Glossary of Terms

CBE 30235

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1 Lecture 1 Terms

Capacity Factor The ratio of the actual electrical energy output of a power plant over a given period to the maximum possible electrical energy output over that same period.

Curtailment The deliberate reduction in output below what could have been produced (usually renewables) in order to balance energy supply and demand or due to transmission constraints.

Duck Curve A graph of power production over the course of a day that shows the timing imbalance between peak demand and renewable energy production, specifically the drop in net load during midday and the sharp ramp-up at sunset.

Dunkelflaute A German term ("dark wind lull" or "dark doldrums") referring to periods of time in which little to no energy can be generated using wind and solar power, typically lasting several days.

Firm Power Power generation capacity that can be controlled by the grid operator and is guaranteed to be available at any time, for any duration, regardless of weather conditions (e.g., nuclear, hydro, fossil).

Inertia (Grid) The kinetic energy stored in the rotating mass of large synchronous generators (like steam turbines) that resists changes in grid frequency, providing a buffer against sudden power imbalances.

LCOE (Levelized Cost of Electricity) A measure of the average net present cost of electricity generation for a generating plant over its lifetime, often broken down into Plant-Level LCOE and System-Level LCOE.

Rankine Cycle A thermodynamic cycle which converts heat into mechanical work (and then electricity), commonly used in coal, nuclear, and natural gas power plants.

Swing Equation An electromechanical equation describing the relative motion of the rotor of a synchronous machine, relating the change in frequency ($\frac{df}{dt}$) to the imbalance between mechanical power input and electrical power output.

Terawatt-hour (TWh) A unit of energy equal to 10^{12} watt-hours; commonly used to measure annual national electricity consumption.

2 Lecture 2 Terms

Atomic Mass Unit (u) A unit of mass used to express atomic and molecular weights, defined as one-twelfth of the mass of an unbound neutral atom of carbon-12. ($1 \text{ u} \approx 931.5 \text{ MeV}/c^2$).

Baryon A composite subatomic particle made up of three quarks (e.g., protons and neutrons). Baryons are a subtype of Hadrons.

Boson A particle with integer spin $(0, 1, 2...)$ that does not obey the Pauli Exclusion Principle. Bosons include force carriers like photons and gluons.

Electron-volt (eV) A unit of energy equal to the amount of kinetic energy gained by a single electron accelerating from rest through an electric potential difference of one volt. ($1 \text{ MeV} = 1.602 \times 10^{-13} \text{ J}$).

Fermion A particle with half-integer spin $(1/2, 3/2...)$ that follows the Pauli Exclusion Principle. Includes quarks, leptons, protons, and neutrons.

Hadron Any composite particle made of quarks held together by the strong force. Hadrons are categorized into Baryons (stable) and Mesons (unstable).

Isobar Nuclides which have the same mass number (A) but different atomic numbers (Z).

Isotone Nuclides which have the same neutron number (N) but different atomic numbers (Z).

Isotope Nuclides which have the same atomic number (Z) but different neutron numbers (N).

Lepton An elementary particle of half-integer spin that does not undergo strong interactions. The most prominent examples are the electron and the neutrino.

Pauli Exclusion Principle A quantum mechanical principle stating that two or more identical fermions cannot occupy the same quantum state within a quantum system simultaneously.

Strong Force The fundamental interaction that confines quarks into hadrons and binds protons and neutrons together in the atomic nucleus.

3 Lecture 3 Terms

Binding Energy The energy required to separate a nucleus into its constituent protons and neutrons; equivalently, the energy released when nucleons bind together.

Chart of the Nuclides A two-dimensional graph in which the X-axis represents the number of neutrons and the Y-axis represents the number of protons, mapping all known stable and radioactive isotopes.

Gamma Ray (γ) High-energy electromagnetic radiation (photons) emitted by an atomic nucleus during a transition from a higher energy state to a lower energy state.

Generator ($^{99}\text{Mo}/^{99m}\text{Tc}$) A device used in nuclear medicine to extract the short-lived isotope Technetium-99m from decaying Molybdenum-99.

Isomeric Transition (IT) A radioactive decay process in which a metastable nucleus releases energy via gamma emission to reach a lower energy state without changing its proton or neutron number.

Magic Numbers Specific numbers of nucleons (2, 8, 20, 28, 50, 82, 126) that correspond to complete shells within the atomic nucleus, resulting in higher stability.

Metastable State (m) A nuclear isomer that has a half-life longer than 10^{-9} seconds, often designated with an "m" (e.g., ^{99m}Tc).

Mass Defect The difference between the sum of the masses of the individual components of a nucleus (protons and neutrons) and the actual mass of the nucleus.

Technetium-99m A metastable nuclear isomer used in tens of millions of medical diagnostic procedures annually due to its ideal gamma energy (140 keV) and short physical half-life (6 hours).

Valley of Stability The region in the Chart of the Nuclides where stable isotopes are found; isotopes outside this valley are radioactive and decay toward it.

4 Lecture 4 Terms

Activity (A) The rate at which a sample of radioactive material decays; defined as the number of disintegrations per second. ($A = \lambda N$).

Beta Particle (β) A high-energy, high-speed electron or positron emitted by the radioactive decay of an atomic nucleus.

Becquerel (Bq) The SI unit of radioactivity, defined as one disintegration per second.

Bremsstrahlung "Braking radiation"; electromagnetic radiation (X-rays) produced by the deceleration of a charged particle (like a beta particle) when deflected by another charged particle (like an atomic nucleus).

Curie (Ci) A non-SI unit of radioactivity roughly equivalent to the activity of 1 gram of Radium-226 ($1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{Bq}$).

Electron Capture (EC) A decay mode for proton-rich nuclei where an orbital electron is captured by the nucleus, converting a proton into a neutron. It competes with positron emission.

Half-Life ($T_{1/2}$) The time required for a quantity to reduce to half of its initial value. In nuclear physics, $T_{1/2} = \ln(2)/\lambda$.

Mean Life (τ) The average time a radioactive particle exists before decaying. Mathematically, the reciprocal of the decay constant ($\tau = 1/\lambda$).

Neutrino (ν) A fermion that interacts only via the weak subatomic force and gravity. It is electrically neutral and has a very small, non-zero mass. Essential for conserving energy and momentum in beta decay.

Positron Emission (β^+) A type of radioactive decay in which a proton inside a nucleus is converted into a neutron while releasing a positron and an electron neutrino.

5 Lecture 5 Terms

Atmospheric Spallation A nuclear reaction in which a high-energy particle (cosmic ray) strikes an atomic nucleus (like atmospheric Nitrogen), shattering it into smaller component particles and releasing a shower of neutrons.

Cosmogenic Radionuclide Rare isotopes (e.g., ^{14}C, ^{10}Be) created when high-energy cosmic rays interact with an atomic nucleus in the atmosphere or on the surface of Earth.

Coulomb Barrier The energy barrier due to electrostatic interaction that two nuclei must overcome to get close enough to undergo a nuclear reaction. Solar wind protons generally lack the energy to overcome this barrier.

Coronal Mass Ejection (CME) A significant release of plasma and accompanying magnetic field from the solar corona. While they cause magnetic storms, the particles are generally too low-energy to cause nuclear transmutations.

Geomagnetically Induced Current (GIC) Quasi-DC electrical currents induced in power lines and pipelines by rapid changes in the Earth's magnetic field during a solar storm (Space Weather).

Galactic Cosmic Ray (GCR) High-energy particles (mostly protons) originating from outside the solar system (e.g., supernovae) capable of penetrating the Earth's magnetosphere and triggering spallation.

Heliopause The theoretical boundary where the Sun's solar wind is stopped by the interstellar medium; the outer edge of the Sun's magnetic influence.

Single Event Upset (SEU) A change of state caused by a single ionizing particle (like a cosmic ray secondary neutron) striking a sensitive node in a microelectronic device, such as a memory bit flip.

Solar Wind A stream of charged particles (plasma) released from the upper atmosphere of the Sun, consisting mostly of electrons, protons, and alpha particles with kinetic energies in the keV range.

6 Lecture 6 Terms

Accelerator Mass Spectrometry (AMS) A technique that separates isotopes by mass and charge using high-energy acceleration. It allows for the counting of individual ^{14}C atoms, requiring only milligram-sized samples and removing Nitrogen-14 interference.

Bomb Pulse The sudden, massive increase in atmospheric ^{14}C concentration (peaking in 1963) caused by neutron activation during atmospheric thermonuclear weapons testing.

Curve of Knowns The initial validation plot created by Willard Libby, comparing the measured radiocarbon age of artifacts against their known historical age (e.g., Egyptian timber) to prove the method's accuracy.

Dendrochronology The scientific method of dating tree rings. It provides the absolute timeline (Master Chronology) used to calibrate radiocarbon dates against calendar years.

De Vries Effects ("Wiggles") Fluctuations or "wiggles" in the radiocarbon calibration curve caused by variations in solar activity. These plateaus can lead to large uncertainties where a single radiocarbon age corresponds to multiple calendar dates.

Modern Standard (pMC) The baseline activity for radiocarbon dating, defined as 95% of the activity of Oxalic Acid I (normalized to 1950 AD), representing the pre-industrial atmosphere (approx. 15.3 dpm/g).

Poisson Statistics The probability theory governing random events like radioactive decay. It dictates that the standard deviation of a measurement is the square root of the total counts ($\sigma = \sqrt{N}$), defining the precision limit of dating.

Reservoir Effect The phenomenon where different carbon reservoirs (atmosphere, ocean, biosphere) have different ^{14}C concentrations. The ocean acts as a buffer, damping atmospheric fluctuations but also causing marine samples to appear "older" than terrestrial ones.

Suess Effect The dilution of atmospheric ^{14}C levels caused by the combustion of fossil fuels (coal, oil) which contain stable carbon but no radiocarbon, causing modern samples to appear artificially old.

7 Lecture 7 Terms

Alpha Decay A type of radioactive decay where an atomic nucleus emits an alpha particle (two protons and two neutrons), transforming into a new element with a mass number reduced by 4 and atomic number reduced by 2.

Bragg Peak The phenomenon where energetic charged particles (like alphas) deposit most of their energy at the very end of their path. This makes alpha emitters extremely dangerous if internalized, as they dump their energy into a small volume of tissue.

Geiger-Nuttall Law An empirical rule relating the short half-life of an alpha emitter to the high energy of the emitted particle. It was later explained by quantum tunneling mechanics.

Linear Energy Transfer (LET) A measure of the energy transferred from ionizing radiation to soft tissue per unit distance. Alpha particles are "High-LET" radiation.

Quantum Tunneling The quantum mechanical phenomenon where a particle passes through a potential energy barrier that it classically could not surmount. This is the mechanism allowing alpha particles to escape the strong nuclear force.

Radon-222 A radioactive, colorless, odorless noble gas produced by the decay of Radium-226. It is the primary cause of environmental radiation exposure for the general public.

Secular Equilibrium A steady-state condition in a radioactive decay chain where the quantity of a radioactive daughter remains constant because its production rate (from a long-lived parent) equals its decay rate.

Sub-Slab Depressurization The standard engineering solution for high indoor radon. It involves installing a fan and vent pipe to create a vacuum beneath a building's foundation, venting soil gases to the outside air before they can enter.

TENORM "Technologically Enhanced Naturally Occurring Radioactive Material." Natural radioactive material that has been concentrated or exposed to the environment by human activities, such as mining or coal combustion.

8 Lecture 8 Terms

Closure Temperature The temperature below which a specific mineral crystal structure "locks in" its isotopes, preventing the diffusion of parent or daughter atoms. For dating, this marks the "time zero" of the clock.

Concordia Diagram A plot used in U-Pb dating. The "Concordia" is the curve of points where the ^{238}U and ^{235}U clocks agree. Points falling off this curve ("Discordant") indicate lead loss or contamination.

Discordia Line A linear regression line drawn through discordant data points on a Concordia diagram. The upper intercept with the Concordia curve indicates the original crystallization age, while the lower intercept indicates the time of a metamorphic event (lead loss).

Isochron A graphical technique used in Rb-Sr and other dating methods to solve for age when the initial amount of daughter isotope is unknown. By plotting ratios of different minerals from the same rock, the age is determined by the slope of the resulting line.

K-Ar Dating A radiometric dating method useful for volcanic rocks. It relies on the branching decay of ^{40}K to ^{40}Ar. Because Argon gas escapes from magma, the clock effectively resets upon eruption/solidification.

Radiogenic Heat Thermal energy produced within the Earth by the radioactive decay of isotopes, primarily ^{238}U, ^{232}Th, and ^{40}K. It accounts for approximately 50% of the Earth's total heat flux.

Zircon ($ZrSiO_4$) A nesosilicate mineral widely used in U-Pb dating. It is mechanically hard, chemically resistant, and has a high closure temperature. Crucially, it accepts Uranium into its lattice but excludes Lead during formation.

9 Lecture 9 Terms

Barn (b) The standard unit of area for nuclear cross sections. 1 b = 10^{-24} cm^2. It was named "barn" because, to nuclear physicists, a nucleus as large as Uranium looked "as big as a barn."

Elastic Scattering KE is conserved in the center-of-mass system; the neutron bounces off. (Moderation).

Flux (ϕ) The scalar flux is the total distance traveled by all neutrons in a unit volume per unit time. Defined as $\phi = nv$ (neutron density $\times$ speed), with units of neutrons/cm^2-s. It determines the rate of reactions in a reactor.

Inelastic Scattering The neutron strikes the nucleus and excites it; the nucleus later emits a gamma, and the neutron loses significant energy. (Fast neutron slowing).

Macroscopic Cross Section (Σ) The probability of neutron interaction per unit path length of travel in a bulk material. $\Sigma = N\sigma$, where N is the atom density. Units are cm^{-1}.

Mean Free Path (λ) The average distance a neutron travels in a material before undergoing an interaction. It is the reciprocal of the total macroscopic cross section: $\lambda = 1/\Sigma_t$.

Microscopic Cross Section (σ) The effective target area a single nucleus presents to an incident neutron, representing the probability of a specific interaction (scattering, fission, etc.). Units are barns.

Radiative Capture (n, γ) An absorption reaction where the neutron is captured by the nucleus, which then releases the excess excitation energy as a gamma ray. This is the primary mechanism for creating isotopes (e.g., Co-60) and breeding fuel (e.g., Pu-239).

10 Lecture 10 Terms

1/v Region The low-energy "thermal" region where the neutron absorption cross-section is inversely proportional to the neutron velocity ($\sigma_a \propto 1/v$). This explains why slow neutrons are so efficient at causing fission.

Center of Mass (COM) System A coordinate system that moves with the average velocity of the colliding particles. In nuclear kinematics, analyzing collisions in the COM frame simplifies the math because the total momentum is zero, making calculations of energy transfer straightforward.

Collision Parameter (α) A distinct property of a target nucleus determined by its mass number A. It defines the minimum energy a neutron can retain after a single elastic collision: $E_{min} = \alpha E_{in}$. For Hydrogen, $\alpha = 0$; for heavy elements, $\alpha \approx 1$.

Fast Reactor A nuclear reactor design that utilizes fast neutrons (un-moderated) to sustain the chain reaction. It requires highly enriched fuel and non-moderating coolants (like liquid sodium) but offers the ability to breed fissile material.

Logarithmic Energy Decrement (ξ) The average loss in the natural logarithm of neutron energy per collision. It serves as a figure of merit for moderators; a higher ξ means fewer collisions are required to thermalize a neutron.

Moderator A material with low atomic mass (high ξ) and low absorption cross-section used to slow down fast neutrons to thermal energies. Common examples include light water (^1H_2O), heavy water (D_2O), and nuclear graphite.

Resonance Region The energy range (typically 1 eV to 100 keV) where the neutron cross-sections of heavy nuclei (like ^{238}U) exhibit sharp peaks (resonances). This is the "Valley of Death" where neutrons are easily lost to non-fission capture.

Thermal Neutron A neutron that has slowed down enough to reach thermal equilibrium with its surroundings (typically ~ 0.025 eV at room temperature).

11 Lecture 11 Terms

Decay Heat The heat released by the radioactive decay of fission products after the fission event itself. Although it accounts for only $\sim 7\%$ of total power, it continues after reactor shutdown, necessitating active cooling to prevent meltdown (e.g., Fukushima).

Fissile Isotope An isotope (like ^{235}U or ^{239}Pu) that can be fissioned by *thermal* (slow) neutrons. This occurs because the binding energy released by neutron capture alone is sufficient to overcome the critical deformation threshold.

Fissionable Isotope An isotope (like ^{238}U) that can undergo fission, but only if struck by a high-energy (*fast*) neutron. The binding energy of capture is insufficient to split the nucleus; the neutron must bring kinetic energy to bridge the gap.

Liquid Drop Model A theoretical model treating the nucleus as a drop of incompressible nuclear fluid. It successfully explains fission as a competition between the disruptive Coulomb force (protons repelling) and the restorative Surface Tension (strong force).

Prompt Neutrons Neutrons emitted almost instantaneously ($< 10^{-14}$ s) during the fission process. They consist of "scission neutrons" (from the neck snap) and "evaporation neutrons" (boiled off by hot fragments).

Reproduction Factor (η) The average number of fission neutrons produced per neutron *absorbed* in the fuel. $\eta = \nu(\sigma_f/\sigma_a)$. This determines the maximum possible breeding ratio or multiplication factor for a given fuel type.

Scission The exact moment when the highly deformed nuclear "neck" snaps, separating the nucleus into two distinct fission fragments.

12 Lecture 12 Terms

Four Factor Formula The equation describing the infinite multiplication factor in a thermal reactor: $k_\infty = \eta \epsilon p f$. It decomposes the neutron life cycle into four distinct physical probabilities.

Heterogeneous Reactor A reactor design where the fuel and moderator are physically separated (e.g., solid fuel rods in liquid water). This geometry is essential for using low-enriched uranium because it dramatically increases the Resonance Escape Probability (p).

Infinite Multiplication Factor (k_∞) The ratio of neutrons in one generation to the previous generation in an infinite medium (ignoring leakage). If $k_\infty = 1$, the population is stable.

Oklo Reactor A set of natural nuclear fission reactors that operated in Gabon, West Africa, approximately 1.7 billion years ago. They are the only known instance of naturally occurring critical chain reactions on Earth, made possible by higher ancient concentrations of ^{235}U.

Resonance Escape Probability (p) The probability that a neutron will slow down from fission energy to thermal energy without being captured by the resonance peaks of ^{238}U. "Lumping" fuel into rods increases p.

Thermal Utilization Factor (f) The ratio of thermal neutrons absorbed in the fuel to the total thermal neutrons absorbed in the entire unit cell (fuel + moderator + cladding). "Lumping" fuel decreases f due to self-shielding.

Unit Cell The fundamental, repeating geometric component of a nuclear reactor core (typically a single fuel rod surrounded by its associated coolant/moderator channel). Reactor physics calculations are often performed on a single unit cell and then scaled up.

13 Lecture 13 Terms

Buckling (B^2) A measure of the "bending" of the neutron flux profile. "Material Buckling" (B_m^2) depends on fuel properties (k_∞) and describes what the fuel *can* do. "Geometric Buckling" (B_g^2) depends on the reactor size and describes what the core *needs* to be critical. For criticality, $B_m^2 = B_g^2$.

Chicago Pile-1 (CP-1) The world's first artificial nuclear reactor, built by Enrico Fermi's team in 1942. It used natural uranium fuel and graphite moderation to achieve criticality ($k = 1.0006$) at 0.5 Watts of power.

Diffusion Coefficient (D) In nuclear engineering, a parameter representing the ability of neutrons to travel through a medium without scattering back. Unlike chemical diffusivity, it has units of **Length (cm)** because it is derived from the transport mean free path ($\lambda_{tr}/3$).

Fick's Law The approximation used to model neutron transport in high-scattering media. It states that the net neutron current is proportional to the negative gradient of the flux: $J = -D\nabla\phi$.

Homogenization The approximation method where complex heterogeneous lattices (fuel rods + water + steel) are treated as a single uniform material with "effective" cross-sections. This is valid because the reactor scale is much larger than the neutron mean free path.

Neutron Current (J) A vector quantity representing the net number of neutrons crossing a unit surface area per unit time. It describes the *flow* or leakage of neutrons.

SCRAM The emergency shutdown of a nuclear reactor. While often attributed to the "Safety Control Rod Axe Man" from CP-1, it technically refers to the rapid insertion of negative reactivity (control rods) to immediately halt the fission chain reaction.

14 Lecture 14 Terms

Autocatalysis A chemical reaction where a product also serves as a catalyst for the reaction (e.g., $A + B \to 2A$). Nuclear fission is a physical form of autocatalysis (neutrons produce more neutrons), and its governing diffusion equation is identical to that of chemical autocatalysis.

Geometric Buckling (B_g^2) A parameter that describes the neutron leakage of a specific reactor shape and size. It is mathematically the lowest eigenvalue of the Helmholtz equation ($\nabla^2\phi + B^2\phi = 0$) for the system's geometry. For a reactor to be critical, the geometric buckling (demand) must equal the material buckling (supply).

Reflector A layer of material (usually a moderator like water, beryllium, or graphite) surrounding the reactor core. It scatters escaping neutrons back into the fuel, reducing leakage and improving the neutron economy.

Reflector Savings (δ) The reduction in the critical dimension of a reactor core made possible by the addition of a reflector. Mathematically, the reflected core behaves like a bare core of size $L + 2\delta$.

Robin Boundary Condition A type of boundary condition that specifies a linear combination of the function and its derivative on the boundary ($a\phi + b\phi' = 0$). In reactor physics, this describes the interface between the core and a reflector, analogous to the convective heat transfer boundary condition in thermodynamics.

Vacuum Boundary Condition The approximation that no neutrons enter the reactor from the outside vacuum. This mathematically implies that the neutron flux goes to zero at a specific distance slightly beyond the physical edge of the reactor (the Extrapolated Distance).

15 Lecture 15 Terms

Delayed Neutrons A small fraction ($\beta \approx 0.65\%$) of fission neutrons that are emitted seconds or minutes after the fission event. They originate from the decay of fission products (Precursors) rather than the fission itself. They are the essential physical phenomenon that makes nuclear reactor control possible.

Fermi Age (τ_T) Despite the name, this parameter has units of Area (cm^2). It represents roughly 1/6 of the mean square distance a fast neutron travels while slowing down to thermal energy. It is the "fast" analog to the diffusion length squared (L^2).

Six-Factor Formula The extension of the Four-Factor Formula to finite reactors. It includes two new terms: the Fast Non-Leakage Probability (P_{FNL}) and the Thermal Non-Leakage Probability (P_{TNL}). $k_{eff} = \epsilon p \eta f P_{FNL} P_{TNL}$.

Prompt Neutrons Neutrons emitted immediately at the moment of scission ($< 10^{-14}$ s). In a prompt-critical excursion (like the Cecil Kelley accident), power rises on a millisecond timescale driven purely by these neutrons.

Reactivity (ρ) A measure of the departure of a reactor from criticality. Defined as $\rho = (k_{eff} - 1)/k_{eff}$. It is often measured in units of "dollars" and "cents," relative to the delayed neutron fraction β.

Reactor Period (T) The time required for the neutron population (and reactor power) to change by a factor of e (≈ 2.718). In the prompt approximation, $T = l/(k-1)$. A short period means rapid, potentially dangerous power changes.

16 Lecture 16 Terms

Dollar ($) A unit of reactivity defined relative to the delayed neutron fraction. One dollar ($1.00) of reactivity is equal to β. A reactor with $1.00 of excess reactivity is Prompt Critical.

Inhour Equation The equation relating the reactivity (ρ) of a reactor to its stable period (T). It demonstrates that for small reactivity insertions ($\rho < \beta$), the reactor period is determined by the long decay times of the precursors, not the short lifetime of the prompt neutrons.

Point Kinetics A simplified model of reactor dynamics that ignores spatial variations in neutron flux. It assumes the "shape" of the flux remains constant while the "amplitude" changes over time. It consists of coupled differential equations for the neutron density (n) and precursor concentration (C).

Precursors Fission products (such as ^{87}Br or ^{137}I) that undergo beta decay and subsequently emit a neutron. These atoms act as a "storage bank" for neutrons, releasing them seconds or minutes after the fission event, which slows down the overall reactor response.

Prompt Critical The state where a reactor is critical ($k = 1$) based solely on prompt neutrons, without needing the delayed neutrons. This occurs when $\rho \geq \beta$. In this state, the reactor period becomes extremely short (milliseconds), usually leading to a destructive power excursion.

17 Lecture 17 Terms

Doppler Broadening The physical phenomenon where the thermal motion of nuclei "blurs" the energy of incoming neutrons relative to the nucleus. In U-238, this widens the resonance capture peaks, increasing neutron absorption as temperature rises. It provides the essential instantaneous negative feedback that stabilizes a reactor.

Moderator Temperature Coefficient (α_{mod}) The change in reactivity per degree change in moderator temperature. In a properly designed PWR (under-moderated), this is negative: as water heats and expands, moderation becomes less efficient, and the chain reaction slows down.

Positive Void Coefficient A dangerous design characteristic (found in the Chernobyl RBMK design) where a reduction in coolant density (boiling/voids) leads to an *increase* in reactivity. This creates a runaway positive feedback loop: Power $\rightarrow$ Boiling $\rightarrow$ Reactivity $\uparrow$ $\rightarrow$ More Power.

Power Defect The total amount of negative reactivity inserted by the feedback mechanisms (Doppler + Moderator) as the reactor goes from zero power (hot standby) to full operating power. The control rods must add enough positive reactivity to "pay" for this defect to maintain criticality at full power.

Prompt Criticality The threshold where the reactor becomes critical on prompt neutrons alone ($\rho \geq \beta$). While typically associated with rod withdrawal accidents, it can also be triggered by a "Cold Water Accident" (rapid cooling of the moderator) if the negative temperature coefficient is strong enough.

18 Lecture 18 Terms

Burnout (Nuclear) The process by which a high-cross-section isotope (like ^{135}Xe) is removed from the reactor by capturing a neutron and transmuting into a lower-cross-section isotope. For Xenon, burnout is the dominant removal mechanism during full-power operation.

Iodine Pit The temporary surge in Xenon-135 concentration that occurs after a reactor is shut down. Because the "burnout" mechanism stops (no flux) but the "production" mechanism continues (decay of existing Iodine-135), the poison level rises to a peak roughly 10 hours after shutdown, making restart difficult or impossible ("Xenon Precluded").

Neutron Poison A material with a large neutron absorption cross-section that absorbs neutrons without causing fission, thereby decreasing reactivity. Some are added intentionally (Control Rods, Burnable Absorbers), while others are unwanted fission products (Xenon, Samarium).

Promethium-149 The radioactive fission product precursor to Samarium-149. Its decay after shutdown leads to the "Samarium Peak."

Samarium-149 A stable fission product poison. Unlike Xenon, it does not decay. Once formed (mostly after shutdown), it remains in the core until the reactor is restarted and the poison is "burned out" by neutron flux.

Xenon-135 The most significant fission product poison in thermal reactors, with a thermal absorption cross-section of 2.6×10^6 barns. Its dynamic behavior dictates the timescales for reactor restart and load-following operations.

Xenon Oscillation A spatial instability in large reactors where power shifts back and forth between different regions of the core (like water sloshing in a bathtub) due to the delay between flux changes and Xenon production/burnout.

19 Lecture 19 Terms

Differential Rod Worth ($d\rho/dz$) The amount of reactivity added per unit of control rod movement (e.g., pcm per inch). It follows the square of the neutron flux (ϕ^2), resulting in a peaked distribution that is highest in the center of the core and near zero at the boundaries.

Integral Rod Worth The cumulative reactivity inserted by a control rod as it is withdrawn from zero to a specific position z. The plot of Integral Worth vs. Position forms the characteristic "S-Curve" (Sigmoid shape), which dictates how operators respond to reactivity changes.

Perturbation Theory A mathematical method used to estimate the effect of small changes (like inserting a thin absorber rod) on the reactor system. It demonstrates that the reactivity worth of an absorber is proportional to the product of the Flux (ϕ) and the Adjoint Flux ($\phi^\dagger$, or "Importance").

Rod Ejection Accident A Design Basis Accident (DBA) where a failure of the control rod drive housing causes the high-pressure coolant to shoot a control rod out of the core like a projectile. The safety limits (Rod Insertion Limits) are calculated to ensure that even if the highest-worth rod is ejected, the reactor does not go Prompt Critical.

SL-1 Accident A fatal nuclear accident in 1961 caused by the manual withdrawal of a central control rod. It highlighted the danger of the "steep" portion of the integral rod worth curve and led to regulations requiring that reactors remain subcritical even with the single most reactive rod fully stuck out of the core (The Stuck Rod Criterion).

20 Lecture 20 Terms

Chemical Shim The practice of dissolving a neutron absorber (typically Boric Acid) directly into the reactor coolant. This provides global, uniform reactivity control, allowing control rods to be kept fully withdrawn to minimize flux distortion and power peaking.

Flux Flattening The engineering process of modifying the reactor design (via reflectors, variable enrichment, or poisons) to make the neutron flux distribution as uniform as possible. This lowers the Peaking Factor, allowing the reactor to be run at a higher total power without melting the central fuel pins.

Gadolinium (Burnable Poison) A simplified method of flux shaping where a high-cross-section material (Gadolinium) is mixed directly into the fuel pellets of fresh assemblies. It suppresses the high power density of new fuel and burns out as the fuel depletes, keeping the power distribution stable over time.

Peaking Factor (F_q) The ratio of the maximum power density in the core to the average power density (P_{max}/P_{avg}). A high F_q indicates inefficient fuel usage and thermal bottlenecks. Minimizing this ratio is a primary goal of core design.

Xenon Oscillation A spatial instability occurring in large reactors where power shifts between different regions of the core (e.g., top vs. bottom) due to the time-delayed interaction between Iodine decay (production) and Xenon burnout (removal). Operators must carefully manage control rods to dampen these waves.

Zone Loading A fuel management strategy where fuel assemblies with different U-235 enrichments are placed in specific patterns. Typically, higher enrichment fuel is placed at the core periphery (to boost low flux) and lower enrichment at the center (to suppress high flux), flattening the overall power shape.

21 Lecture 21 Terms

Group Constants The averaged nuclear cross-sections ($D_g, \Sigma_{ag}, \Sigma_{fg}$) used in multigroup diffusion theory. They are obtained by weighing the energy-dependent cross-sections by the neutron flux spectrum within that energy group.

Reflector Hump A phenomenon observed in the thermal neutron flux profile near the interface of a reactor core and a moderator (reflector). Fast neutrons leak into the reflector, slow down, and accumulate because they are not absorbed. This causes a local peak in thermal flux, often exceeding the flux at the core boundary.

Removal Cross Section ($\Sigma_{1\to2}$) A macroscopic cross-section representing the probability that a fast neutron will scatter out of the fast group (Group 1) and enter the thermal group (Group 2). It effectively acts as the "absorption" term for the fast group and the "source" term for the thermal group.

Two-Group Approximation A simplified model of neutron transport where the energy spectrum is divided into two discrete bins: Fast (born from fission) and Thermal (in equilibrium with the moderator). It is the minimum level of complexity required to accurately model reflected reactors and criticality in water-moderated systems.

22 Lecture 22 Terms

TBA Glossary terms for this lecture will be compiled based on the specific technical topics covered by Captain Ryan.

23 Lecture 23 Terms (Historical Context)

CRUD Acronym for **C**halk **R**iver **U**nidentified **D**eposit. Originally describing radioactive corrosion products found in Canadian test loops, it is now the standard industry term for activated corrosion products (rust) that circulate in the primary coolant and deposit on reactor surfaces.

Polaris The first submarine-launched ballistic missile (SLBM) system. Unlike Regulus missiles (which required the sub to surface), Polaris could be launched while submerged, creating a survivable second-strike nuclear deterrent.

Admiral H.G. Rickover The Director of the Naval Reactors Branch. Known for his "persuasive personality," he shifted the AEC's focus from breeding reactors to submarine propulsion and established the rigorous engineering standards (the "philosophy of worry") that define the naval nuclear program.

Sodium-Cooled Reactor A reactor design using liquid sodium metal as the coolant. Used in the USS *Seawolf* (SSN-575). While it offers high thermal efficiency, it was abandoned for naval use due to maintenance difficulties (high gamma radiation from Sodium-24) and the logistical benefits of water.

USS Nautilus The world's first nuclear-powered ship (SSN-571), launched in 1954. It utilized a Pressurized Water Reactor (PWR) and demonstrated the capability to circumnavigate the globe submerged.

Zirconium A metal chosen for fuel cladding because of its high strength, corrosion resistance, and remarkably low neutron absorption cross-section. Its industrial development was forced rapidly by the Naval Reactors program in the late 1940s.

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Shippingport Atomic Power Station The first full-scale commercial nuclear power plant in the United States (1957). It served as a bridge between the military technology of the *USS Nautilus* and civilian utility requirements, proving the viability of the Pressurized Water Reactor (PWR).

Seed and Blanket A unique core geometry used in Shippingport consisting of a high-enrichment "Seed" (to drive the chain reaction) surrounded by a natural uranium "Blanket" (to capture neutrons and breed fuel). This zoning allowed the reactor to operate with natural uranium feed while maintaining a compact size.

Zircaloy A zirconium alloy developed by the Naval Reactors program for fuel cladding. It was chosen for its extremely low neutron absorption cross-section ($\sigma_a \approx 0.18$ b) and high corrosion resistance in hot water.

Hafnium A metal found naturally mixed with zirconium ores. It is a potent neutron poison ($\sigma_a \approx 105$ b) that must be removed from cladding material but is highly valued for control rods because its isotopes form a "resonance chain" that remains absorbing over decades of irradiation.

Liquid-Liquid Extraction A chemical engineering unit operation used to separate compounds based on their relative solubilities in two immiscible liquids. It was the only viable method to separate Zirconium from Hafnium (using MIBK and Thiocyanate) due to their nearly identical chemical properties caused by the Lanthanide Contraction.

Burnable Poison A neutron absorber (like Boron-10) intentionally added to the fuel or core structure. It is designed to deplete ("burn out") at the same rate as the fuel, compensating for the high excess reactivity of fresh fuel and allowing for a flatter power distribution.

Lanthanide Contraction A quantum mechanical phenomenon where the atomic radii of elements in the lanthanide series decrease steadily. This causes Hf (period 6) to have virtually the same atomic radius as Zr (period 5), making them chemically almost indistinguishable.

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Breeder Reactor A nuclear reactor designed to generate more fissile material than it consumes. It achieves a Breeding Ratio (BR) greater than 1.0 by capturing neutrons in fertile material (like ^{238}U or ^{232}Th) to create new fuel.

Thorium Fuel Cycle A nuclear fuel cycle that uses naturally occurring Thorium-232 as the fertile material. Upon neutron absorption and decay, it produces fissile Uranium-233 (^{233}U). Unlike the Uranium-Plutonium cycle, the Thorium cycle can achieve breeding in thermal (water-moderated) reactors because $\eta > 2.0$.

Light Water Breeder Reactor (LWBR) The final core configuration of the Shippingport Atomic Power Station (1977–1982). It successfully demonstrated that breeding is possible in a light water environment using the Thorium/U-233 cycle and a unique "movable fuel" control system.

Uranium-233 (^{233}U) A fissile isotope of uranium that does not exist in nature. It is bred from Thorium. It is the only fissile nuclide with a regeneration factor (η) high enough (≈ 2.30) to sustain breeding in a thermal neutron spectrum.

Uranium-232 (^{232}U) A troublesome byproduct formed during the irradiation of Thorium. Its decay chain includes Thallium-208, which emits a high-energy (2.6 MeV) gamma ray. This makes reprocessed U-233 fuel highly radioactive and difficult to handle (requires remote fabrication), unlike fresh U-235.

THOREX Process The chemical reprocessing method required to separate U-233 from Thorium and fission products. It is significantly more difficult than the standard PUREX process because Thorium Dioxide is resistant to nitric acid, requiring the addition of corrosive Hydrofluoric Acid (HF).

Movable Fuel Control A reactivity control method used in the LWBR to avoid the neutron waste associated with parasitic poisons (control rods). The reactor power was changed by physically lifting the "Seed" assemblies relative to the "Blanket," altering the neutron leakage geometry rather than absorbing neutrons.

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Pressurized Water Reactor (PWR) The most common type of commercial nuclear reactor (approx. 65% of the global fleet). It uses light water as both coolant and moderator, keeping it under high pressure (≈ 15.5 MPa) to prevent boiling in the primary loop.

Pressurizer A specialized vessel connected to the hot leg of a PWR primary loop. It is the only point in the system where water exists at saturation (liquid and steam). By heating or spraying water in this tank, operators control the pressure of the entire primary circuit.

Uranium Dioxide (UO_2) The standard ceramic fuel material used in commercial reactors. It is chemically stable and radiation-resistant but has very low thermal conductivity ($\approx$ 3 W/m·K), which necessitates the use of thin fuel rods ($\approx$ 1 cm diameter) to prevent centerline melting.

Doppler Broadening A prompt negative feedback mechanism where an increase in fuel temperature widens the neutron absorption resonance peaks of ^{238}U. This increases parasitic capture, reducing reactivity instantly and stabilizing the reactor against power excursions.

Moderator Temperature Coefficient (MTC) A reactivity coefficient that describes the change in reactivity per degree change in moderator temperature. In a PWR, it is designed to be negative (under-moderated), so that if the water heats up (density decreases), moderation becomes less efficient and power drops.

Chemical Shim (Soluble Boron) The practice of dissolving a neutron absorber (Boric Acid) directly into the primary coolant to control long-term reactivity changes due to fuel depletion. This allows mechanical control rods to be kept fully withdrawn, ensuring a uniform power distribution.

Chemical and Volume Control System (CVCS) The "chemical plant" attached to the primary loop of a PWR. It manages the water inventory, cleans the coolant using ion exchange beds, and adjusts the boron concentration for reactivity control.

Rod Cluster Control Assembly (RCCA) The standard mechanical control device in a PWR. It consists of a "spider" hub holding multiple thin absorber rods ("fingers") that insert into guide thimbles within the fuel assembly, avoiding the flux-peaking problems of large cruciform blades.

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Boiling Water Reactor (BWR) The second most common nuclear reactor design ($\approx$ 15% of global fleet). Unlike the PWR, it uses a single direct cycle where water boils within the reactor vessel at $\approx$ 7 MPa, and the resulting steam drives the turbine directly.

CANDU Reactor "CANadian Deuterium Uranium." A pressurized heavy water reactor design that uses deuterium oxide (D_2O) for both moderation and cooling. Its superior neutron economy allows it to operate using natural (unenriched) uranium fuel.

Jet Pump A fluid device used in BWRs to circulate coolant through the core. It uses a high-velocity driving flow from external pumps to entrain a larger volume of suction flow within the vessel annulus, minimizing the number of large pipe penetrations below the water line.

Nitrogen-16 (^{16}N) A short-lived radioisotope ($T_{1/2} = 7.1$ s) produced by neutron capture in oxygen. In a BWR, it travels with the steam to the turbine, creating a high-radiation field in the turbine hall during operation, though it decays away rapidly after shutdown.

Deuterium Oxide (D_2O) Also known as "Heavy Water." It absorbs far fewer neutrons than light water ($\sigma_a^D \ll \sigma_a^H$), making it an excellent moderator for natural uranium systems. However, it is less efficient at slowing neutrons down, requiring a much larger core lattice pitch.

Calandria The large, low-pressure vessel in a CANDU reactor that holds the heavy water moderator. It is pierced by hundreds of high-pressure tubes containing the fuel and coolant, isolating the hot pressure boundary from the cool moderator tank.

Tritium Production In heavy water reactors, deuterium captures neutrons to form Tritium (^{3}H). This creates a radiological hazard for workers (inhalation/absorption of tritiated water) but also yields a valuable byproduct used for medical tracers, fusion research, and nuclear weapons boosting.

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HTGR (High Temperature Gas-Cooled Reactor) A Generation IV reactor concept that uses graphite as a moderator and helium gas as a coolant. Operating at high temperatures (700–950°C), it offers high thermal efficiency and process heat applications but requires a physically larger core than LWRs due to the longer slowing-down length of neutrons in graphite.

TRISO Fuel "Tristructural-Isotropic" particle fuel. It consists of a uranium kernel coated with porous carbon, pyrolytic carbon, and a rigid Silicon Carbide (SiC) layer. The SiC acts as a containment vessel for fission products, allowing the fuel to remain intact at extreme temperatures (1600°C).

Pebble Bed Reactor A type of HTGR where the fuel is contained in graphite spheres ("pebbles") that flow slowly through the core like a gumball machine. This allows for online refueling (adding fresh pebbles to the top, removing used ones from the bottom) and eliminates refueling outages.

Liquid Metal Fast Breeder Reactor (LMFBR) A reactor designed to operate with a "fast" neutron spectrum (no moderator) using liquid sodium coolant. By maintaining high neutron energies, it maximizes the number of neutrons produced per fission ($\eta \approx 2.9$ for Pu-239), allowing it to breed more fissile fuel than it consumes.

Doppler Feedback A safety mechanism where increasing fuel temperature broadens the neutron absorption resonances of ^{238}U. In fast reactors, where the delayed neutron fraction (β) is small, this prompt negative feedback is critical for preventing runaway power excursions.

RBMK A Soviet reactor design (e.g., Chernobyl) that uses graphite as a moderator and light water as a coolant. It is infamous for its **Positive Void Coefficient**: if the water coolant boils (voids), neutron absorption decreases while moderation remains high (due to graphite), causing power to spike uncontrollably.

Sodium Coolant Used in fast reactors because it does not moderate neutrons and has excellent thermal conductivity. However, it is opaque (blind refueling), burns in air, and reacts explosively with water, necessitating an intermediate coolant loop to isolate the radioactive core sodium from the steam generator.

29 Lecture 29 Terms

Displacements Per Atom (dpa) The standard unit for measuring radiation damage in materials. 1 dpa means that, on average, every atom in the lattice has been knocked out of its site once. Reactor internals can experience 50–100 dpa over their lifetime.

Frenkel Defect A pair of point defects created when an atom is knocked out of its lattice site. It consists of a **Vacancy** (the empty hole left behind) and an **Interstitial** (the atom lodged in a non-lattice position).

DBTT (Ductile-to-Brittle Transition Temperature) The temperature below which a material changes from ductile (plastic/tough) to brittle (glass-like). Neutron irradiation hardens steel, causing the DBTT to shift significantly higher (e.g., from $-20°$C to $+100°$C), increasing the risk of brittle fracture during operation.

Pressurized Thermal Shock (PTS) A dangerous accident scenario where cold emergency cooling water is injected into a hot reactor vessel while it is still under high pressure. If the vessel's DBTT has shifted due to radiation damage, the sudden thermal stress can cause the brittle steel wall to shatter.

Wigner Effect A phenomenon in graphite moderators where displaced atoms store potential energy in the lattice. If the graphite is heated, these atoms can suddenly snap back into place, releasing a massive burst of heat. This was the cause of the 1957 Windscale fire.

Zircaloy A zirconium-tin alloy used for fuel cladding due to its low neutron absorption. However, it reacts with water to form hydrogen (hydride embrittlement) and, at high temperatures, undergoes rapid exothermic oxidation (the mechanism behind the Fukushima hydrogen explosions).

Pellet-Cladding Interaction (PCI) The mechanical interaction that occurs when the fuel pellet swells and the cladding creeps inward, closing the gap between them. This physical contact, combined with corrosive fission products (Stress Corrosion Cracking), can cause the fuel rod to fail during rapid power ramps.

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In-Situ Leaching (ISL) The modern standard for uranium mining ($> 50\%$ of global supply). Instead of digging open pits, oxygenated water and bicarbonate are injected into underground aquifers to dissolve uranium. The solution is pumped to the surface and the uranium is filtered out.

Yellowcake (U_3O_8) The concentrated uranium oxide powder produced by milling or ISL mining. It acts as the raw commodity traded on the uranium market before conversion.

Uranium Hexafluoride (UF_6) The only stable gaseous compound of uranium. It is a solid at room temperature but sublimes at 56°C. It is required for enrichment but presents a significant safety hazard because it reacts with moisture to form lethal Hydrofluoric Acid (HF).

SWU (Separative Work Unit) The standard unit of measurement for the effort required to enrich uranium. It is a function of the amount of material processed and the difference between the feed, product, and tails assays.

Gas Centrifuge The current standard technology for enrichment. UF_6 gas is spun in a vacuum rotor at supersonic speeds, causing heavier ^{238}U to drift to the wall while lighter ^{235}U remains in the center. It uses $\approx 50\times$ less energy than the older gaseous diffusion method.

HALEU (High-Assay Low-Enriched Uranium) Uranium enriched between 5% and 20% ^{235}U. While current LWRs use ≈ 5%, many advanced Gen IV reactor designs (SMRs, HTGRs) require HALEU to achieve higher burnup and longer cycle lengths.

Seawater Extraction A method of harvesting the ≈ 4.5 billion tonnes of uranium dissolved in the oceans using polymer braids. While currently more expensive (≈ $300+ kg/U) than mining, it effectively sets a permanent "price ceiling" on nuclear fuel, ensuring reserves are inexhaustible.

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High-Level Waste (HLW) Waste containing highly radioactive fission products and transuranic elements. In the commercial sector, this refers exclusively to **Spent Nuclear Fuel** (solid ceramic pellets in Zircaloy tubes). It accounts for $< 1\%$ of waste volume but 99% of the radioactivity.

Low-Level Waste (LLW) Items that have come into contact with radioactive materials (rags, filters, tools, booties). It comprises 90% of waste volume but only 1% of radioactivity and is disposed of in secure shallow land burial sites (e.g., Clive, UT).

Actinides The heavy elements (Atomic Number > 89) formed by neutron capture, such as Plutonium, Neptunium, and Americium. While fission products decay within centuries, actinides remain radiotoxic for over 10,000 years, necessitating deep geological disposal.

Dry Cask Storage (ISFSI) The standard interim storage method for used fuel after it has cooled in a pool for 3–5 years. Fuel assemblies are sealed in stainless steel canisters surrounded by concrete. Cooling is entirely passive, driven by natural air convection vents.

PUREX "Plutonium Uranium Redox EXtraction." The standard chemical process for reprocessing spent fuel. It dissolves fuel in nitric acid and uses organic solvents (TBP) to separate uranium and plutonium from fission products.

Hanford Site A decommissioned nuclear production complex in Washington State that holds 56 million gallons of liquid radioactive "defense waste" in underground tanks—a legacy of the Manhattan Project. It is the site of the world's largest environmental cleanup effort.

Vitrification The process of immobilizing high-level waste by mixing it with glass-forming chemicals (silica, boron) and melting it at 1150°C. The resulting glass logs entrap radioactive isotopes at the molecular level, preventing leaching for thousands of years.

32 Lecture 32 Terms

Design Basis Accident (DBA) A postulated accident that a nuclear facility must be designed and built to withstand without loss to the systems, structures, and components necessary to assure public health and safety. The classic example for LWRs is the Large Break LOCA.

LOCA (Loss of Coolant Accident) An accident where a breach in the primary pressure boundary results in the loss of cooling fluid faster than the makeup systems can replenish it. The most severe version is the **Double-Ended Guillotine Break (DEGB)** of the cold leg pipe.

ECCS (Emergency Core Cooling System) A series of redundant safety systems designed to inject water into the reactor vessel during a LOCA to prevent fuel damage. It typically includes passive accumulators, high-pressure injection pumps, and low-pressure injection pumps.

Accumulator (Safety Injection Tank) A passive ECCS component consisting of a large tank partly filled with borated water and pressurized with Nitrogen gas (≈ 600 psi). When reactor pressure drops below the tank pressure during a break, the gas expansion forces water into the core without need for pumps or electricity.

10 CFR 50.46 The US NRC regulation that defines the acceptance criteria for ECCS performance. It famously sets the limit for Peak Cladding Temperature (PCT) at 2200°F (1204°C) to prevent brittle failure from oxidation.

Zirconium-Steam Reaction An exothermic chemical reaction ($Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$) that occurs when cladding overheats. Above 2200°F, the heat generated by the reaction itself can exceed the decay heat, creating a runaway "autocatalytic" oxidation process.

Small Break LOCA A LOCA where the leak is small enough that system pressure remains high, potentially confusing operators and preventing low-pressure safety systems from activating automatically. This was the mechanism of the TMI accident.

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Defense in Depth The fundamental safety philosophy of nuclear engineering. It relies on multiple independent layers of protection (Fuel Cladding → Reactor Vessel → Containment Building) to prevent radioactive release even if one or more barriers fail.

TMI Unit 2 (1979) A partial meltdown of a PWR in Pennsylvania caused by a stuck-open relief valve (Small Break LOCA). It is a classic example of a **Man-Machine Interface** failure: operators turned off safety pumps because ambiguous instrumentation led them to believe the system was over-pressurized when it was actually boiling dry.

Chernobyl Unit 4 (1986) A catastrophic explosion of an RBMK reactor in Ukraine. The accident was driven by fundamental design flaws: a **Positive Void Coefficient** (boiling increased power) and control rods with graphite tips that momentarily added reactivity upon insertion (Positive Scram Effect).

Fukushima Daiichi (2011) A multi-unit meltdown of GE BWRs in Japan. The initiating event was a **Beyond Design Basis** tsunami that flooded the basement, destroying the emergency diesel generators (Station Blackout). The core melted due to the loss of the ultimate heat sink, and hydrogen explosions destroyed the secondary containment.

Passive Safety A safety design approach (used in Gen III+ and Gen IV reactors) that eliminates reliance on AC power, pumps, or operator action. It uses natural forces like gravity, convection, and conduction to cool the core indefinitely during an accident (e.g., AP1000, NuScale).

Core Damage Frequency (CDF) A statistical metric used to estimate the likelihood of an accident damaging the fuel. As the number of reactors scales up (e.g., thousands of SMRs), the required CDF per reactor must decrease (from 10^{-5} to 10^{-8}) to keep the global accident rate acceptable.

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Bremsstrahlung German for "Braking Radiation." Secondary X-rays produced when charged particles (like beta electrons) rapidly decelerate upon hitting a high-Z material (like lead). To prevent this, beta sources are shielded with low-Z materials (plastic) first to slow them gently.

Pair Production The dominant gamma interaction mechanism at high energies (> 1.02 MeV). A photon strikes the electric field of a nucleus and spontaneously converts into an electron (e^-) and a positron (e^+). It represents the direct conversion of energy into matter.

Half-Value Layer (HVL) The thickness of a material required to reduce the intensity of a radiation beam by 50%. It is inversely related to the attenuation coefficient: $\text{HVL} = \ln(2)/\mu$.

Buildup Factor (B) A correction factor ($B \geq 1$) applied to the attenuation equation ($I = I_0 B e^{-\mu x}$) to account for "scattered" radiation. It corrects for photons that interact via Compton scattering but are deflected toward the detector rather than being absorbed.

Thermal Shield A thick layer of steel placed inside or immediately around the reactor vessel. Its primary purpose is not to protect humans, but to protect the **concrete** biological shield from gamma heating, which would otherwise dehydrate and crack the cement.

Radiation Streaming The phenomenon where radiation shoots down straight paths (pipes, ducts, wire penetrations) without interacting with the shield. Engineering solutions include "step plugs" (zigzagged plugs) and maze-like entrance corridors.

Galactic Cosmic Rays (GCR) High-energy heavy ions originating from supernovae. They are difficult to shield because hitting them with heavy metals (Lead) causes **Spallation** (nuclear fragmentation), creating a shower of secondary radiation. The best shield is Hydrogen (polyethylene/water).

35 Lecture 35 Terms

Absorbed Dose (Rad/Gray) The physical measure of energy deposited per unit mass of material (1 Gy = 1 J/kg). It describes the physics of the interaction but not the biological severity.

Equivalent Dose (Rem/Sievert) The biological measure of risk, calculated by multiplying the Absorbed Dose by a **Quality Factor (Q)**. It accounts for the fact that some particles (neutrons/alphas) cause more cellular damage per Joule than others (gammas/betas).

Linear Energy Transfer (LET) A measure of how densely a particle deposits energy along its track (dE/dx). High-LET radiation (Alphas, Neutrons) creates dense ionization trails that cause difficult-to-repair **Double Strand Breaks** in DNA, resulting in a high Quality Factor ($Q \approx 20$).

Isotopic Dilution (KI) A countermeasure for **Iodine-131** exposure. By saturating the thyroid gland with stable non-radioactive iodine (Potassium Iodide pills), the gland's uptake channels are blocked, preventing the absorption of carcinogenic I-131.

Acute Radiation Syndrome (ARS) The sequence of physiological effects following a high dose (> 1 Gy). It progresses from the **Prodromal** phase (nausea), to the **Latent** phase (temporary recovery or "Walking Ghost"), to **Manifest Illness** (Hematopoietic, GI, or CNS collapse).

ALARA "As Low As Reasonably Achievable." The regulatory philosophy that dictates that simply staying below the legal limit (5 Rem/yr) is not enough; operators must make every reasonable effort to minimize dose further.

Background Radiation The natural radiation field from cosmic rays, radon gas, and terrestrial isotopes. It varies by location (higher at high altitudes like Denver) and lifestyle (higher indoors due to Radon accumulation).

36 Lecture 36 Terms

Oklo Aurora A liquid-metal cooled, fast-spectrum micro-reactor (1.5–50 MWe). Distinct features include the use of metallic fuel, passive heat pipes for cooling, and a "functional containment" strategy rather than a traditional pressure vessel/dome.

HALEU (High-Assay Low-Enriched Uranium) Uranium enriched between 5% and 20% ^{235}U. Traditional LWRs use LEU ($< 5\%$), while weapons require HEU ($> 90\%$). HALEU allows smaller core designs like Aurora to sustain criticality for long periods (decades) without refueling.

Heat Pipe A passive heat transfer device with very high thermal conductivity. It relies on a phase-change cycle (evaporation at the hot end, sonic vapor flow, condensation at the cold end, and capillary return of liquid). It eliminates the need for mechanical coolant pumps.

Control Drums A reactivity control mechanism used in compact reactors instead of insertion rods. Cylinders with one neutron-absorbing face (Boron Carbide) and one reflecting face (Beryllium/Steel) rotate on the core periphery to leak or reflect neutrons.

Square-Cube Law An economic barrier for SMRs. Since power scales with volume (R^3) but containment cost scales with surface area (R^2), small reactors have a disadvantageous cost-to-power ratio for civil structures. This drives the need to eliminate the traditional containment building.

Sodium-Water Reaction A violent exothermic reaction ($2Na + 2H_2O \rightarrow 2NaOH + H_2 + \text{Heat}$) that produces hydrogen gas and caustic hydroxide. It is a primary risk in sodium-cooled reactors if the barrier between the sodium loop and the steam cycle fails.

37 Lecture 37 Terms

Small Modular Reactor (SMR) A class of nuclear reactors with a power output less than 300 MWe, designed for factory fabrication and modular assembly to reduce on-site construction risk.

Square-Cube Law In the context of nuclear economics, the disadvantage whereby shrinking a reactor reduces revenue-generating volume (R^3) faster than it reduces material costs (R^2). This often results in SMRs having a higher capital cost per kilowatt than gigawatt-scale plants.

TRISO Fuel "Tristructural Isotropic" particle fuel consisting of a uranium kernel coated with porous carbon, pyrolytic carbon, and Silicon Carbide (SiC). The SiC layer acts as a pressure vessel for fission products, allowing the fuel to remain intact at temperatures up to 1600°C.

Pebble Bed Reactor A reactor design where TRISO fuel is embedded in graphite spheres ("pebbles") that flow continuously through the core. This allows for online refueling but introduces the risk of radioactive graphite dust generation due to mechanical abrasion.

FLiBe A molten salt coolant composed of Lithium Fluoride and Beryllium Fluoride ($2LiF-BeF_2$). It is used in designs like the Kairos Hermes because it remains liquid at high temperatures (> 600°C) without requiring high pressure, though it produces tritium under irradiation.

Tritium (^3H) A radioactive isotope of hydrogen produced in salt reactors by neutron capture in Lithium-6 (^6Li). Because it is a hydrogen isotope, it easily diffuses through hot metallic heat exchangers, posing a significant radiation containment challenge.

Sodium-Cooled Fast Reactor (SFR) A reactor using liquid metal sodium as a coolant. It benefits from high thermal conductivity and the ability to operate at atmospheric pressure, but suffers from opacity (cannot see fuel) and violent chemical reactivity with air and water.

HALEU "High-Assay Low-Enriched Uranium," which is enriched between 5% and 20% ^{235}U. Most advanced reactors require this higher enrichment (compared to the 3-5% of LWRs) to maintain criticality with smaller cores or longer fuel cycles.