firing together with preprinted precious metal electrodes.
* MLC are tiny but with a very high capacitance, can meet the demands for miniaturization.
* A typical Z5U chip-protection capacitor:

  Dielectric constant - from 6000 to 24,000

  Layer thickness - from $\sim 30\ \mu m$ to $< 15\ \mu m$

Market:

* For VCRs, TVs, communications equipment and many other electronic devices.

  U.S. - approximately 11 billion ceramic units

  Japan - 33 billion to 44 billion ceramic units

PIEZOELECTRIC CERAMICS TRANSDUCERS

* Piezoelectricity - refers to the creation of electricity by pressure, and conversely, the creation of mechanical strain by electricity.
* Piezoelectric ceramics serve as a transducer for electrical and mechanical energy.

Materials:

* Barium titanate
* Lead metaniobate
* Lead titanate zirconate of various compositions
* Lead titanate, lead magnesium niobate and sodium bismuth titanate

Features:

* High energy-conversion efficiency
* Compactness
* A wide range of operating temperatures
* Capability of being manufactured in various shapes

PIEZOELECTRIC IGNITERS

Materials:

* PZT ceramics - Lead titanate zirconate

Types:

* Handy lighters
- The coiled nose is flexible
- It can ignite any kind of household gas fuels
* Multispark handy lighters
- Suited for the ignition of oxy-acetlyene welders and other burners
- 4 or 5 spark discharges occur continuously to ensure ignition of the fuel gas
* Spark units
- It uses a battery power source
- When switched, spark discharges occur continuously to ensure ignition of increased calories city gas

Features:

* Resist heat and moisture, and semipermanent
* Does not require replacement of battery & elements
* City gas, propane gas butane gas, and natural gas can be ignited
* Ignition can be done by anyone with safty

PIEZOELECTRIC ACOUSTIC ELEMENTS - BIMORPHS

Materials:

* 2 thin piezoelectric ceramic plates bonded together

Features:

* A high-compliance, high output, voltage transducer
* Small size and lightweight
* Compactness and low power consumption (less than 1/5 as compared with the conventional magnetic buzzers
* Life is semipermanent because the contactless construction has no wering parts

Applications:

* The pick-up element of medium- & high-class stereo set cartridges, other vibration pick-up elements
* A sound generater in all types of electronic watches and alarms

CERAMIC FILTERS

- Ceramic filters are those components which use the resonant characteristics of piezoelectric ceramics to isolate a specific frequency.

Materials:

* PZT ceramics with different compositions

Features:

* A large electro-mechanical coupling coefficient
* Has advantages over conventional intermediate-frequency transformers using LC coils
- A single ceramic filter does the work of four of five conventional, medium frequency transistors.
- Non-adjusting performance
- High selectivity and compactness
* Emits noise in radios, TV sets, and communications equipment
* Surface acoustic wave (SAW) filters give more distinct TV pictures, and produce a distortion-free sound when used in a hi-fi set

SENSORS UTILIZING THE PIEZOELECTRIC PROPERTIES

Materials:

* $PbTiO_3$ & PZT with a variety of oxide additives

1) Knock Sensors

- This sensor makes the gasoline engine to achieve optimum ignition timing, resulting in improved output and fuel economy.
- A piezoelectric element is built into the spark plug washer to detect the cylinder pressure and convert it to an electric signal.

2) Raindrop Sensor

- Employs $BaTiO_3$ element to detect the impact of rain-drops, then the operation of wipers can be controlled to optimum speed.

3) Road Clearance and Rear Obstacle Sensor

- This sensor emits an ultrasonic wave toward the road surface and picks up the reflected wave to detect unevenness and obstacle in the road, then the damping force of the shock absorbers will be adjusted to march road condition.

MAGNETIC APPLICATIONS

Materials:

- The main ceramic magnetic materials are FERRITES.
- Ferrites are solid solutions of mixed oxides having in common the Fe_2O_3 in compositions.
- Yttrium-Iron garnet and γ-Fe_2O_3 should also be considered as ferrites.

Two classifications of ferrites:

1) Hard Magnetic Ferrites

* Formula - $MeO \cdot 6Fe_2O_3$ or $MeFe_{12}O_{19}$ (M=Ba or Sr)
* The crystal structure is hexagonal with the uniaxial C axis which the magnetic moment prefers to align.
* Energy is required to rotate the magnetic moment from this axis, so that to produce the permanent strongest magnets.
* Made by pressing the raw materials in a magnetic field, sintered and then magnetized, so that the tiny particles are oriented in the same direction.
* Used for the magnetic fields they produced.

2) Soft Magnetic Ferrites

* Formula - $MO\cdot Fe_2O_3$ or MFe_2O_4

  Mn-Zn ferrite, Ni-Zn ferrite, Mg-Mn ferrite etc.

* The crystal structure is cubic spinel, preference for any crystal direction should be very slight.

* This is to allow rapid reversal of the magnetic moment in response to rapid alterations (frequency) of the energizing field.

* A great number of different compositions are used depending on the application, frequency, cost, stability requirements, temperature, etc.

* Main applications

- Magnetic recording heads
  - must have excellent wear resistance
  - must be dense, large voids must be avoided
  - easy to machine and be able to take lap finish
  - become a huge business with the advent of audio, video recording and computers.

- Switch-Mode Power Supply (SMPS)

  Inverter Converter

  - takes 50-60 cycle ac or bettery powered dc, converts it to high frequency(20-50 kHz) ac, transforms it to different voltage levels, then rectifies them back to regulated dc, to power computers, microprocessors,instruments.
  - Comparison between metal & ferrite inverters (laminated metal at 60 Hz vs ferrite at 20 kHz)

  Advantages of ferrites:

  1. more efficient, lighter and smaller
  2. can be easily formed into different shapes
  3. can be used at high frequencies
  4. can be tailored for temperature coefficient
  5. generally low cost

  Disadvantages:

  1. low saturation flux density (B_s)
  2. low Curie point (T_c)
  3. decrease of permeability with time
  4. inability to lose heat rapidly
  5. brittle

- Ferrites for low field applications
- used in telecommunications as antennae, channel filters, wide band transformers, etc.

- Magnetic sensors
- ferrites with sharp and definite Curie points
- sensors for temperature control can be made
- position & rotational angle sensors have also been designed

- Magnetic shielding
- to render an aircraft invisible to radar

- Pollution control
- to scavenge pollutant materials such as Hg from waste streams.

- Ferrite electrodes
- used as electrodes in corrosive environments such as chrome plating

- Entertainment ferrites
- widely used in radio and television circuits as antennas, deflection yokes, flyback transformers

3) Applications of Ceramic Matrix Composite Materials

Main systems discussed:

* Fibre-reinforced ceramic composites
* Carbon-carbon composites

Main areas of applications:

* Aerospace
* Military
* Other high-performance applications
* Substitution for metals and traditional ceramics

Main limitations to wide applications:

* High cost of fibres and whiskers
* Increased fabrication complexity and cost
* Lack of high-quality reinforcement materials
* Lack of overall understanding of composite behavior (physical, chemical, & mechanical)

APPLICATIONS OF HIGH PERFORMANCE COMPOSITES

METAL MATRIX COMPOSITE

* METAL REINFORCEMENT

ORGANIC MATRIX COMPOSITE

* MISSILES
* AERONAUTICS
* SPACE
* AUTOMOTIVE
* SPORTS
* MISCELLANEOUS

HIGH TEMPERATURE ORGANIC MATRIX COMPOSITE

* AERO-ENGINES
* LEADING EDGES
* HIGH SPEED MISSILES

APPLICATIONS OF HIGH PERFORMANCE COMPOSITES

CARBON-CARBON COMPOSITE

* BIOMATERIALS
* BRAKING
* SOLID PROPULSION

CARBON-CERAMIC COMPOSITE

* SHORT LIFE HOT PARTS: MISSILES, RAMJETS, TURBOJETS, SPACE
* LIQUID PROPULSION

CERAMIC-CERAMIC COMPOSITE

* LONG LIFE HOT PARTS: AIRCRAFT, ARMAMENT, SPACE
* AERO-ENGINES
* LAND VEHICLE ENGINES
* ARMORS
* INDUSTRIAL PARTS

AIRCRAFT BRAKES

Materials:

* Carbon/Carbon Composite Materials

Functions:

* Friction members - generate required stopping torque over a wide range of environmental conditions.

* Heat sink elements - absorb the kinetic energy of the aircraft.

* Structural elements - transfer torque to the tire.

Features:

* 40% weight savings

- The total weight of brakes for Boeing 767 aircraft

  Steel: 1085 kg   C/C composite: 690 kg

* Higher heat capacity - 2.5 times that of steel

* Higher strength at elevated temperatures
  - 2 times that of steel

* Longer service life

- C/C brakes on Boeing 767-300 aircraft are expected yield up to 3000 landings per overhaul as compared to 1500 landings for steel brakes.

Evolution of aircraft brakes:

* Brakes of 1940 vintage aircraft used organic linings

* Metal-ceramic composite brake lining materials for brakes were introduced in 1949 and became mainstay of the aircraft brake industry.

* C/C composites are the third generation of brakes

Severe working conditions:

* At takeoff, the kinetic energy of a Boeing 767 aircraft - weighing 170,000 kg and moving at 320 km/h - is 670 MJ.

* This energy is equivalent to the kinetic energy of 2,000 automobiles at highway speed.

* During landing, this energy must be dissipated in 30 sec. by the 8 brakes on the aircraft.

RACING CAR BRAKES

* Replacing conventional brakes with C/C saves 11kg on a racing car

* Lighter weight & faster stopping can win races

* C/C brakes are stopping motocycles, trains, tanks

HEAT SHIELD MATERIALS FOR SPACE SHUTTLE

Functions:

* To protect the space shuttle from reentry heating
  - surface temperatures up to ~ 1650°C
* To develop a nonablative thermal protection system
  - make the surface insulation reusable and quick turn-around between space shuttle flights

Materials for Reusable Surface Insulation:

1) FRSI - Felt Reusable Surface Insulation

* made of nylon felt
* located on the upper trailing surfaces of the body and wings

2) LRSI - Low Temp. Reusable Surface Insulation

* made of LI-900 material
* located on the top surfaces of the vehicle
* have a white, glassy coating to reflect solar radiation
* maximum temperature - not exceed 650°C

3) HRSI - High Temp. Reusable Surface Insulation

* made of LI-900 and LI-2200 ceramic composites
* located on the lower surfaces of vehicle
* have a black, glassy coating to efficiently radiate heat during reentry
* maximum temperature - can reach 1260°C

4) RCC - Reinforced Carbon-Carbon composites

* made of carbon/carbon composite materials
* located on the nose and the leading edge of wings
* highest temp. - in the range of 1425 to 1650°C
* have a SiC-based coating to prevent oxidation

5) FRCI - Fibrous Refractory Composite Insulation

The second generation RSI material

* made of FRCI-12 material
* used on the DISCOVERY and ATLANTIS space shuttles
* less dense, more rigid and stronger than LI-2200

LI-900 material:

* an all-silica material
* made of amorphous silica fibers - purity > 99.7%
* uses a colloidal silica binder
* the fibers should be carefully pretreated
* after sintering density - ~144 kg/m^3 (~9 lb/ft^3)
* the composition of coating is:
  93% SiO_2, 5% B_2O_3, and 2% boron silicide.
* highly porous structure & low thermal conductivity
* good thermal shock resistance & strain tolerance
* relatively low strength & poor erosion resistance

LI-2200 material:

* essentially the same as LI-900
* a small amount of SiC powder is added to provide additional thermal protection
* no heat treatment for silica fibers is needed
* some chopping action of fiber packing is needed
* after sintering density - ~ 352 kg/m^3 (22 lb/ft^3)
* a higher strength than that of LI-900
* used in areas such as around the windows, landing-gear doors and adjacent to the RCC insulation

FRCI-12 material:

* contains ~80% SiO_2 fibers + ~ 20% ABS fibers
  = aluminum-borosilicate fibers =
* SiC powder is added for the same reason
* final density is between 11.9 & 13.5 lb/ft^3
* the density is 45% less than that of LI-2200
* the tensile strength is slightly greater than that of LI-2200
* a 390 kg weight saving for the 2246 FRCI-12 tiles that were substituted for LI-2200 tiles on the third and fouth space shuttles

RCC materials:

* made by graphite cloth, pre-impregnated with phenolic resin, pyrolyzed to convert the resin to graphite, then impregnated with furfuryl alcohol and pyrolized.
* with a density of 85 lb/ft^3 (1.38 g/cc)
* have a SiC + SiO_2 coating on the surface
* resists thermal shock from -158°C to 1650°C
* the temperature capabilities extend to 3300°C

COMPOSITE MATERIALS FOR HYPERSONIC AEROSPACE PLANE

Disadvatages of the present space shuttle:

* The very high cost of shuttle operations
- $3 million per tonne into Low Earth Orbit
- $30 million per tonne into Geostationary Orbit

* The high costs of shuttle are attributable to
- The very large number of personnel required to support operations (4000-5000)
- The complexity of the launch bases
- The throw-away External Tank, recovery and refurbishment of the Solid Rocket Boosters
- Only 16% of the costs are due to reusable hardware and expendables

The second generation of space shuttle:

* The Aerospace plane can take-off and land from conventional runways with minimum support staff (estimated as 200-250)
* Total reusability - no throwaway hardware
* Unmanned operation in primary role of satellite launch and recapture, saving the weight and cost of life support systems, cutting down launch preparation and check-out costs

Updates on Programs of Hypersonic Flight Vehicles

1) The British HOTOL program

(HOTOL - Horizontal take-off and landing)

* A single-stage-to-orbit unmanned space vehicle
* With a hybrid air-breathing propulsion system
* Utilizing atmospheric air as the oxidant whilst climbing to 26 km (M=5), liquid oxygen at higher attitude - liquid oxygen required can be halved
* Payload fraction reaches 3.5% vs 1-1.5% for the present space shuttle
* The nosecone, the leading edges of wings, the intake lips, center body and part of the ducts all will be made of C/C or SiC matrix composites

2) The European/French HERMES program

* A small orbiter with a span of 10m & a length of 15m
* It weighs 21 tonnes with a 3 tonne payload and a crew of 3
* 70% of the whole weight will use composites

- Fiber reinforced organic matrix composites:
  as inner construction materials (200 ~ 220°C)
- C/C composites with an oxidation-resistant coating:
  as nose cone and leading edges of wings (~1800°C)
- Fiber reinforced ceramic matrix composites:
  (SiC fiber or whisker/Al_2O_3 composite etc.)
  as shields on the lower surface of the body(1100°C)

3) The Japanese HOPE program

(HOPE - H-2 orbiting plane)

* An unmanned, winged, space shuttle-like orbiter
* Will be launched atop the country's H-2 booster
* It weighs 10 tonnes with a payload of 3 tonnes
* It may go into space as early as 1996
* The materials will be used are:
- Fiber reinforced organic matrix composites
- Fiber reinforced metal matrix composites
- C/C composites - nose cone, leading edges of wings
  (1300 ~ 1700°C)

4) The U.S. X-30 or NASP program

(NASP - National Aerospace Plane)

* A single-stage-to-orbit vehicle
* The hydrogen-fueled scramjet engines will be used to accelerate the vehicle to Mach 25 for flight into orbit
* The first flight may be in 1994-1995
* This program could lead to a commercial "Orient Express" hypersonic transport that could take off from Washington and reach Tokyo within 2 hours
  Speed: 5,000 km/h Altitude: 30 km
* Materials for advanced propulsion systems
- 40 vol% SiC fiber / Ti_3Al + Nb protected by thermal barrier coatings: Max. surface use temperature of uncooled turbine blade could rise to 1260°C in 1990's
- SiC fiber / Si_3N_4 and C / C composites: Max. surface use temperature could reach 1370° - 1650°C
* Materials for the spacecraft structure
- SiC fiber / Ti matrix composite
- C and SiC fibers / Ti alloys
- Rapid solidified titanium-aluminide alloys
- Carbon / Carbon composites

5) The West German SANGER program

* A two-stage-to-orbit vehicle

* It is a bridge between shuttle-like orbiters and single-stage-to-orbit spaceplanes

* The first stage of the SANGER program could be the basis for an hypersonic passenger transport

6) The AGV High-Speed Civil Transport program

* A hypersonic aircraft

* Sponsored by France, England, West Germany & Spain

* Flight speed - 5,000 km/h

* Flight altitude - 30,000 m

* Flight range - 12,000 km

* Passengers:- 150

* With both turbojet and ramjet

* The nosecone, the leading edges of the wings, and some parts of the body will be constructed from C/C or SiC/SiC composite materials due to the high re-entry temperatures - up to 1800° to 2000°C

* This vehicle will be put into practical flights in 2010 - 2015

ANTENA WINDOW FOR SATELLITES & OTHER SPACE VEHICLES

Materials:

* C/C composite materials

- Antena frame or antena supporters

* BN/Si_3N_4 composite materials

* BN/SiO_2 composite materials

- Antena windows to receive microwave signals from the control center

Features:

* Low ablation rate

* Low dielectric constant

* Low dielectric loss

* Sufficient strength

Applications:

* Antena windows for recoverable satellite

* Antena windows for long distance missiles

ROCKET NOZZLES AND JET ENGINE AFTERBURNERS

* Rocket nozzles for different kinds of missiles
* Rocket nozzles for Orbit Transfer Vehicle(OTV)

Materials:

* 3-dimensional weaving C/C composites
- Reinforcement in three directions protects the composites from interlaminate shear
- 3-D weaves have more isotropic properties
* SiC/SiC composites

Features:

* Can endure flame temperatures up to 3,300°C
* Can resist erosion and abrasion by extreme hot gases rushing through at high velocity
* Withstand prolonged heat exposure & thermal cycling
- 600 to 1200°C for 500 starts lasting some 20 hrs
* Can be built from 50 mm to more than 3.7 m (d)
* Light weight
- A high-performance C/C rocket nozzle rocket gives the Pershing II twice the range of the Pershing IA

NOSE-TIP FOR LONG-RANGE ICBM

(ICBM - Intercontinental Ballistic Missile)

Materials:

* Multi-dimensionally reinforced C/C composites

Needs for reentry vehicle nose-tip(nose-cap):

* High selective omni-directional strength
* Good thermal shock resistance
* Good resistance to mechanical erosion in clouds and rains
* High ablation resistance with uniformly smooth recession (minimum shape change)
* Compliance to mechanical shock loading
* Good thermo-chemical ablative performance in high-enthalpy air
* Minimum thermo-mechanical erosion
* Effectively absorb the heat energy by surface reactions

Features:

* Excellent ablation resistance
* High-temperature thermo-chemical stability
* High strength and thermal stress resistance

CERAMIC COMPOSITE CUTTING TOOLS

Materials:

* SiC whisker/Al_2O_3 matrix composite (WG-300)

- Commercially available grades contain 30% whisker

* SiC whisker/Si_3N_4 or Al_2O_3-TiC matrix composites

- Commercially not available now

Features:

* Higher toughness

* Better thermal conductivity

* Cutting speeds increase up to a factor of 10

* Lower wear rates and decrease in indexing

* Highly predictable tool failure times

* Applied mostly in machining nickel based superalloys

Examples:

* An operation using SIALON roughing and WC finishing tool required 5 h, WG-300 reduces the time to 20 min.

- Saving $250,000 per year and 3000 machine hours

* Machining of a blade lock groove in a turbine disk WG-300 reduces machining time from 3 h to 18 sec.

CERAMIC COMPOSITE ENGINE COMPONENTS

1) One-piece bladed turbine rotor

* Made from advanced C/C composite with SiC coating

- Graphite fiber/Carbon matrix composite

* Higher temperature performance without cooling

* Low weight

* Potential low cost, non-strategic materials

* Passes performance testing at more than 40000 rpm

* Under development

2) Cylinder head plate

* Made from 3D mullite fiber preform/Silica matrix composite material

* Under development

3) Valve

* Made of SiC fiber/SiC matrix composite material

* Under development

4) Other gas turbine engine components

* Exhaust nozzle flaps and seals

* Augmenters, combustors, and acoustic panels