Technical Terms & Technologies

The Advanced Test Reactor (ATR) is a research reactor at the Idaho National Laboratory. This reactor is primarily designed and used to test materials to be used in other, larger-scale and prototype reactors. It can operate at a maximum power of 250 MW and has a "Four Leaf Clover" design that allows for a variety of testing locations. The unique design allows for different flux in various locations and specialized systems also allow for certain experiments to be run at their own temperature and pressure.

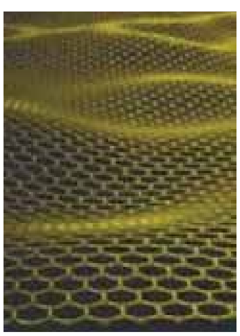
The ATR is light water moderated and cooled, with a beryllium neutron reflector. It is pressurized and housed in a stainless steel tank.

High Flux Isotope Reactor (HFIR) Oak Ridge National Laboratory

Operating at 85 MW, HFIR is the highest flux reactor-based source of neutrons for research in the United States, and it provides one of the highest steady-state neutron fluxes of any research reactor in the world. The thermal and cold neutrons produced by HFIR are used to study physics, chemistry, materials science, engineering, and biology. The intense neutron flux, constant power density, and constant-length fuel cycles are used by more than 200 researchers each year for neutron scattering research into the fundamental properties of condensed matter.

The neutron scattering research facilities at HFIR contain a world-class collection of instruments used for fundamental and applied research on the structure and dynamics of matter. The reactor is also used for medical, industrial, and research isotope production; research on severe neutron damage to materials; and neutron activation to examine trace elements in the environment. Additionally, the building houses a gamma irradiation facility that uses spent fuel assemblies and is capable of accommodating high gamma dose experiments.

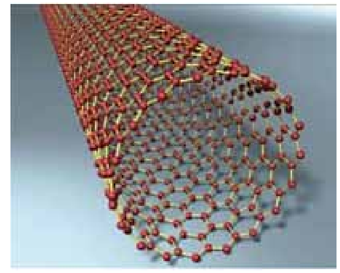
Graphene is an allotrope of carbon. Its structure is one-atom-thick planar sheets of sp^2-bonded carbon atoms that are densely packed in a honeycomb crystal lattice. The term graphene was coined as a combination of graphite and the suffix -ene by Hanns-Peter Boehm, who described single-layer carbon foils in 1962. Graphene is most easily visualized as an atomic-scale chicken wire made of carbon atoms and their bonds. The crystalline or "flake" form of graphite consists of many graphene sheets stacked together.



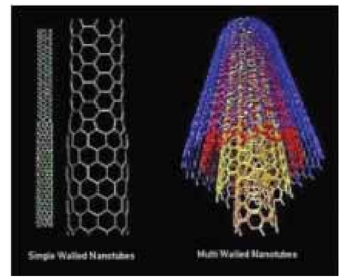
The carbon-carbon bond length in graphene is about 0.142 nanometers. Graphene sheets stack to form graphite with an interplanar spacing of 0.335 nm, which means that a stack of three million sheets would be only one millimeter thick. Graphene is the basic structural element of some carbon allotropes including graphite, charcoal, carbon nanotubes and fullerenes. It can also be considered as an indefinitely large aromatic molecule, the limiting case of the family of flat polycyclic aromatic hydrocarbons.

Carbon nanotubes (CNTs) are allotropes of carbon with a cylindrical nanostructure.

Nanotubes have been constructed with length-to-diameter ratio of up to 132,000,000:1, significantly larger than for any other material. These cylindrical carbon molecules have unusual properties that have been applied to electronics, optics and other fields of materials science and technology. In particular, owing to their extraordinary thermal conductivity and mechanical and electrical properties, carbon nanotubes find applications as additives to various structural materials. Nanotubes are members of the fullerene structural family, which also includes the spherical buckyballs, and the ends of a nanotube may be capped with a hemisphere of the buckyball structure. Their name is derived from their long, hollow structure with the walls formed by one-atom-thick sheets of carbon, called graphene. These sheets are rolled at specific and discrete ("chiral") angles, and the combination of the rolling angle and radius decides the nanotube properties; for example, whether the individual nanotube shell is a metal or semiconductor. Nanotubes are categorized as single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs). Individual nanotubes naturally align themselves into "ropes" held together by van der Waals forces, more specifically, pi-stacking.



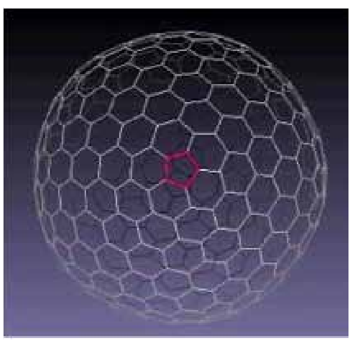
Applied quantum chemistry, specifically, orbital hybridization best describes chemical bonding in nanotubes. The chemical bonding of nanotubes is composed entirely of sp2 bonds, similar to those of graphite. These bonds, which are stronger than the sp3 bonds found in alkanes, provide nanotubes with their unique strength.

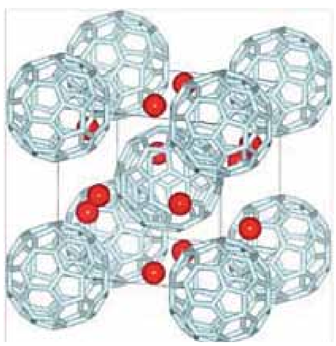


Fullerene or "Buckyball"

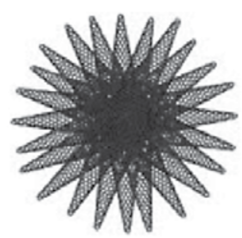
A fullerene is any molecule composed entirely of carbon in the form of a hollow sphere, ellipsoid, or tube. Spherical fullerenes are also called buckyballs, and they resemble the soccer balls. Cylindrical ones are called carbon nanotubes or buckytubes. Fullerenes are similar in structure to graphite, which is composed of stacked graphene sheets of linked hexagonal rings; but they may also contain pentagonal (or sometimes heptagonal) rings.

The first fullerene to be discovered, buckminsterfullerene (C60), was prepared in 1985 by Richard Smalley, Robert Curl, James Heath, Sean O'Brien, and Harold Kroto at Rice University. The name was an homage to Buckminster Fuller, whose geodesic domes it resembles.

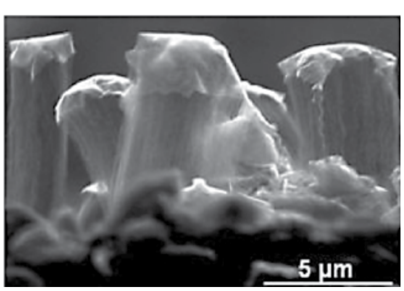


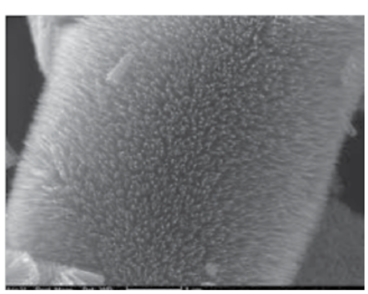


Nanohorns: tubes of graphitic carbon which differ from nanotubes in their "horn-like" shape similar to a sewing thimble giving them numerous applications as both the stiffest and strongest known fibers and because of their unique shape gives them an enormous amount of surface area. The resulting material has found application in proton exchange membrane (PEM) and Polymer Electrolyte (PEFC) fuel cells because they have the dual capability of providing a high surface area conductive layer and open gas paths.

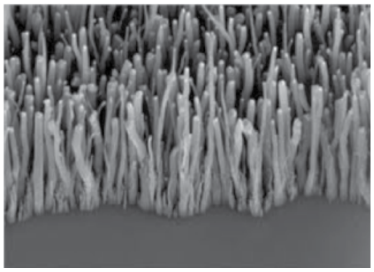


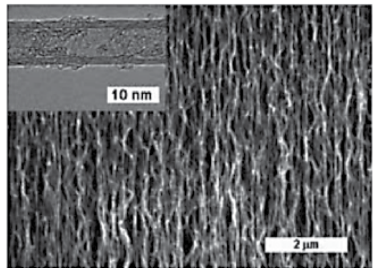
Nanocarpets:

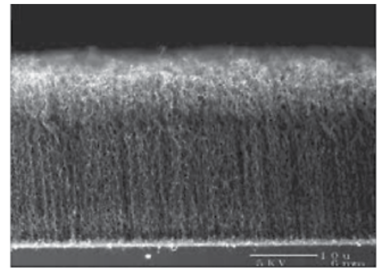


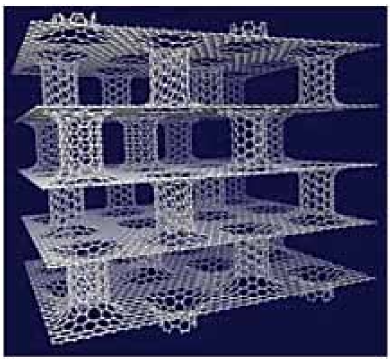


Nanoforests:



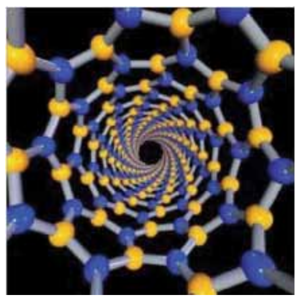


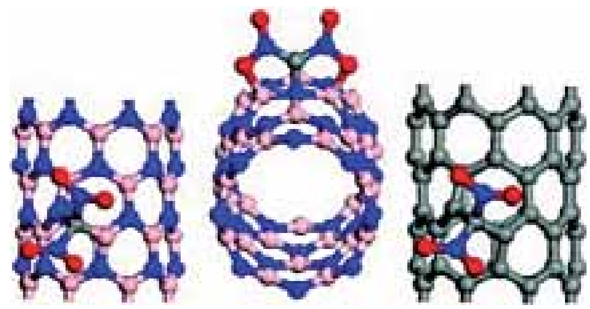




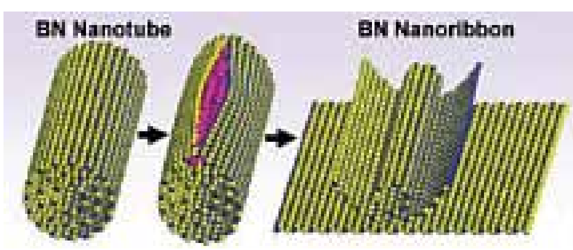
Nanopillars:

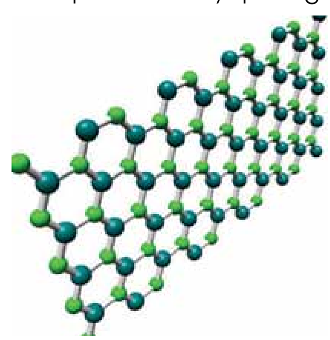
Boron Nitride Nanotubes: Hexagonal boron nitride (h-BN) is a layered material with a graphite-type structure in which planar networks of BN hexagons are regularly stacked. As a structural analogue of carbon nanotubes (CNTs) a BN nanotube (BNNT) was first predicted in 1994 and synthesized the next year.

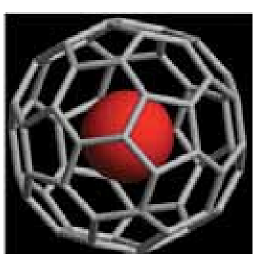




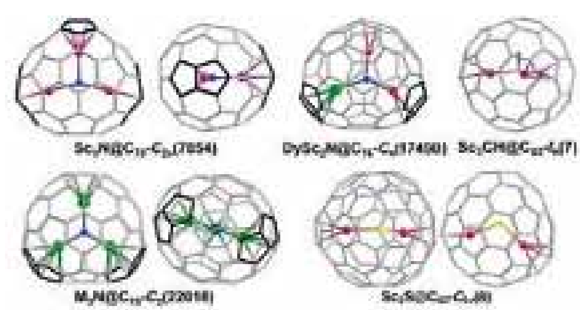
Boron Nitride Nanosheets: a single atom thick layer of boron nitride produced by splitting a boron nitride nanotube.







Endohedral Metallofullerenes: Endohedral fullerenes are fullerenes that have additional atoms, ions, or clusters enclosed within their inner spheres. The first lanthanum C60 complex was synthesized in 1985 called La@C60. The @ sign in the name reflects the notion of a small molecule trapped inside a shell. Two types of endohedral complexes exist: endohedral metallofullerenes containing metal atoms or metallic compounds and non-metal doped fullerenes. Endohedral metallofullerenes are characterised by the fact that electrons will transfer from the metal atom to the fullerene cage and that the metal atom takes a position off-center in the cage. The size of the charge transfer is not always simple to determine. In most cases it is between 2 and 3 charge units, in the case of the La_2@C80 however it can be even about 6 electrons such as in Sc_3N@C80 which is better described as $(Sc_3N)^{+6}$@$(C80)^{-6}$. These anionic fullerene cages are very stable molecules and do not have the reactivity associated with ordinary empty fullerenes.



Definitions of Key Terms

Band Gap: the span of energies that lie between the valence and conduction bands for insulators and semiconductors.

Barn: a unit of area. Originally used in nuclear physics for expressing the cross sectional area of nuclei and nuclear reactions, today it is used in all fields of high energy physics to express the cross sections of any scattering process, and is best understood as a measure of the probability of interaction between small particles.

Burn-up: a measure of how much energy is extracted from a primary nuclear fuel source. It is measured both as the fraction of fuel atoms that underwent fission in % of fissions per initial metal atom and as the actual energy released per mass of initial fuel in gigawatt-days/metric ton of heavy metal (GWd/MTHM), or similar units. Typical PWR burnup is less than 0.7% of initial U-235.

Chart of the Nuclides: an extensive table that portrays the interrelationship of isotopes of a chemical element and the isotopes of neighboring elements to which it may either be transmuted or to which it may decay. This chart illustrates all of the transmutation and decay pathways between isotopes and elements.

Creep: plastic deformation occurring as a constant volume process, normally at low stresses below the yield stress. The deformation occurs by the motion of dislocations and irradiation-produced defects under the influence of stress. Neutron irradiation produces large quantities of point defects – vacancies and SIAs (self interstitial atoms) – which migrate to and collect at various sinks. With zirconium, the anisotropy of the crystal lattice causes both dislocations and SIAs to be anisotropic, and consequently these occur parallel to the basal plane in the <a> directions of the lattice. Dislocations are sinks for both vacancies and SIAs, but normally it is considered that an edge dislocation attracts SIAs more than vacancies. Dislocations produced by deformation and by irradiation lie on both basal and prism planes. Because of the diffusional anisotropy of SIAs, they tend to be absorbed by dislocations lying on prism planes. The diffusion of vacancies is isotropic, and they tend to be absorbed preferentially by dislocations lying on basal planes. Similarly, SIAs tend to be absorbed at grain boundaries oriented parallel to prism planes and vacancies on boundaries parallel to basal planes. Absorption of either vacancies or SIAs at dislocations of grain boundaries causes plastic strain; positive for SIAs and negative for vacancies. If the absorptions occurred randomly and in non-biased fashion, the net strain would be zero; however in zirconium alloys the built-in anisotropy results in separate positive and negative strains, and in constant volume deformation. Also, in addition to the natural anisotropy of the zirconium crystal lattice, another factor is the concept that anisotropic diffusion is enhanced by stress.

Critical Heat Flux (CHF): describes the thermal limit of a phenomenon where a phase change occurs during heating, which suddenly decreases the efficiency of heat transfer, thus causing localized overheating of the heating surface.

Departure from Nucleate Boiling (DNB): The point at which the heat transfer from a fuel rod rapidly decreases due to the insulating effect of a steam blanket that forms on the rod surface when the temperature continues to increase.

Delayed Hydride Cracking (DHC): Zirconium alloy components can fail by a time-dependent mechanism of cracking if they contain hydrides, sharp flaws and are sufficiently stressed. The mechanism of time-dependent hydride cracking is based on diffusion of hydrogen to the flaw tip, followed by nucleation, growth, and fracture of the flaw-tip hydride. By repeating these processes, a crack can propagate through the component at a rate that, above a threshold stress intensity factor, is mainly dependent on temperature.

Displacements per Atom (dpa): a calculated, hypothetical measure of radiation damage that reflects not only the dose and type of irradiation, but also includes some measure of the material's response to the irradiation. DPA is not a measure of the residual crystal lattice defects actually created in a material, but rather it is a measure of the "damage energy" deposited in the material by the irradiating particles in terms of how many atoms could possibly be permanently displaced from their lattice sites to stable interstitial sites by this damage energy. In each individual radiation damage event, the primary knock-on atom (PKA, an atom that has received kinetic energy through interaction with an irradiating neutron) imparts energy to neighboring atoms, producing a cascade of collisions. Within the affected volume of the collision cascade many atoms are displaced significantly from their lattice sites, creating a near-molten zone in the crystal. But within picoseconds, many of the displaced atoms return to vacant sites, healing much of the damage. The actual number of lattice defects ("permanently" displaced atoms) remaining after the cascade region cools is usually a small fraction of the atoms initially displaced in the cascade. This fraction is often referred to as the "efficiency" of defect production relative to the calculated DPA value, and it can vary considerably depending on the material and the irradiating conditions, including neutron energies and irradiation temperature. Although it does not reflect the actual residual defects produced in the material, DPA has been found to be an extremely useful damage parameter for correlating the effects of radiation damage in the same material irradiated in different neutron environments, and it is the standard damage parameter for nuclear structural materials.

Doppler Broadening: Frequency spreading which causes broadening of single-frequency radiation (e.g., spectral lines) when the radiating bodies (atoms, molecules, etc.) have different velocities. Radiation from each individual radiating body has a different Doppler shift, and the collection of radiations at different frequencies broadens the peak of the line in an intensity-vs-frequency plot.

Fast neutrons: a free neutron with a kinetic energy level close to 1 MeV (100 TJ/kg), hence a speed of 14,000 km/s. They are named fast neutrons to distinguish them from lower-energy thermal neutrons, and high-energy neutrons produced in cosmic showers or accelerators. Fast neutrons are typically produced by nuclear processes such as fission.

Flow Instability: Unstable flow can occur in the form of flow oscillations or flow reversals. Flow oscillations are variations in flow due to void formations or mechanical obstructions from design and manufacturing. A flow oscillation in one reactor coolant channel sometimes causes flow oscillations in the surrounding coolant channels due to flow redistribution. Flow oscillations are undesirable for several reasons. First, sustained flow oscillations can cause undesirable forced mechanical vibration of components. This can lead to failure of those components due to fatigue. Second, flow oscillations can cause system control problems of particular importance in liquid-cooled nuclear reactors because the coolant is also used as the moderator. Third, flow oscillations affect the local heat transfer characteristics and boiling. It has been found through testing that the critical heat flux (CHF) required for departure from nucleate boiling (DNB) can be lowered by as much as 40% when flow is oscillating. This severely reduces the thermal limit and the power density along the length of the reactor core. Again, it has been found through testing that flow oscillations are not a significant problem for some pressurized water reactors unless power is above 150% for the normal flow conditions. Flow oscillations can be a problem during natural circulation operations because of the low flow rates present. During natural circulation, the steam bubbles formed during a flow oscillation may have enough of an effect to actually cause complete flow reversal in the affected channel.

Fluence: the time integral of flux or total incident particles per unit area

Flux: the rate of particle flow through a defined area per unit time usually measured in neutrons/cm^2-s.

k-effective (k_{eff}): The "Six-factor formula" is the neutron life-cycle balance equation, which includes six separate factors, the product of which is equal to the ratio of the number of neutrons in any generation to that of the previous one; this parameter is called the effective multiplication factor (k), a.k.a. k_{eff}. $k = L_f \rho L_t h_f \eta$, where L_f = "fast non-leakage factor"; ρ = "resonance escape probability"; L_{th} = "thermal non-leakage factor"; f = "thermal fuel utilization factor"; η = "reproduction factor"; = "fast-fission factor". k = (Neutrons produced in one generation)/(Neutrons produced in the previous generation) When the reactor is critical, $k = 1$. When the reactor is subcritical, $k < 1$. When the reactor is supercritical, $k > 1$.

Moderator: a neutron moderator is a medium that reduces the speed of fast neutrons, thereby turning them into thermal neutrons capable of sustaining a nuclear chain reaction involving uranium-235.

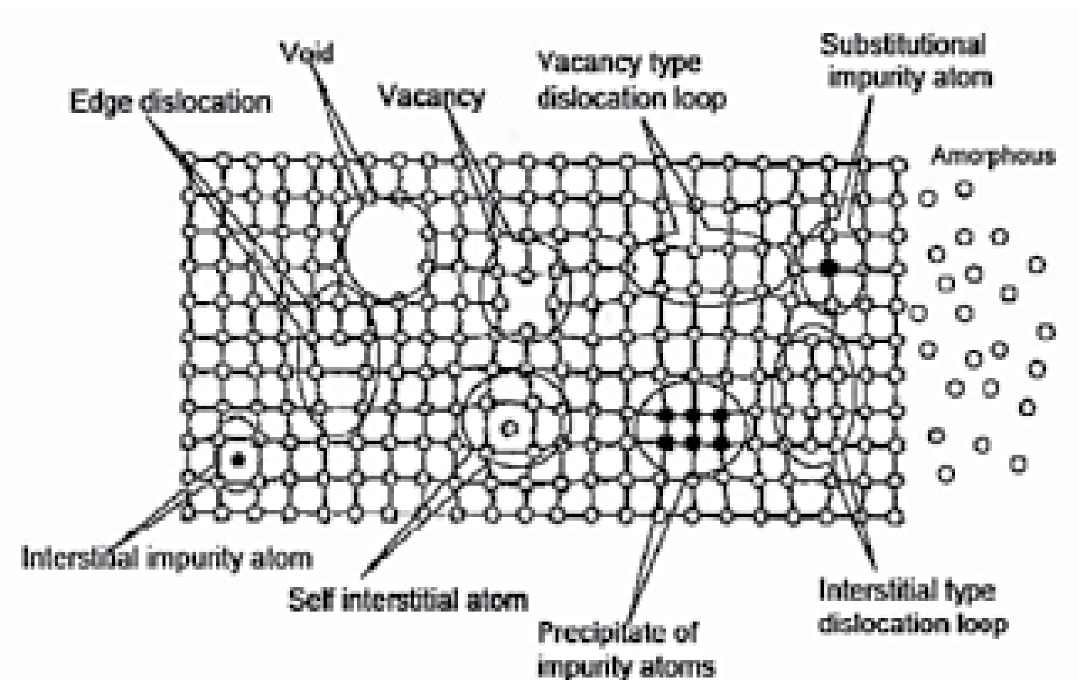
Nuclear Cross Section: used to characterize the probability that a nuclear reaction will occur. The concept of a nuclear cross section can be quantified physically in terms of "characteristic area" where a larger area means a larger probability of interaction. The standard unit for measuring a nuclear cross section (denoted as) is the barn, which is equal to 10^{-28} m² or 10^{-24} cm².

Nuclear Transmutation: the conversion of one chemical element or isotope into another. This occurs either through nuclear reactions (in which an outside particle reacts with a nucleus), or through radioactive decay (where no outside particle is needed). Artificial transmutations are those instigated by bombardment of a nucleus with high energy particles or photons resulting in an instability. Neutron capture is a frequently exploited means of causing transmutations, but high energy photons, protons, and electrons of the right energy levels can also be used. The resultant decay chains are described in the chart of the nuclides.

Nucleon: Common name for a constituent particle of the atomic nucleus. At present, applied to protons and neutrons, but may include any other particles found to exist in the nucleus.

Nuclide: A general term referring to all known isotopes, both stable (279) and unstable (about 2,700), of the chemical elements.

Radiation Induced Defects: Radiation induced changes in material properties are the result of microstructural defects. An energetic particle (e.g. neutron or fission fragment) collides with an atom in a material, transferring to it some energy and knocking it out of its lattice position. This primary knock-on atom and the recoiling particle cause additional collisions with other atoms generating a cascade of displaced atoms. Given that the average energy of a fission neutron is ~2 MeV and the threshold energy to displace an atom from its lattice position in metals is ~20–40 eV, a typical number of displaced atoms in a displacement cascade is ~50,000. In most metals, 90–99% of these displaced atoms eventually recombine to vacated lattice positions. It is the remaining non-correctly but stably sited radiation defects and microstructural re-arrangements that constitute the radiation damage that changes the material's microscopic and macroscopic properties. Various types of radiation-induced defects are illustrated in the figure below:



Oxide Dispersion Strengthened Metals: typically consist of a high temperature metal matrix - such as iron aluminide, iron chromium, iron-chromium-aluminium, nickel chromium or nickel aluminide - with small (5-50nm) oxide particles of alumina (Al_2O_3) or yttria (Y_2O_3) dispersed within it. Iron-based and nickel-based oxide dispersion strengthened alloys exhibit good corrosion resistance and mechanical properties at elevated temperatures. These alloys also show excellent creep resistance, which stems partly from the dispersion of oxide and other particles, and partly from the very large elongated grain structure.

RAD: A unit of energy absorbed from ionizing radiation, equal to 100 ergs per gram or 0.01 joules per kilogram of irradiated material. It has been replaced as a standard scientific unit by the gray.

Rem: A unit of absorbed radiation in biological tissue. Rem is equal to n times the number of rads, where the factor n is dependent on the type of radiation absorbed.

Reactivity: an expression of the departure from criticality. k = (k - 1)/k When the reactor is critical, k = 0. When the reactor is subcritical, k < 0. When the reactor is supercritical, k > 0. A positive reactivity addition indicates a move toward supercriticality (power increase). A negative reactivity addition indicates a move toward subcriticality (power decrease). Reactivity is also represented by the lowercase Greek letter rho ( ). Reactivity is commonly expressed in decimals or percentages or pcm (per cent mille) of Δk/k. When reactivity is expressed in units of delayed neutron fraction , the unit is called the dollar (and correspondingly, fractions thereof are measured in "cents").

Stress Corrosion Cracking (SCC): is the growth of cracks in a corrosive environment. It can lead to unexpected sudden failure of normally ductile metals subjected to a tensile stress, especially at elevated temperature in the case of metals. SCC is highly chemically specific in that certain alloys are likely to undergo SCC only when exposed to a small number of chemical environments. The chemical environment that causes SCC for a given alloy is often one, which is only mildly corrosive to the metal otherwise.

Swelling: the increase of volume and decrease of density of materials subjected to intense neutron radiation. Neutrons impacting the material's lattice rearrange its atoms, causing buildup of dislocations, voids, and Wigner energy.

Many mechanisms of irradiation creep have been proposed. No single mechanism has been accepted as the dominating mechanism and very likely several processes contribute simultaneously. The two most prominent mechanisms are Stress Induced Preferential Absorption (SIPA) and climb and glide. SIPA assumes a bias of the motion of vacancies and SIAs to dislocations depending on the orientation of the Burgers vectors with respect to the applied shear stress. There are several variations of SIPA, including the elasto-diffusion modification that invokes the effect of stress on the diffusion anisotropy itself. Elasto-diffusion appears to have the strongest effect on creep within the SIPA "family".

The most straightforward irradiation creep mechanism is the climb and glide mechanism, by which deformation-producing dislocations are aided in bypassing obstacles to their motion by irradiation-induced point defects. As long as an individual dislocation attracts a net flux of either vacancies or SIAs, it can "climb around" a barrier and under the influence of an applied stress, glide to the next barrier, thereby producing strain and eventually cause a slip step at the material surface. The weak dependence of creep rate on dislocation density suggests that glide may not be the main strain-generating process.

A further contributor to the strain measured in a creep experiment is irradiation growth. Although not strictly in the "creep" category because it occurs in the absence of an applied stress, it is inevitably measured as part of the overall strain in all in-reactor experiments, except for bent beam stress relaxation tests. Irradiation growth results from mechanisms similar to irradiation creep in that it is dependent on the anisotropic properties of the zirconium crystal lattice.

Thermal neutrons: Thermal does not mean hot in an absolute sense, but means in thermal equilibrium with the medium it is interacting with, the reactor's fuel, moderator and structure, which is much lower energy than the fast neutrons initially produced by fission.

Worth: the general term describing reactivity expressed in units of dollars and cents.

Acronyms

AFC—Advanced Fuel Cycle
AFIT—Air Force Institute of Technology
ANL—Argonne National Laboratory
ATR—Advanced Test Reactor
ATRC—Advanced Test Reactor Critical Facility
BNL—Brookhaven National Laboratory
BNNT—Boron Nitride Nanotubes
BNNS—Boron Nitride Nanosheets
CHF—Critical Heat Flux
CNT—Carbon nanotubes
DHC—Delayed Hydride Cracking
DNBR—Departure from Nucleate Boiling Ratio
DOD—Department of Defense
DOE—Department of Energy
DOT—Department of Transportation
EFPD—Effective Full Power Days
FCRD—Fuel Cycle Research and Development
FIR—Flow Instability Ratio
HFIR—High Flux Isotope Reactor
INL—Idaho National Laboratory
LANL—Los Alamos National Laboratory
LBNL—Lawrence Berkeley National Laboratory
LHGR—Linear Heat Generation Rate
LLNL—Lawrence Livermore National Laboratory
MIT—Massachusetts Institute of Technology
MWD—Mega Watt Days
MWNT—Multi Wall Carbon Nanotubes
NASA—National Aerospace Administration
NE—DOE Office of Nuclear Energy
NF&M—Nuclear Fuels and Materials
NIA—National Institute of Aerospace
NNI—National Nanotechnology Initiative
NRC—Nuclear Regulatory Commission
ODS—Oxide Dispersion Strengthened
ORNL—Oak Ridge National Laboratory
PCS—Primary Coolant System
PIE—Post Irradiation Examination
PNNL—Pacific Northwest National Laboratory
RIT—Rochester Institute of Technology
RPI—Rensselaer Polytechnic Institute
SAR—Safety Analysis Report
SCC—Stress Corrosion Cracking
SINST—Smalley Institute of Nanoscale Science and Technology
SIA—Self Interstitial Atom
SIPA—Self Induced Preferential Absorption
SNL—Sandia National Laboratory
SWNT—Single Wall Carbon Nanotubes
TAMU—Texas A&M University
TREAT—Transient Reactor Test Facility
TRIGA—Training, Research, Isotope, General Atomics reactor