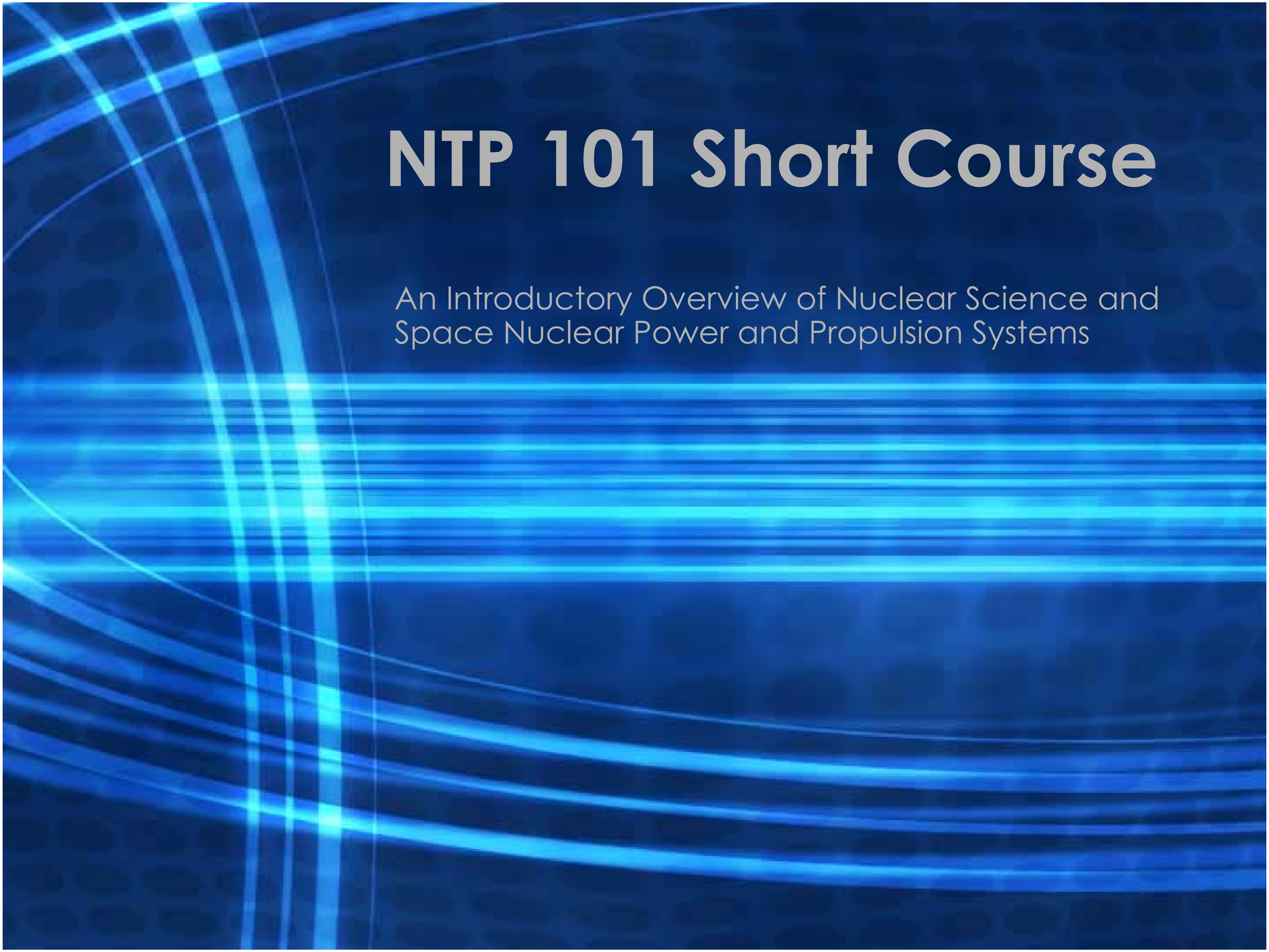
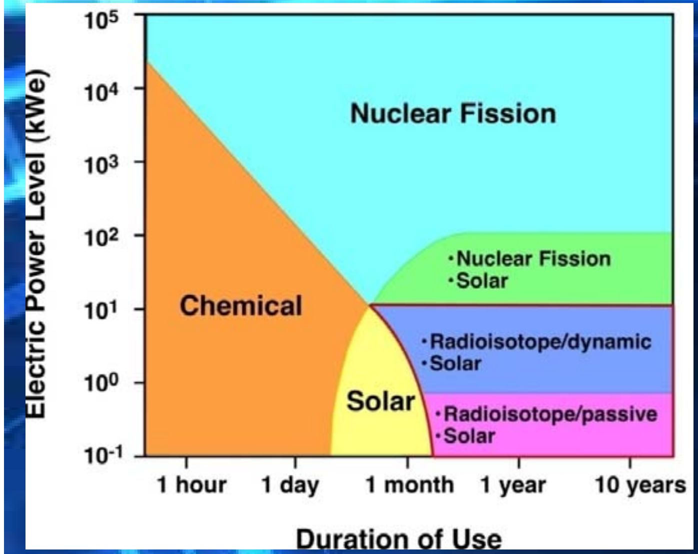


NTP 101 Short Course

An Introductory Overview of Nuclear Science and
Space Nuclear Power and Propulsion Systems

ENERGY COMPARISON

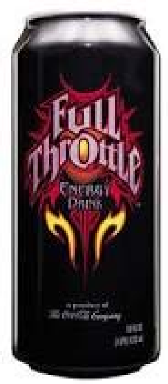


- Chemical: combustion, reaction
- Natural: solar (PV, thermal), EM tethers
- Nuclear: radioactive decay, fission
- Advanced nuclear: fusion, antimatter

Process	Maturity	Reaction	Reaction Energy (eV)	Specific Energy (J/kg)	Specific Cost ($/kg)
Combustion	Proven	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	4	10^6	10^{-1}–10^0 (CH_4) 10^{-1} (O_2)
Fuel Cell	Proven	$2H_2 + O_2 \rightarrow 2H_2O$	10.2	10^7	10^0 (H_2) 10^{-1} (O_2)
Radioisotope	Proven	$^{238}_{94}Pu \rightarrow {}^{234}_{92}U + {}^{4}_{2}He$	5.59×10^6	10^{12}	10^6
Fission	Proven	$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{147}_{57}La + {}^{87}_{35}Br + 2{}^{1}_{0}n + \gamma$	195×10^6	10^{13}	10^4 ($X_F > 93\%$)
Fusion	Research	$^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$ $^{2}_{1}H + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}p$	17.57×10^6 18.35×10^6	10^{14}	10^3 (D) 10^6 (^3He)
Antimatter	Research	$p + p^- \rightarrow \gamma$	1.05×10^9	10^{16}	10^{12}

NUCLEAR = MISSION ENABLING

Fission 341 mL of ^{235}U



= 50x

$L = 46.9$ m

$OD = 8.4$ m

$M_{LOX} = 630$ MT

$M_{H2} = 106$ MT

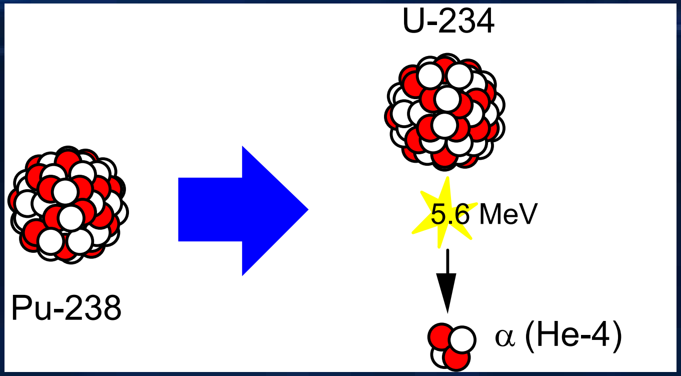
Significantly extends mission capability by overcoming current technology limitations:

- Power → Reliable, robust, long-duration, power dense
- Logistics (consumables)
  - Food, water, oxygen
- Human Factors
  - μg atrophy
  - Psychological isolation
  - Radiation dose → Shielding decreases crew dose

Time dependant factors mitigated by rapid propulsion decreasing transit

RADIOSIOTOPE DECAY

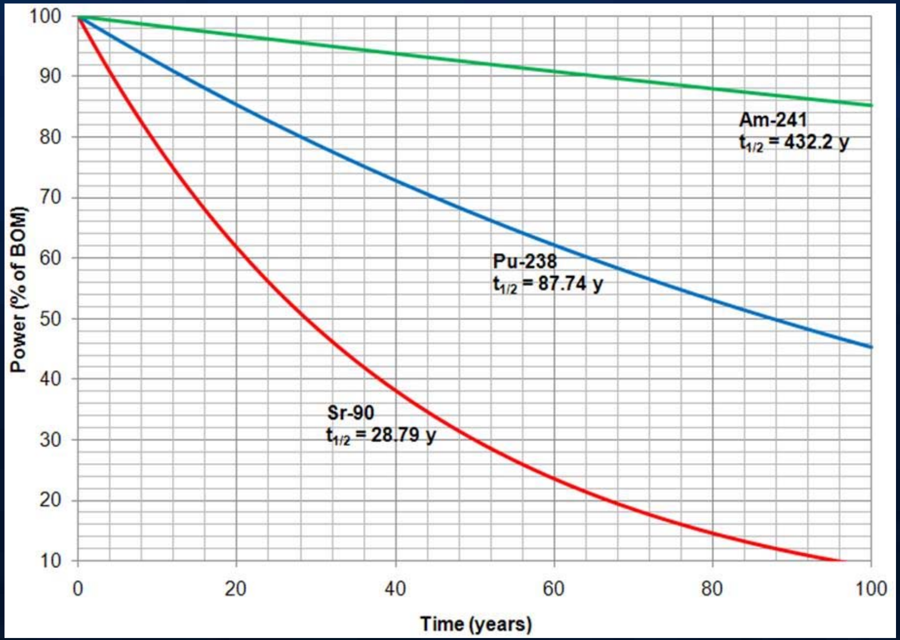
- Heat produced from natural alpha (α) decay



^{238}Pu Decay

- Service life activity (A) inversely proportional to isotope half-life ($t_{1/2}$)

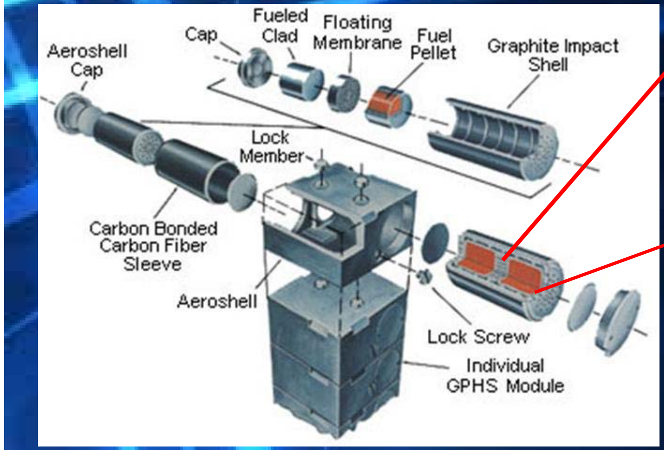
$$A(t) = A_o e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t}$$



Radioisotope Half-life Comparison

RADIOISOTOPE POWER SYSTEMS

- General Purpose Heat Source (GPHS)

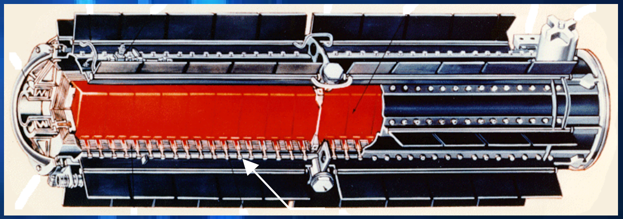


GPHS Stack. *Courtesy Department of Energy.*

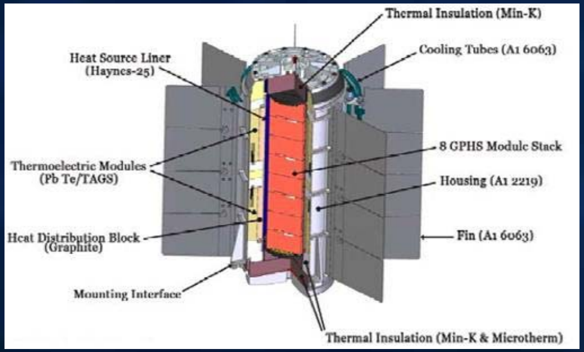
$^{238}PuO_2$ Pellet. *Courtesy Department of Energy.*

Fuel	PuO_2
Power	250 W_{th} (BOM)
Mass	1.44 kg
Size	9.3x9.7x5.3 cm

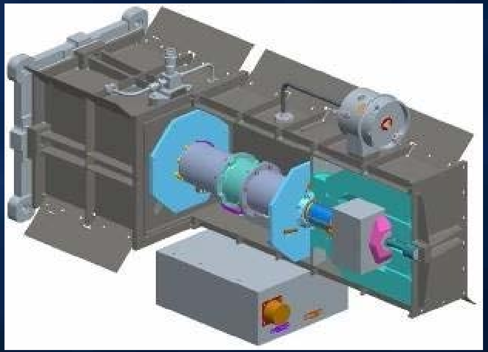
Nuclide	wt %
^{238}Pu	83.6
^{239}Pu	14.0
^{240}Pu	2.0
^{241}Pu	0.4
^{242}Pu	0.1



GPHS-Radioisotope Thermoelectric Generator (RTG). Courtesy Department of Energy.



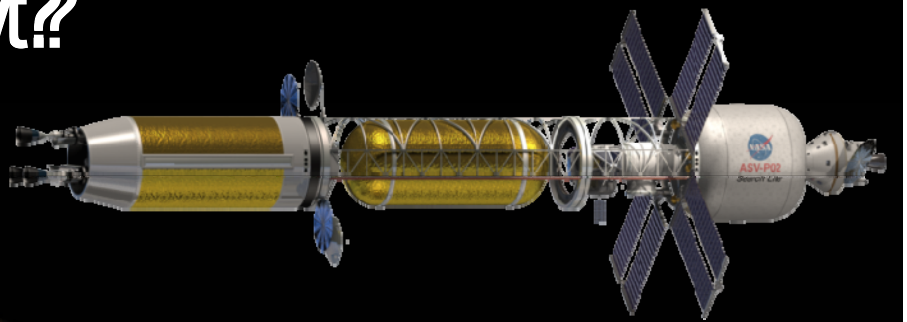
Multi-Mission RTG (MMRTG). Courtesy Department of Energy



Advanced Stirling Radioisotope Generator (ASRG). Courtesy Lockheed Martin

Power (W_e)	290	120	120
Efficiency (%)	6.6	6	24
GPHS Modules	16	8	2
Mass (kg)	54.4	43	27.1
Conversion	SiGe Thermoelectrics	SiGe Thermoelectrics	Stirling Convertors
Mission	Galileo x 2, Cassini x 3 Ulysses x 1, New Horizons x 1	Curiosity x 1 2016 Mars Rover x 1	Development

What? Why?



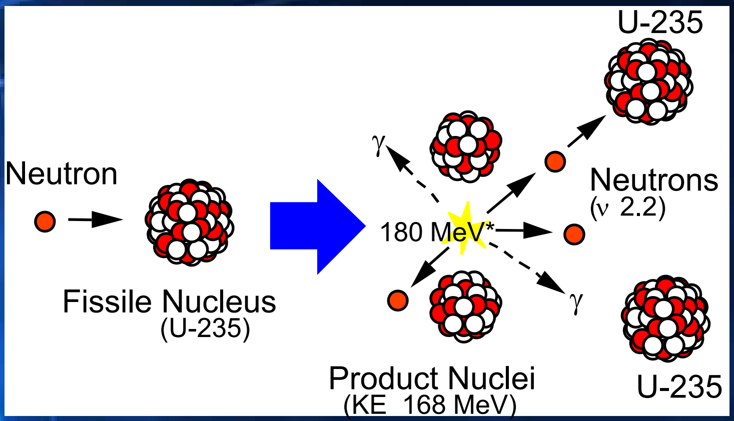
NTP = Mission Enabling
I_{sp} = 880-900 seconds
Leverage existing engine experience

“To extend and sustain human activities beyond LEO, rapid crew transit is required.”

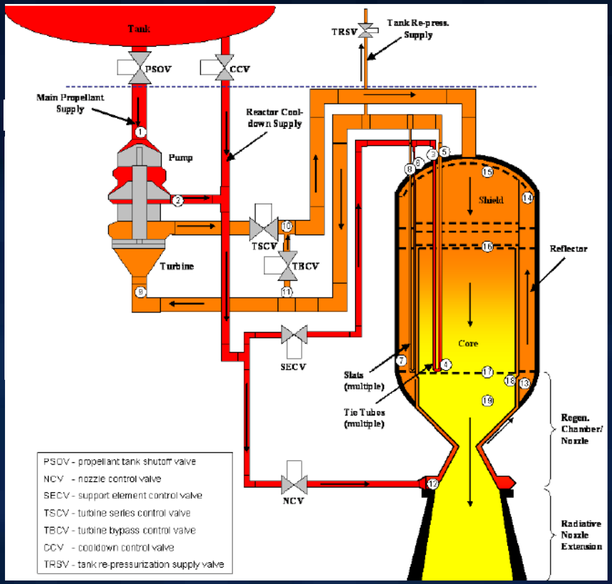
- NASA STMD Technology Roadmap

NUCLEAR THERMAL PROPULSION

- Conventional rockets utilize propellant & oxidizer
- NTP reactor uses nuclear fission to heat LH_2 propellant



$$I_{sp} = \frac{F}{\dot{m}} = AC_F\sqrt{\frac{T_C}{M_P}}$$



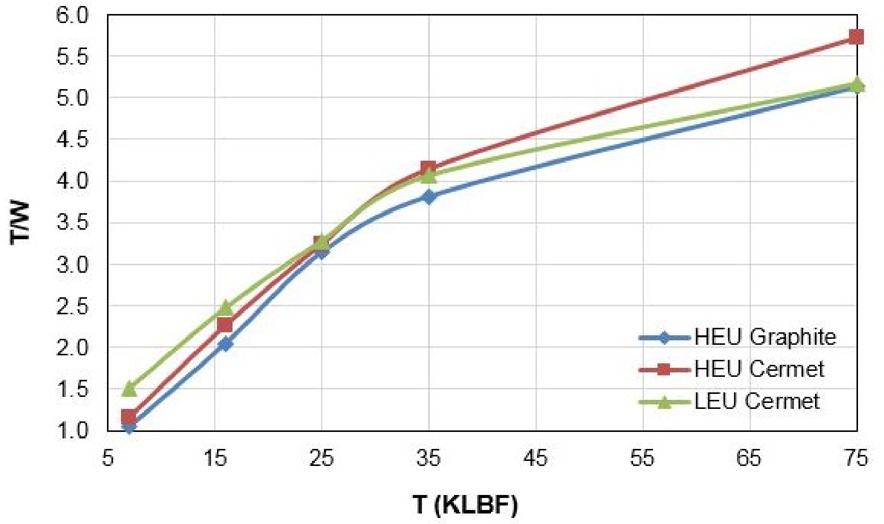
NTP system diagram. *Courtesy*.

- Steady state full power density: MW/L

ROVER/NERVA (1955-1973): KIWI, NRX, PEWEE, NF, PHOEBUS

MISSION DESIGN & THRUST CLASS

- Human requirements drive design
  - 3 engine cluster, total 75-105 klb_f
- Engine Thrust Class
  - NTP T/W not linear with engine size
- Total burn time
  - Lower with higher thrust engine
  - Impact engine duty cycle and reliability
- NTP cost not linear with thrust
  - Majority of cost in fuel development
  - Smaller engine size = negligible cost impact
  - Subscale flight demos cannot be used to meet human rating requirements
  - A second engine will have to be designed and drive up costs

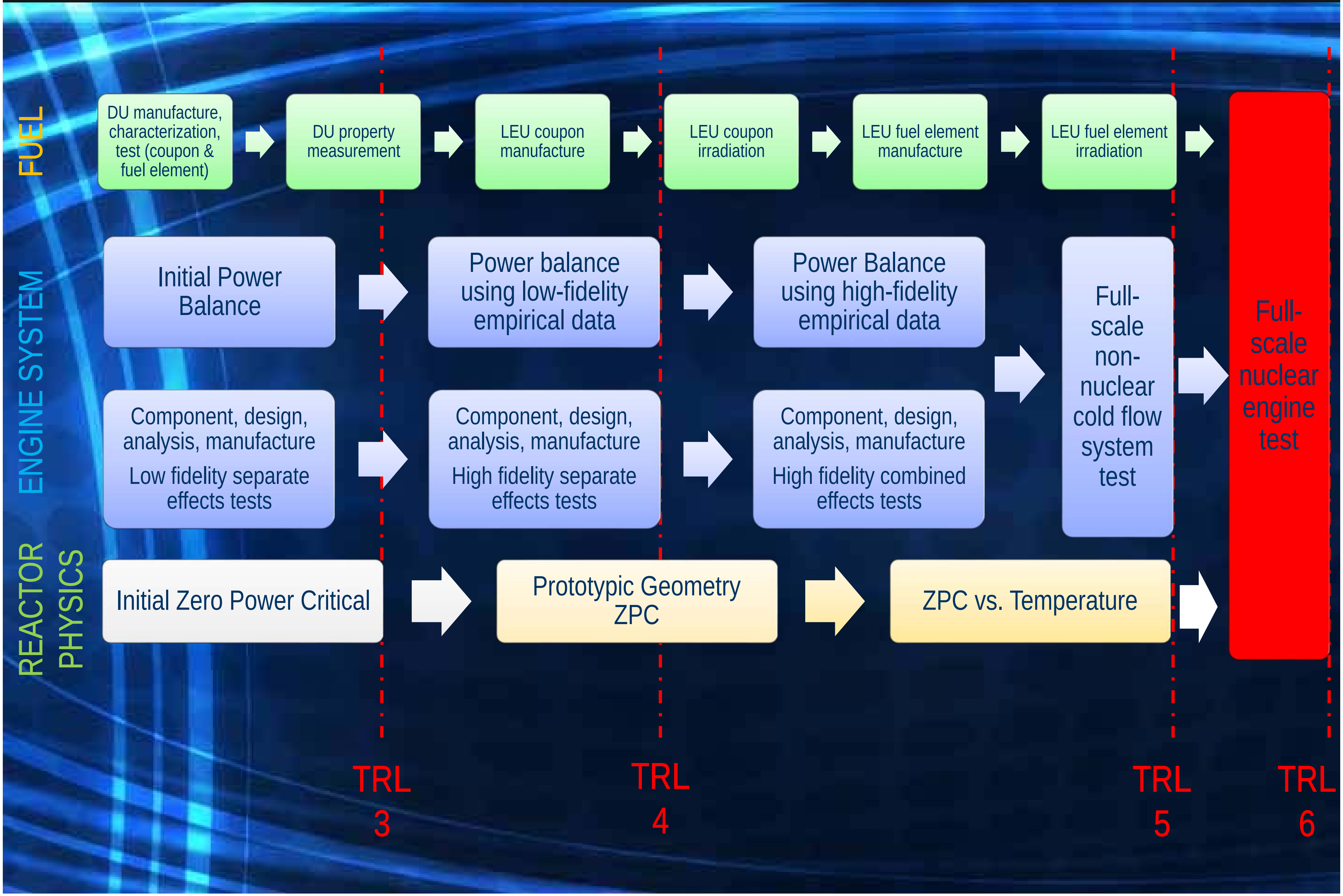


NTP Thrust-to-Weight vs. Thrust. *Courtesy CSNR.*

Engine Thrust (klb)	Burns (no.)	Total Burn time 2033 (min)	Total Burn time 2033 (min)
25	4	101	92
35	4	73	59

Courtesy L. Koss

PARALLEL DEVELOPMENT PLAN



FUEL

DU manufacture, characterization, test (coupon & fuel element)

DU property measurement

LEU coupon manufacture

LEU coupon irradiation

LEU fuel element manufacture

LEU fuel element irradiation

ENGINE SYSTEM

Initial Power Balance

Power balance using low-fidelity empirical data

Power Balance using high-fidelity empirical data

Component, design, analysis, manufacture

Low fidelity separate effects tests

Component, design, analysis, manufacture

High fidelity separate effects tests

Component, design, analysis, manufacture

High fidelity combined effects tests

Full-scale non-nuclear cold flow system test

REACTOR PHYSICS

Initial Zero Power Critical

Prototypic Geometry ZPC

ZPC vs. Temperature

Full-scale nuclear engine test

TRL 3

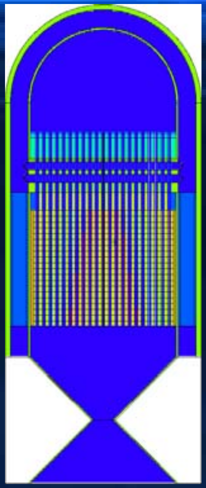
TRL 4

TRL 5

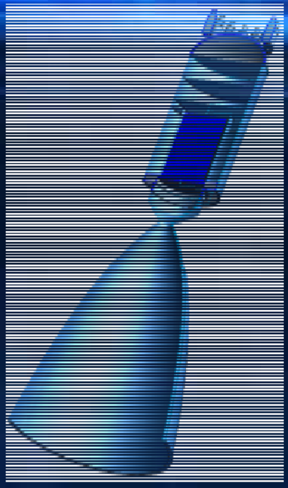
TRL 6

ENGINE COMPONENTS

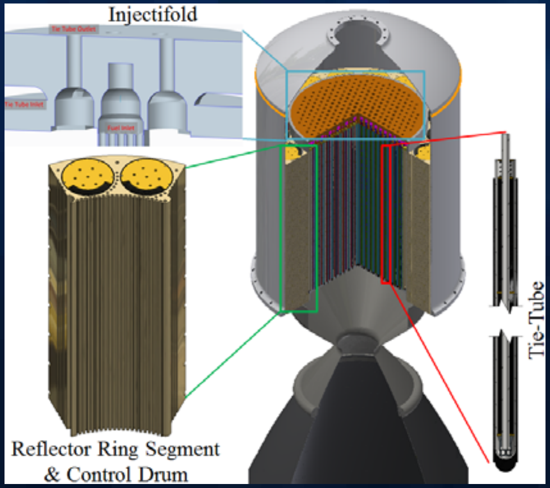
- Engine Systems
  - Reactor Neutronic Analysis
  - Power Balance
- Reactor
  - Fuel
  - Tie-tubes
  - Reflector Rings & Control Drums
  - Injectifold
  - Bottom plate
  - Internal Shield
- Thrust Chamber Assembly
  - Pressure Vessel
  - Regen Nozzle & Nozzle Extension
- Turbopump
- Propulsion Stage
  - Lines, Ducts, Valves
  - Thrust Vector Control
  - Controller
  - Distance truss



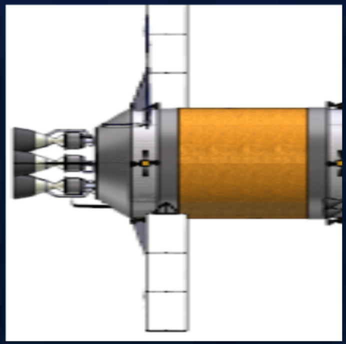
Neutronic Model



Parametric Model

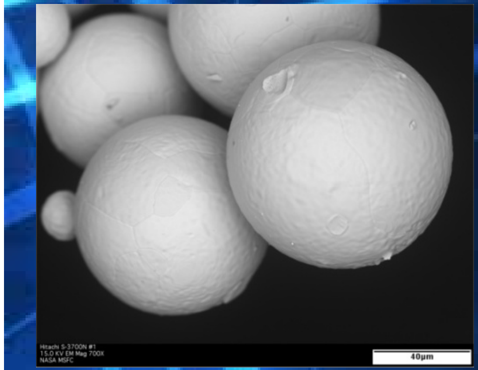


Integrated Component Models

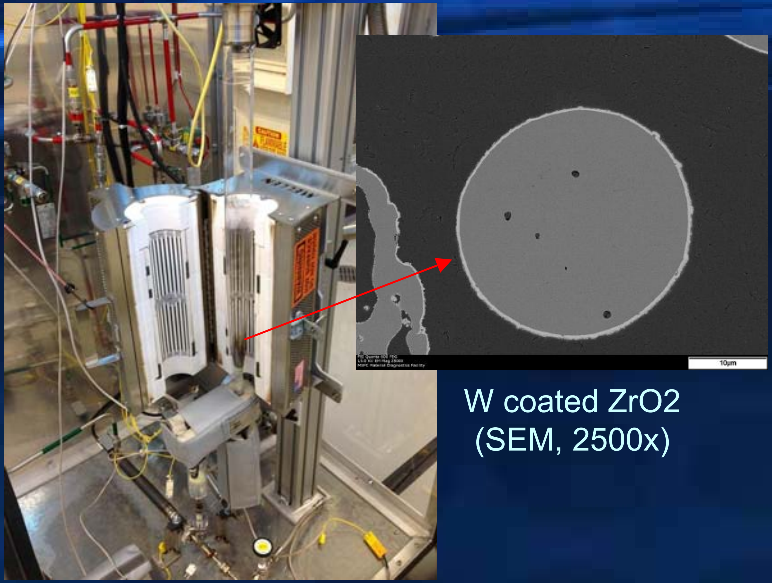


155.7 kN (35 lb$_f$) x 3

FUEL DEVELOPMENT



Sol-Gel dUO_2 Powders
(SEM, 700x)

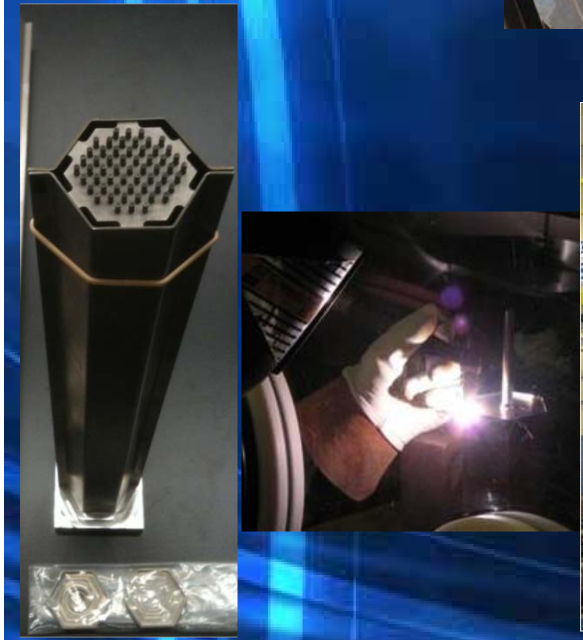


W coated ZrO2
(SEM, 2500x)

CVD System

Spark Plasma Sinter

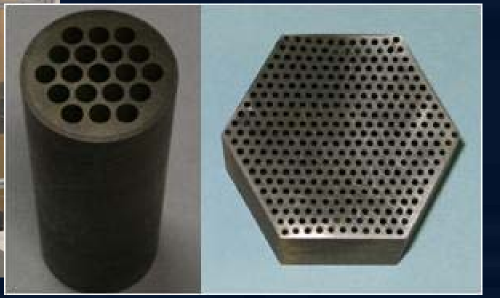
Chemical Etch System



61 Channel Hex HIP Can

HIP Furnace

Grinder



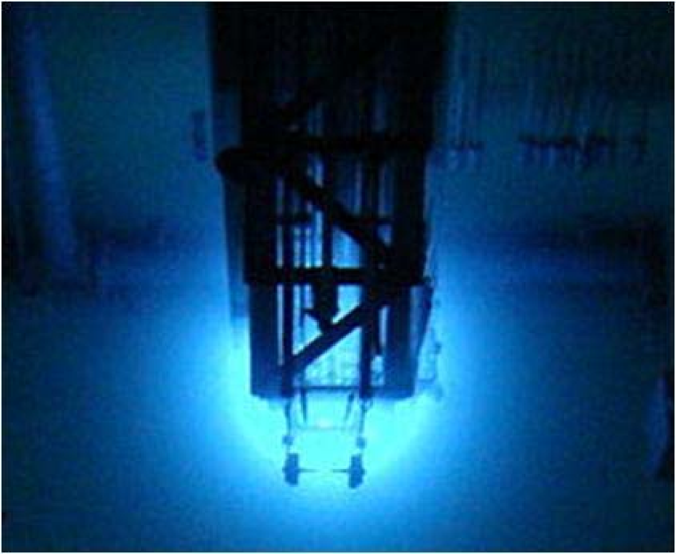
Fuel Sample

FUEL DEVELOPMENT

Compact Fuel Element Environmental Tester

Sample heated to 2900 K

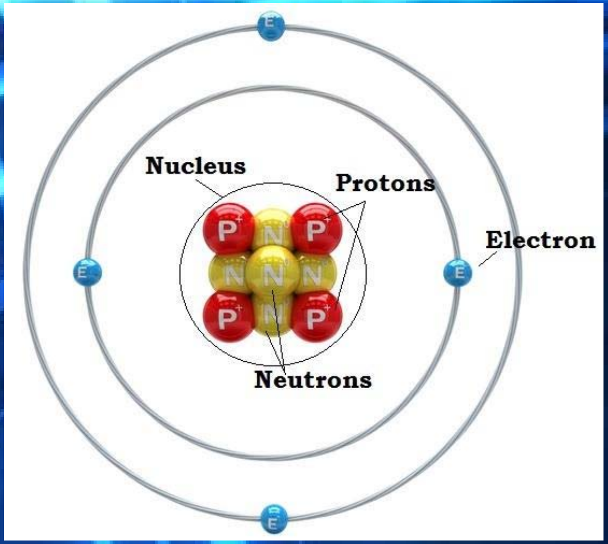
Nuclear Thermal Rocket Element Environmental Simulator (NTREES)



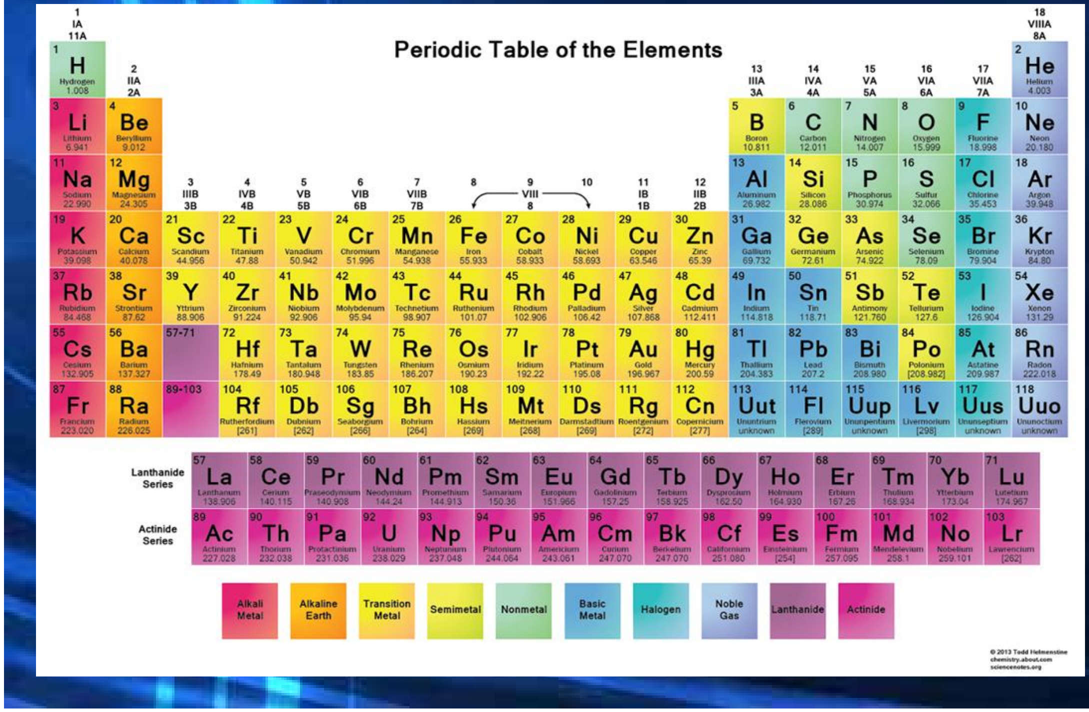
University & DOE Reactor Facilities

Radiation Interactions

THE ATOM



- The Atomic Model ($^{A}_{Z}X$)
  - Atomic number (*Z*): number of protons in the nucleus.
  - Neutron number (*N*): number of neutrons in the nucleus.
  - Mass number (*A*=*Z*+*N*): protons & neutrons in the nucleus.
- Isotope
  - Nuclei with the same *Z* but different *A*
  - Hydrogen ($^{1}_{1}H$), Deuterium ($^{2}_{1}H$), Tritium ($^{3}_{1}H$)



Periodic Table of the Elements

1 IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Semimetal | Nonmetal | Basic Metal | Halogen | Noble Gas | Lanthanide | Actinide

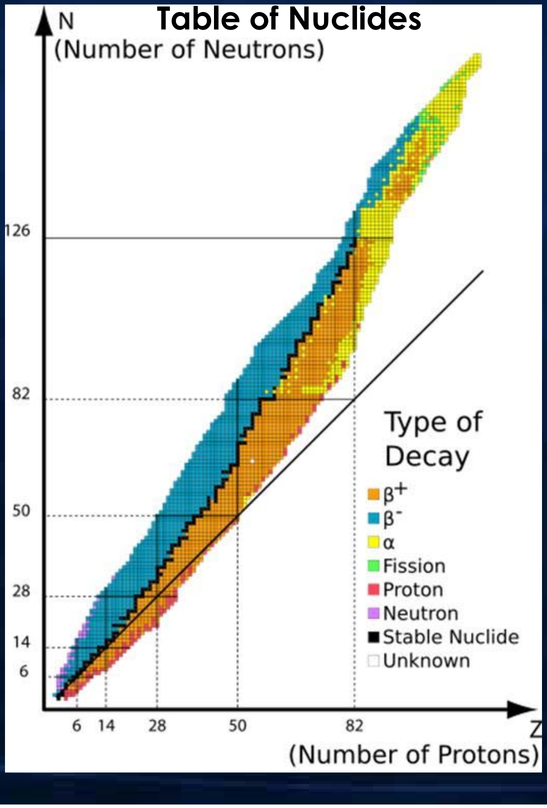
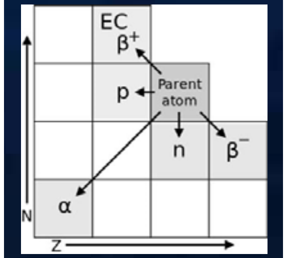
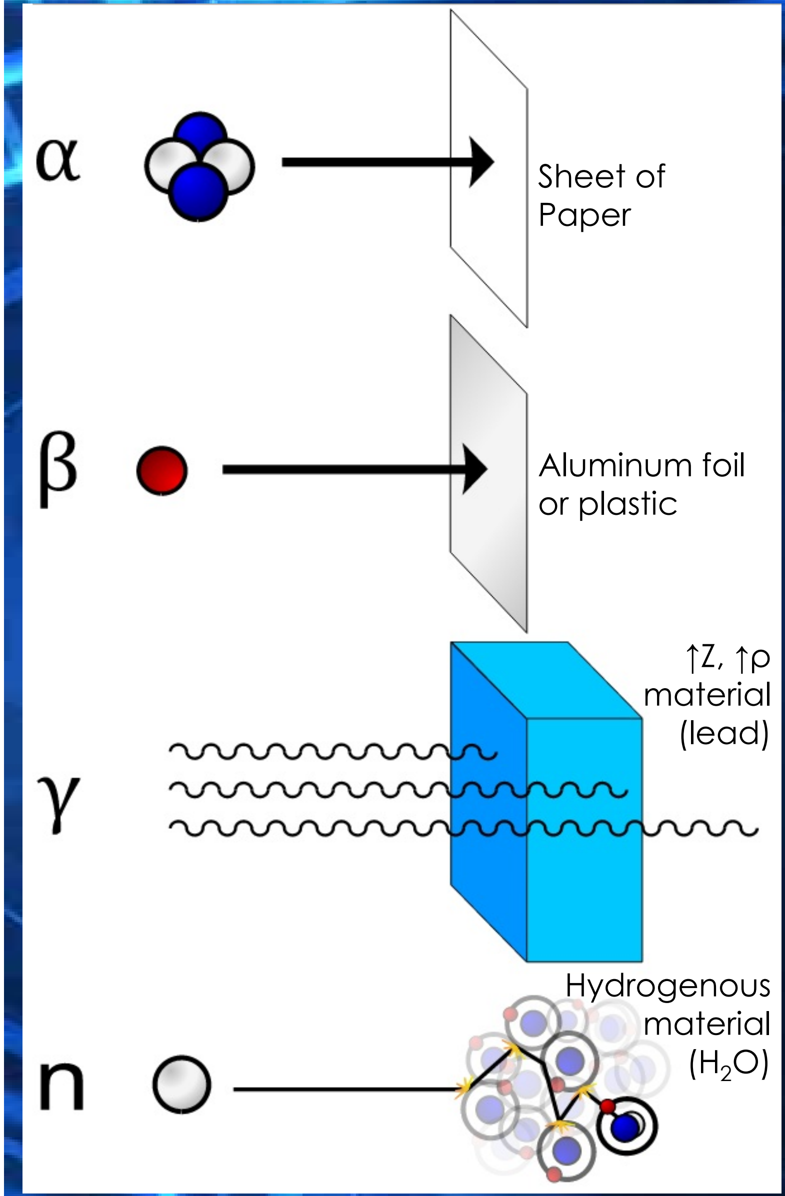


Table of Nuclides



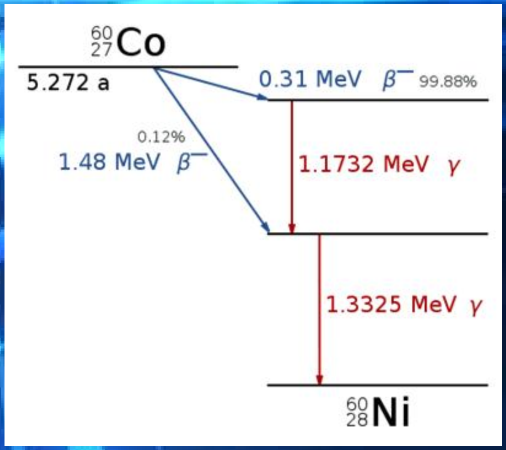
IONIZING RADIATION



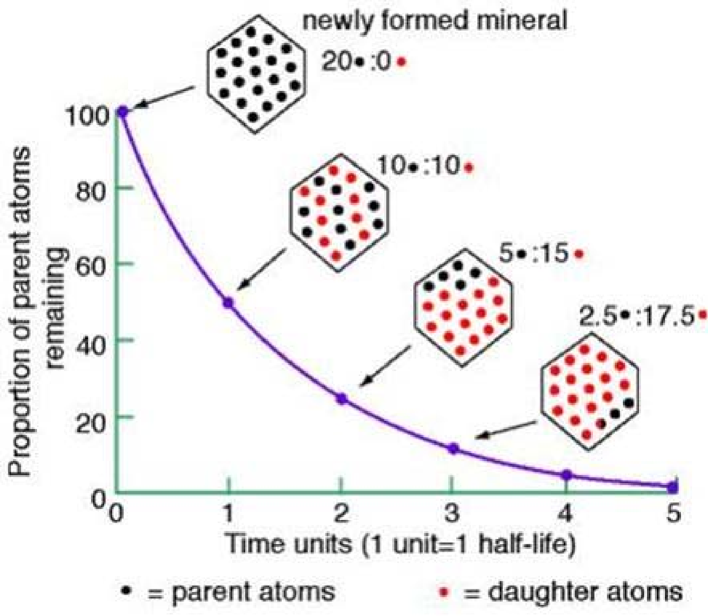
Radiation Types & Shielding Material

- Ionizing: energy to eject electrons (~10 eV)
- Radiation Types
  - *Charged particles*: electrons, protons, heavy part.
  - *Uncharged particles*: x-rays, γ-rays, neutrons
- Alpha (α)
  - He nucleus ejected from the atom nucleus.
  - Range: cm/MeV (air), μm/MeV (solids).
  - Internal hazard
- Beta (β)
  - Electron ejected from the atom nucleus.
  - Range: m/MeV (air), mm/MeV (solids).
  - External hazard
- Heavy Charged Particles
  - Particles with $A > 1$.
  - External hazard
- Gamma-rays (γ)
  - Photon emitted from the atom nucleus.
  - Range: m/MeV (air), cm/MeV (solids)
  - External hazard
- Neutron
  - Originate from the nucleus
  - External hazard

RADIOACTIVE DECAY



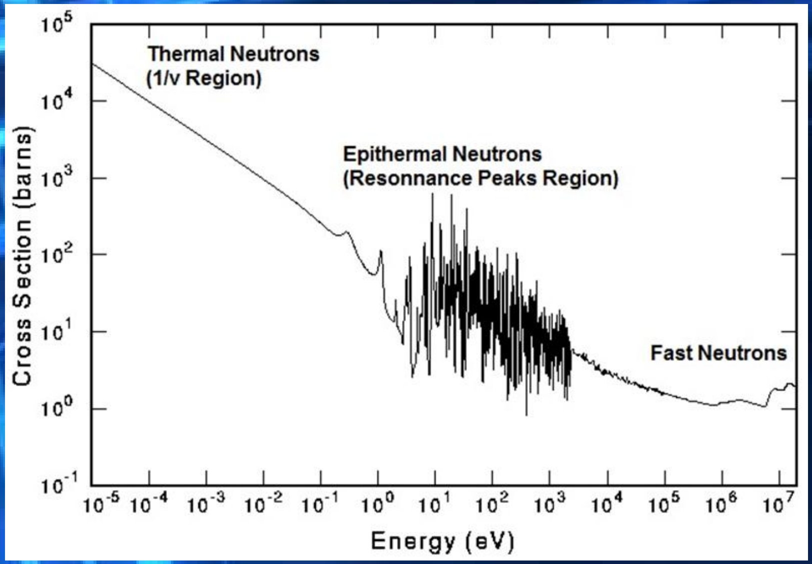
Decay Scheme



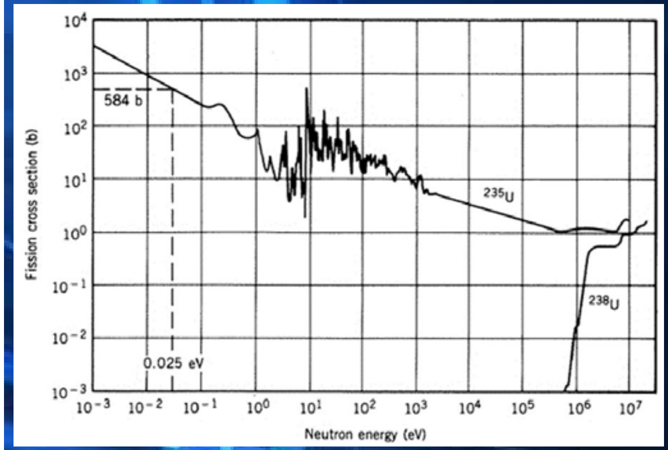
Parent-decay, daughter-production plot

- Radioactivity
  - Unstable nuclei decay to reach the lowest energy (ground) state.
  - Each radioisotope decays at a unique exponential rate.
- Units
  - 1 Becquerel (Bq) = 1 disintegration/second
  - 1 Curie (Ci) = 3.7×10^{10} disintegrations/second
- Half-Life ($t_{1/2}$)
  - The time required for a quantity of radioactive material to be reduced by half of the original activity
  - $A(t)_{Parent} = A_o e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t}$
  - $A(t)_{Daughter} = A_o \left[1 - e^{-\left(\frac{\ln 2}{t_{1/2}}\right)t}\right]$

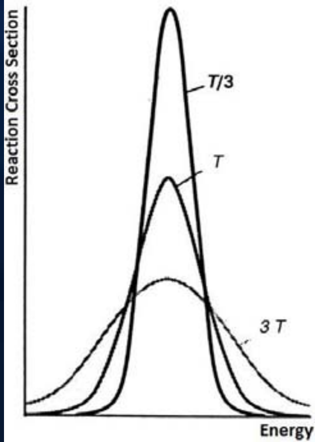
NEUTRON INTERACTIONS



^{235}U Fission Cross Section. Courtesy Duderstdat & Hamilton



^{235}U & ^{238}U fission cross section comparison.
Courtesy Duderstadt & Hamilton.

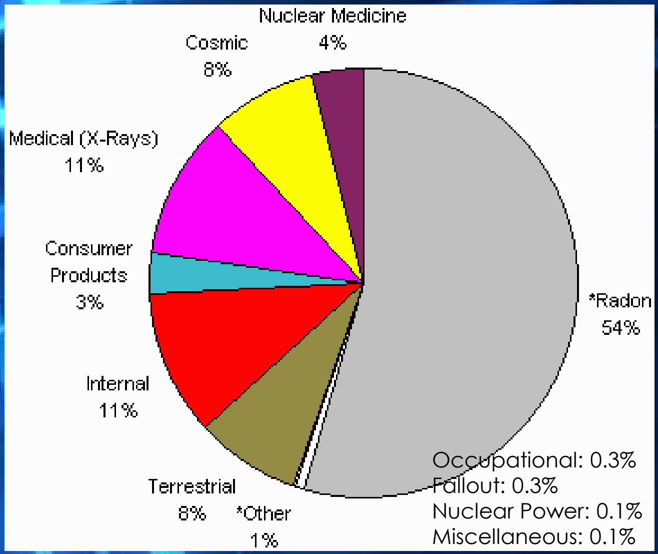


Doppler
Broadening

- Fission
  - Overcome binding energy to induce a nucleus to split
- Fissile: fission with slow (thermal) neutron
  - ^{233}U, ^{235}U, ^{239}Pu, ^{241}Pu, ^{237}Np
- Fissionable: fission with fast neutrons
  - ^{232}Th, ^{238}U, ^{240}Pu (and fissile ^{235}U)
- Microscopic Cross Section (σ)
  - Probability a reaction will occur
  - Dependent on incident neutron energy, nucleus, temperature
  - Units: cm^2 or barns (1 b = 10^{-24} cm^2)
  - Fission, scatter, radiative capture
- Macroscopic Cross Section (Σ)
  - $\sum = N\sigma$ (atoms/cm)
  - N = Atomic Density (atoms/cm^3)

Radiation Protection

DOSE COMPARISONS



Average radiation dose in the United States

Common Natural Radionuclides

Nuclide	Source	Reaction	Exposure
^{3}H (Tritium)	Cosmogenic	$^{14}N(n,T)^{12}C$ $^{16}O(n,T)^{14}N$	Internal
^{14}C	Cosmogenic	$^{14}N(n,p)^{14}C$	Internal
^{40}K, ^{87}Rb	Primordial	long $t_{1/2}$	Internal
^{222}Rn, ^{220}Rn	Primordial Decay	^{238}U & ^{232}Th	External

Scenario	Dose (Rem)	Dose (mSv)
Average U.S. annual whole-body dose	0.36	3.6
NRC annual occupational total effective whole-body dose limit	5	50
No observable effects	< 25	250
Possible temporary blood effects	~25	~250
NRC annual total occupational skin dose limit	50	500
Onset of radiation sickness - acute exposure	50-100	500-1000
NCRP astronaut career total whole-body dose limit	100	1000
Death ($L_{50/60}$) – acute exposure	300-450	3000-4500
Death (100%)	1000	10,000

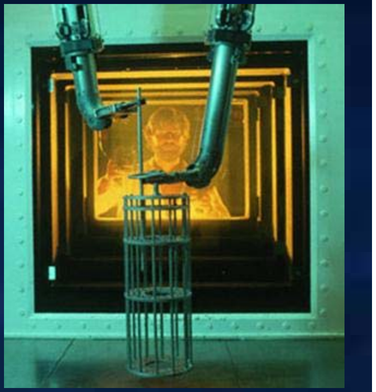
Normal Activity Doses

Activity	Dose
Commercial Air Flight	0.238-0.66 mRem/hr
Head x-ray	78 mrem bone marrow 1500 mrem skin
Abdominal x-ray	535 mrem bone marrow 1700 mrem skin
Tobacco use	8 mrem/yr

ALARA

- As Low As Reasonably Achievable (ALARA)
  - Cumulative dose kept ALARA considering technology, cost, etc.

	Principle	Operating Rule	Method
Time	Dose rate proportional to time spent in radiation.	↓ Time = ↓ dose rate	• Train to perform tasks quickly. • Perform tasks outside the radiation field when possible. • Never loiter.
Distance	Dose rate inversely proportional to the distance squared from a source (↑Lx2 = ↓Dx4).	↑ Distance = ↓ dose rate	• Keep away from sources. • Use long-handled tools. • Use remote manipulators.
Shielding	Appropriate shielding between you & radiation source decreases intensity.	↑ Shielding = ↓ dose rate	• Keep sources in shielded containers (glove boxes, hot cells, pigs, etc.) • Use portable shielding & PPE.



Remote manipulators within a hot cell.

RADIATION SHIELDING

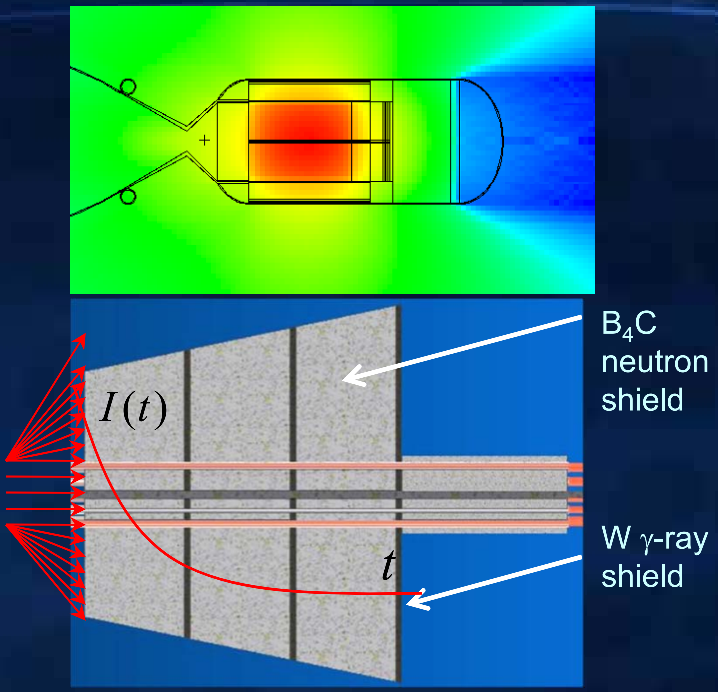
- Shield has the potential to dominate reactor mass
- γ-ray attenuation
  - ↑Z materials: *W, Pb, dU*

$$I(t) = I_o e^{-\left(\frac{\mu}{\rho}\right)_s \rho t}$$

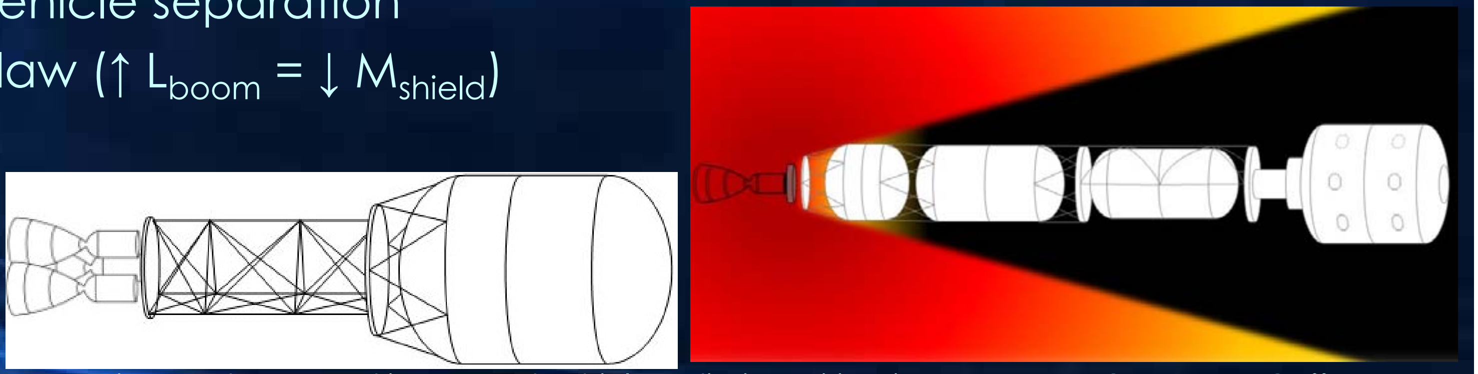
- Neutron attenuation
  - ↓Z materials: *H, Li, B, H_2O, LiH*

$$I(t) = I_o e^{-\Sigma_s t}$$

- Distance Truss
  - Rx-vehicle separation
  - $1/r^2$ law (↑ L_{boom} = ↓ M_{shield})



Shadow Shield Concept



Distance boom and integrated vehicle radiation mitigation concept. *Courtesy J. Caffrey*

Nuclear Materials

ENRICHMENT & SNC Categories

- Fuel enrichment (X_F)
  - $X_F = \frac{Mass\ of\ 235_U}{Mass\ of\ 238_U}$ (%)
- Natural Uranium (natU)
  - 0.711%
- Depleted Uranium (dU)
  - 0.2%
- Low Enriched Uranium (LEU)
  - <20%
  - Light Water Reactor (LWR) 3-5%
  - NTP target 19.75% for affordability
- High Enriched Uranium (HEU)
  - >20%
  - Significant safeguards and expense
  - Most space reactor concepts: ~93%

Isotope	M (kg)
^{235}U (X_F > 20%)	> 5
^{233}U	> 2
^{239}Pu	> 2
^{235}U+2.5(^{233}U+^{239}Pu)	> 2

Category I

Strategic

Specialized facilities
Guards & Guns
High Cost

Isotope	M (kg)
^{235}U (X_F > 20%)	> 1
^{233}U	> 0.5
^{239}Pu	> 0.5
^{235}U+2(^{233}U+^{239}Pu)	> 1
^{235}U (10%< X_F <20%)	> 10

Category II

Mod. Strategic

Isotope	M (kg)
^{235}U (X_F > 20%)	> 0.015
^{233}U	> 0.015
^{239}Pu	> 0.015
^{235}U+^{233}U+^{239}Pu	> 0.015
^{235}U (10%< X_F <20%)	1< M < 10
^{235}U (0.711%< X_F <10%)	> 10

Category III

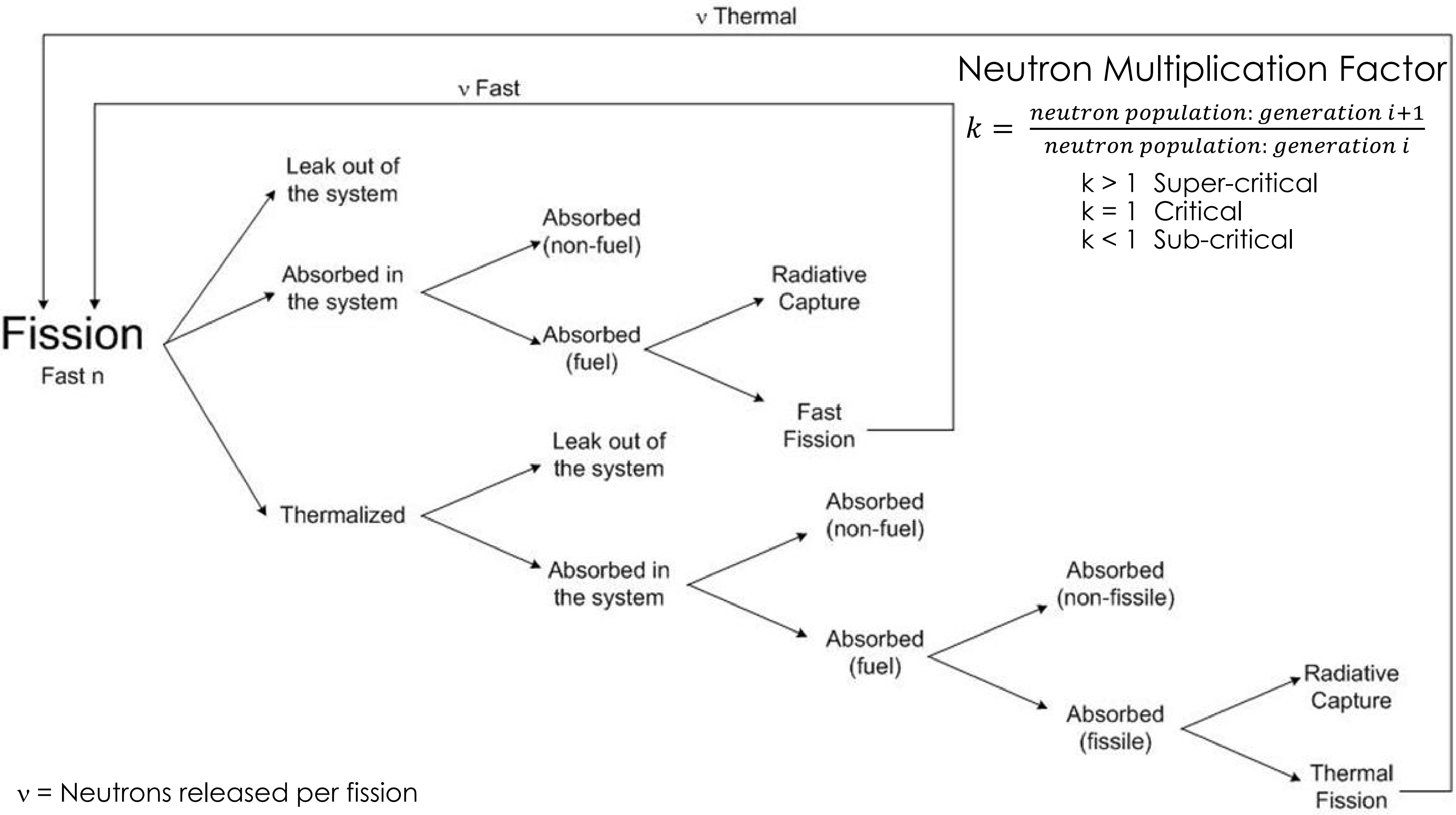
Low strategic

University Reactor
Lower Cost

Reactor Physics

NEUTRON LIFE CYCLE

- Stable fission chain reaction
  - Neutron production, leakage and absorption rates balanced
  - Reactor power proportional to neutron population



ν Thermal

ν Fast

Fission

Fast n

Leak out of the system

Absorbed in the system

Absorbed (non-fuel)

Absorbed (fuel)

Radiative Capture

Fast Fission

Thermalized

Leak out of the system

Absorbed in the system

Absorbed (non-fuel)

Absorbed (fuel)

Absorbed (non-fissile)

Absorbed (fissile)

Radiative Capture

Thermal Fission

Neutron Multiplication Factor

$$k = \frac{neutron\ population: generation\ i+1}{neutron\ population: generation\ i}$$

$k > 1$ Super-critical

$k = 1$ Critical

$k < 1$ Sub-critical

ν = Neutrons released per fission

6-Factor Formula

$$k_\infty = \eta\, p\, \varepsilon\, f$$

$$k_{eff} = k_\infty P_{NL}^F\, P_{NL}^T$$

η = thermal n production factor $= \dfrac{n\ produced\ in\ thermal\ fission}{thermal\ n\ absorptions\ in\ fuel} = \dfrac{\nu\Sigma_{fission}}{\Sigma_{abs}^{Fuel}}$

$p =$ resonance escape probability: fraction of fast n that escape resonance absorption & slow to thermal energies $= \dfrac{n\ downscatter\ to\ thermal\ energies\ from\ above\ thermal\ (TDSCT)}{total\ fast\ n\ absorptions + TDSCT}$

ε = fast fission factor $= \dfrac{total\ fission\ n\ produced\ from\ fast\ \&\ thermal\ fission}{fission\ n\ produced\ from\ thermal\ fission}$

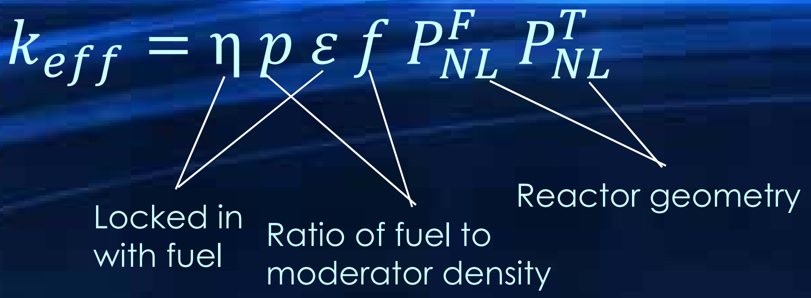
f = thermal utilization factor $= \dfrac{thermal\ n\ absorptions\ in\ fuel}{total\ thermal\ n\ absorptions} = \dfrac{\Sigma_{abs}^{Fuel}}{\Sigma_{abs}^{System}}$

P_{NL}^F = fast non-leakage probability $= \dfrac{fast\ n\ source - fast\ n\ leakage}{fast\ n\ source}$

P_{NL}^T = thermal non-leakage probability $= \dfrac{TDSCT - thermal\ n\ leakage}{TDSCT}$

Typical Thermal Reactor (^{235}U)
k_∞ = 1.04
k_{eff} = 1.00
η = 1.65
p = 0.87
ε = 1.02
f = 0.71
P_{NL}^F = 0.97
P_{NL}^T = 0.99

REACTOR CORE COMPOSITION



$$k_{eff} = \eta \, p \, \varepsilon \, f \, P_{NL}^{F} \, P_{NL}^{T}$$

Locked in
with fuel

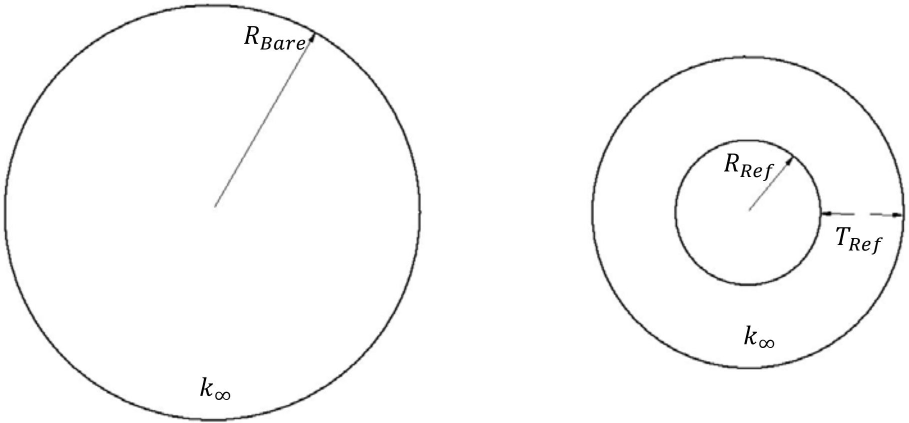
Ratio of fuel to
moderator density

Reactor geometry

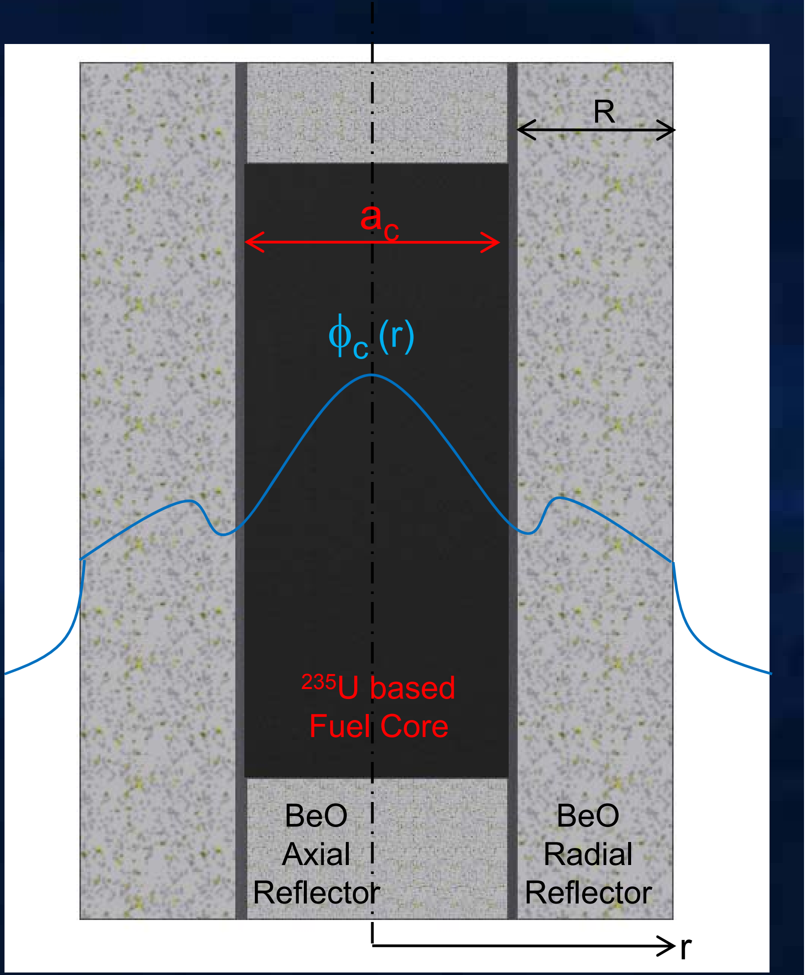
- Fuel
  - Enrichment, density, shape: ^{235}U, 19.75%
- Moderator
  - Low mass number material to slow neutrons: graphite, Be, H_2
  - Fuel-to-moderator ratio: $\frac{N_F}{N_M}$
- Coolant
  - Remove heat, moderate, supplement reactor control with H_2 flow rate
- Structural materials
  - Maintain core geometry: support plates, spacer grids, tie tubes
  - Low neutron absorption cross section materials: Zircaloy, Al, Inconel, SS, ^{184}W
- Control elements
  - Absorbs neutrons to control multiplication
  - High neutron absorption cross section materials: B, B_4C, Cd, Gd, Hf
- Reflector
  - Scatters leaking neutrons back into the core
  - Low neutron absorption cross section materials: Be, BeO, graphite
- Pressure Vessel
  - Core and cooling containment: Al, Inconel, SS

REACTOR GEOMETRY

- Reflected core = ↓ critical size (mass)
- Insulation to prevent heat loss is analogous to reflectors to prevent neutron leakage from the reactor core.



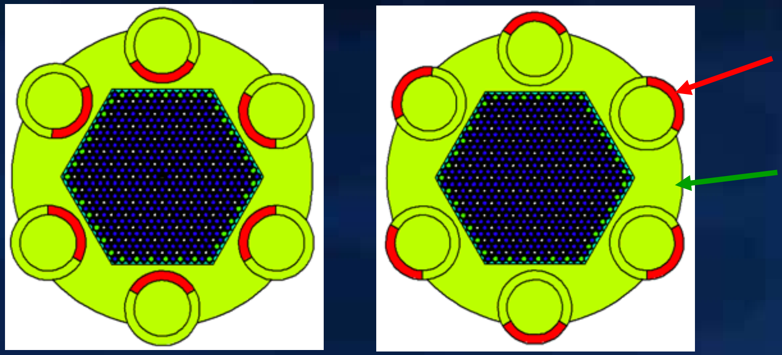
Bare vs. reflected critical assemblies. k_∞ will not change since dependent on fuel composition and not geometry.



Reflected reactor geometry core cross-section

REACTOR KINETICS & CONTROL

- Short-term transients (s, m, hr): start-up, maneuvering, shut-down
- Long-term transients (d, w, m): fuel BU from BOL to EOL
- Neutron population control = reactor control
  - Control drums: vary neutron population with absorber **(vary f)**
  - Coolant flow: harden spectrum with lower coolant flow rate **(vary f)**



Control Drives @ 0°: Subcritical

Control Drives @ 180°: Critical or Super Critical

Rotating Control Drum: B_4C Absorber

Be Reflector

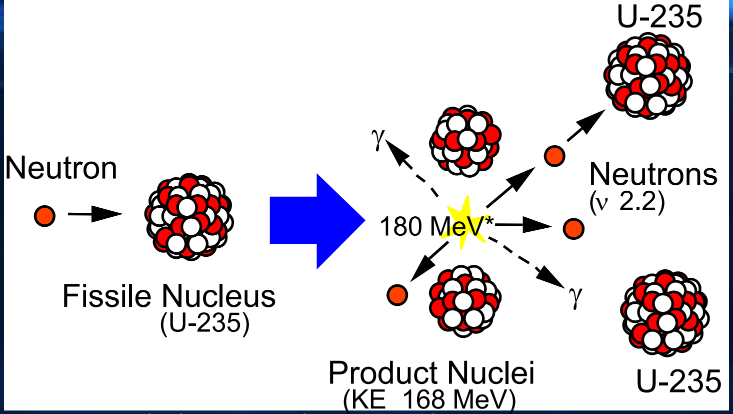
- Reactivity
  - The measure of neutron multiplication deviation from unity

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

  - Units (relative to β): If $\rho = \beta \rightarrow \$1$ of reactivity (^{235}U reactor: \$0.4 is $\rho = 0.4\beta = \$0.4$)
- ρ depends on neutron flux (φ) and thus Rx power
  - $\Delta T_{core} = \Delta V_{Matls} = \Delta density = \Delta C_{atom} = \Delta \Sigma_{a,s} = \Delta\, reaction\, rate = \Delta\varphi = \Delta\rho$

DELAYED NEUTRONS

- Prompt Neutrons
  - Born at fission
  - 98-99% of neutron population
  - Short lifetime ($l = 10^{-4}$ s)
  - Difficult to control (T = 0.1 s)



Fission Chain Reaction Process

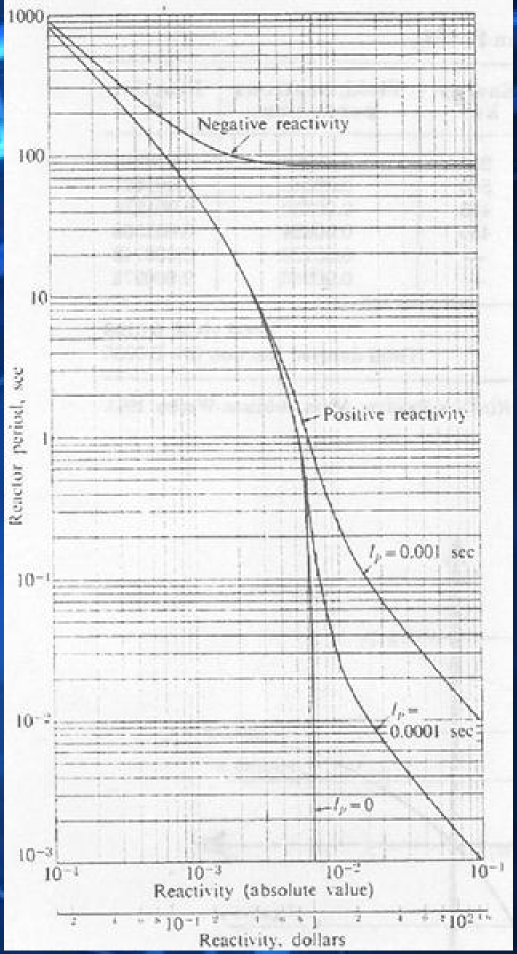
- Delayed Neutrons
  - Born from fission product radioactive decay
  - 1-2% of neutron population
  - Longer lifetime ($l = 0.6 – 80$ s)
  - Controllable (T = 10 s)
  - β = delayed neutron fraction

β_{U235}	0.0065
β_{Pu239}	0.002

^{235}U thermal fission delayed neutrons. Courtesy of Duderstadt & Hamilton.

Group	$t_{1/2}$ (s)	Decay Constant λ_i (s^{-1})	Energy (keV)	Yield (n/fission)	Fraction B_i
1	55.72	0.0124	250	0.00052	0.000215
2	22.72	0.0305	560	0.00346	0.001424
3	6.22	0.111	405	0.00310	0.001274
4	2.30	0.301	450	0.00624	0.002568
5	0.610	1.14	-	0.00182	0.000748
6	0.230	3.01	-	0.00066	0.000273
				0.0158	0.0065

REACTOR PERIOD



Reactivity-Period Chart. Courtesy of Dugan.

- Reactor Period
  - Time required for Rx power to change by “e” (2.718)
  - $T = \frac{l}{k-1}$
  - As $k \rightarrow 1$, T $\rightarrow \infty$ (time independent neutron population)
  - T inversely proportional to ρ: ↑ρ=↓T, ↓ρ=↑T (desirable)
- Example:
  - $k = 1.001$
  - $l = 10^{-4}\ s\ (thermal), 10^{-7}\ s\ (fast)$
  - $T = \frac{l}{k-1} = 0.1\ s$
  - $\frac{N(t)}{N_o} = e^{\left(\frac{k-1}{l}\right)t} = e^{10t} \rightarrow$
  - For $t = 1\ s \rightarrow e^{10} = 22{,}000$ prompt neutrons/sec
- Avoid reactor prompt critical & supercritical
  - Prompt critical ($\rho > \beta$) Super critical ($k - 1 > \beta$)
  - Delayed neutrons not needed to sustain reaction
  - T will be very short (this should never occur)

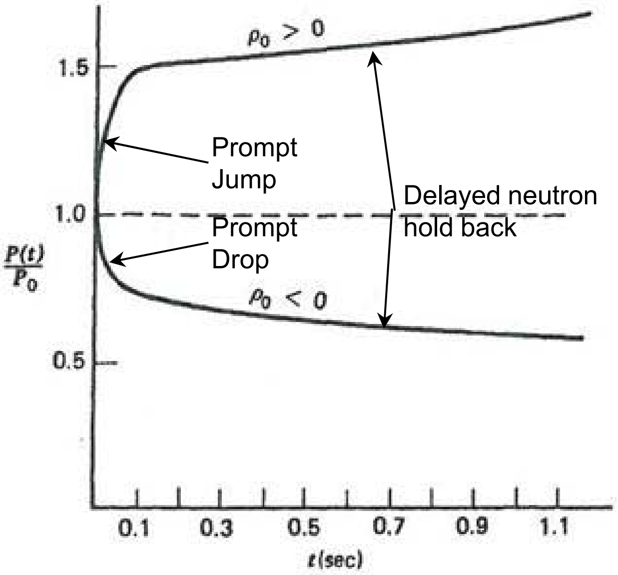
REACTIVITY INSERTION

- Reactor Power Changes
  - *Prompt jump/drop*: Initially behaves as if there are no delayed neutrons.
  - *Delayed neutron hold back effect*: As delayed neutron population increases there is a transition.
  - *Stable Period*: As T → asymptotic the Rx behaves as if there are no prompt neutrons and delayed neutrons control the Rx.

$$\rho = \underbrace{\Lambda\omega}_{\text{Prompt Term}} + \underbrace{\sum_{i=1}^{7}\frac{\beta_i\omega}{\omega+\lambda_i}}_{\text{Delayed Term}}$$

$$\Lambda = \frac{l}{k}$$

ω = decay constant

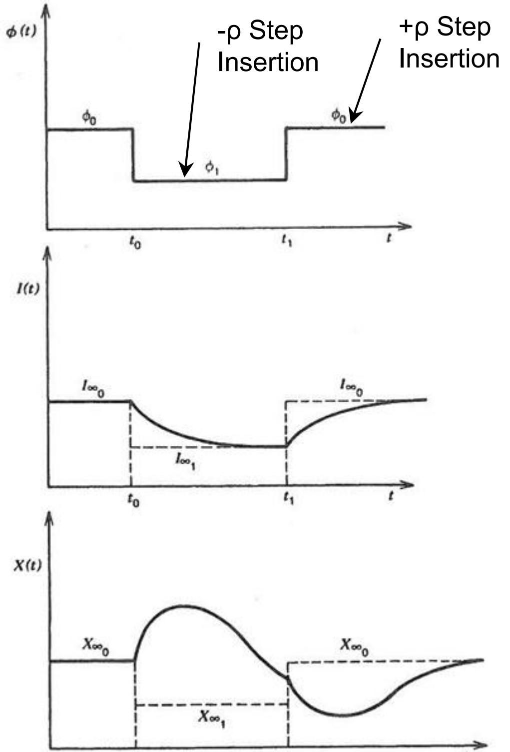


Prompt Jump

Prompt Drop

Delayed neutron hold back

Reactor power level following a step reactivity insertion. Courtesy Duderstadt & Hamilton.



-ρ Step Insertion

+ρ Step Insertion

^{135}Xe variation with reactor power level. Image courtesy of Duderstadt & Hamilton.

TEMPERATURE REACTIVITY FEEDBACK

- Temperature Reactivity Feedback Coefficient
  - $\alpha_T = \frac{\Delta\rho}{\Delta T}$
  - 1. Nuclear: $\Delta T = \Delta\sigma$ (Doppler broadening) = resonance absorption
  - 2. Density: $\Delta T = \Delta V_{Matls} = \Delta density = \Delta C_{atom} = \Delta\, mean\ free\ path = \Delta P_{NL}$

- Fuel & Moderator Feedback Coefficients
  - $\alpha_{T,Fuel} = \frac{\Delta\rho}{\Delta T_{Fuel}}$
  - $\alpha_{T,Mod} = \frac{\Delta\rho}{\Delta T_{Mod}}$

- Stability
  - Positive α_T: ↑T = ↑ρ = ↑P = ↑T = unstable reactor (avoid)
  - Negative α_T: ↑T = ↓ρ = ↓P = ↓T = stable reactor (design requirement)

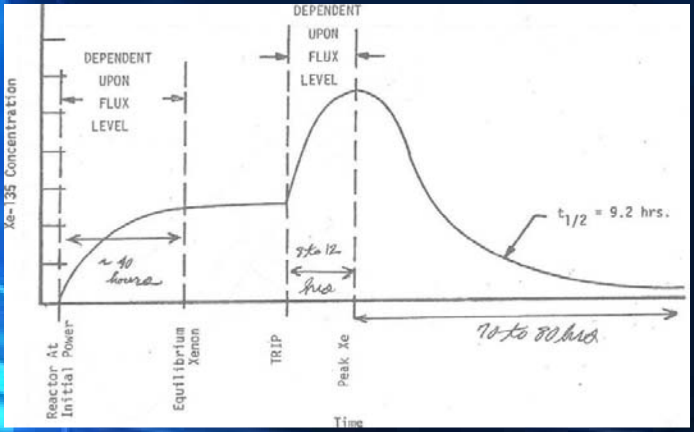
NEUTRON POISONS

- Fission product decay
  - Produces daughter nuclides with large σ_{abs}
  - Proportional to reactor power and operating time
  - ^{135}Xe and ^{149}Sm burnout at start up induce a positive reactivity insertion

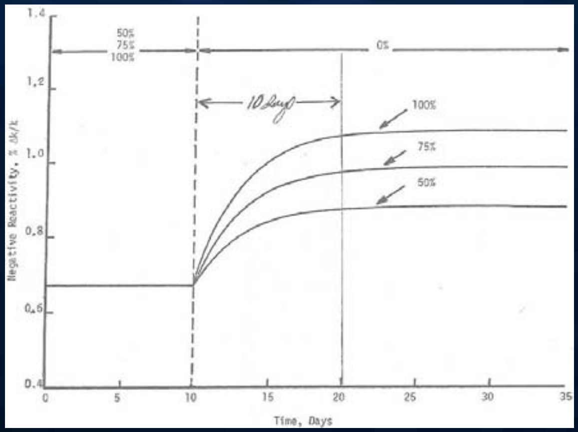
$$\text{fission} \rightarrow {}^{135}_{51}Sb \xrightarrow[1.7\ s]{\beta^-} {}^{135}_{52}Te \xrightarrow[19.2\ s]{\beta^-} {}^{135}_{53}I \xrightarrow[6.58\ hr]{\beta^-} {}^{135}_{54}Xe \xrightarrow[9.17\ hr]{\beta^-} {}^{135}_{55}Cs \xrightarrow[2\cdot 10^6\ yr]{\beta^-} {}^{135}_{56}Ba\ (stable)$$

$$\text{fission} \rightarrow {}^{149}_{60}Nd \xrightarrow[2\ hr]{\beta^-} {}^{149}_{61}Pm \xrightarrow[54\ hr]{\beta^-} {}^{149}_{62}Sm\ (stable)$$

Poison	σ_{Abs} (b)	$t_{1/2}$ (hr)	$\rho_\infty \left(\frac{\Delta k}{k}\right)$	**Peak buildup**
${}^{135}_{54}Xe$	2.7 x 10^6	9.2	2.5 – 3.0	10-11 hrs. Decays
${}^{149}_{62}Sm$	4.1 x 10^4	53	0.4 – 0.6	10 days. No decay



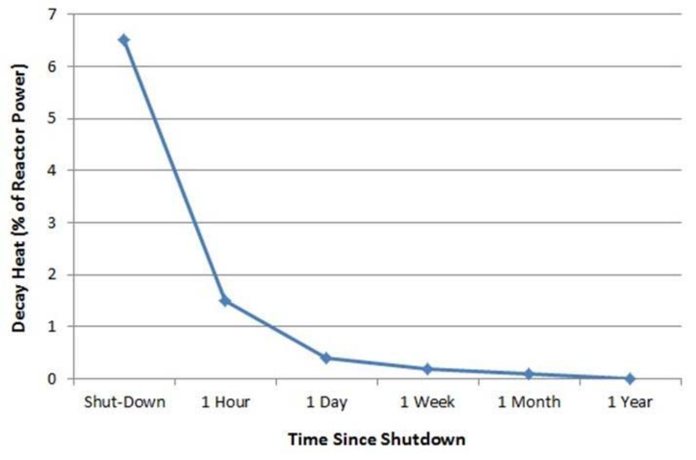
^{135}Xe buildup and decay following shutdown. Courtesy Dugan.



^{149}Sm buildup following shutdown. Courtesy Dugan.

DECAY HEAT

- Heat generation following shut-down
  - Result of fission product decay
  - 6-7% of reactor power generated immediately after shutdown.
  - Active cooling is required to keep core temperature within limits.

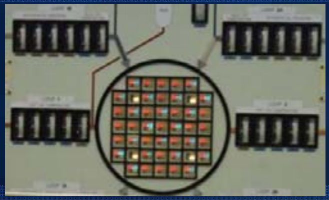


Reactor decay heat vs. time.

- Failure to cool the reactor following shut-down
  - Fuel damage
  - Structural damage
  - Partial/full melt-down

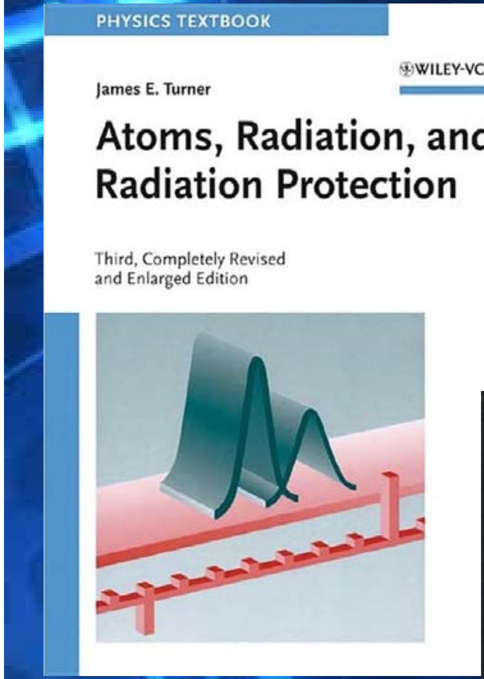
CONFUSED?

OPERATIONAL ANALOGY

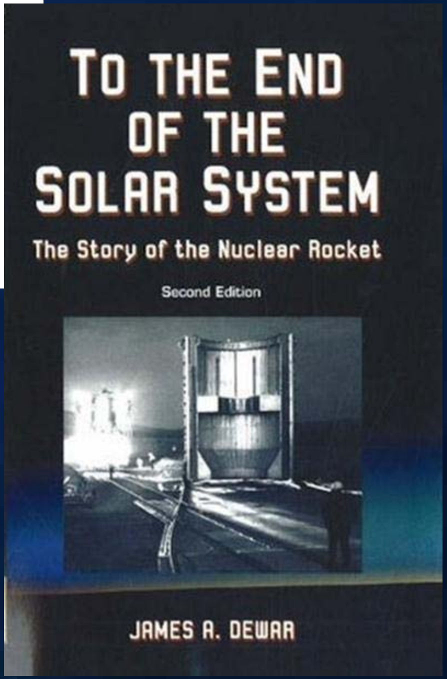


Airplane	Reactor
Altitude (A) -	Power (P)
Airspeed (V) Regulate and limit vehicle energy state (V_{stall}, V_{ne})	Period (T) Regulate and limit reactor energy state (30 s ramp rate, -80 s shut down)
Vertical Velocity Indicator (VVI) Rate of altitude change	Neutron Multiplication Factor (k) Rate of criticality change
Throttle Setting (% max RPM) Adjust fuel flow to vary combustion rate (engine power)	Control Drum Setting (degree) Adjust reactivity to vary reaction rate (reactor power)
Multi-Engine Individual power worth	Multi-Drum Individual reactivity worth
Breaking Distance Runway length to achieve full-stop	Shut-Down Margin (SDM) How far from critical
Dynamic Stability Positive or negative	Reactivity Temp. Feedback (α_T) Positive or negative
Excess Power Overcome induced/parasitic drag, adjust A	Excess Reactivity (ρ_{ex}) Overcome BU,$-\alpha_T$, Xe poison, adjust P level

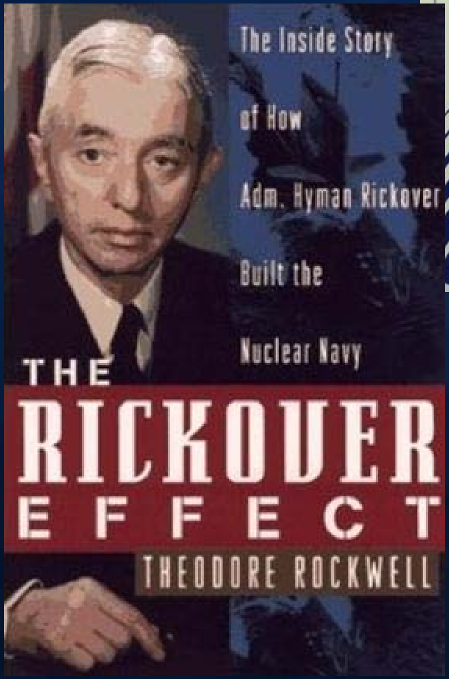
RECOMMENDED READINGS



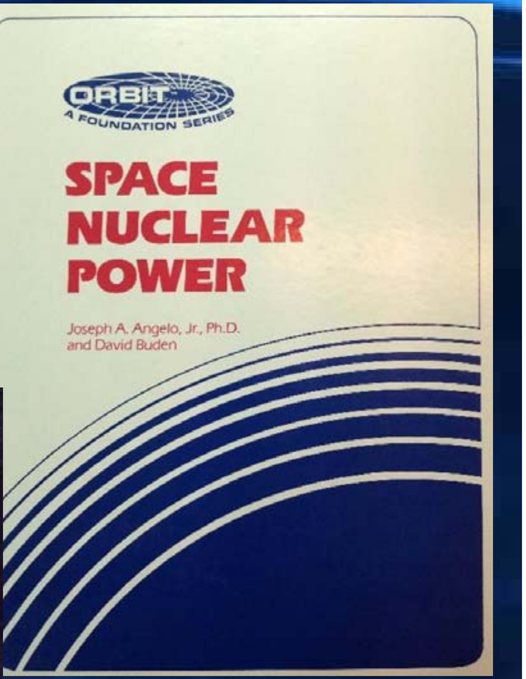
Atoms, Radiation, and Radiation Protection, 3rd Ed. by James E. Turner



To The End Of The Solar System by James Dewar



The Rickover Effect by Theodore Rockwell



Space Nuclear Power by Joseph Angelo and David Buden

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