Power from Nuclear Transmutation
Gen III-IV Fission Reactors

The Diablo Canyon NPPT produced CO_2-free electricity at 2¢/kwh, half the state’s (CA) average cost.

Agenda

- Nuclear stability & particle radiation
  Potential biological hazards

- Energy Generation from Nuclear Fission
  - U.S./World trends,
  - Nuclear fuel resources (U.S.),
  - Fission chain reaction and reactor control,
  - Reactor types,
  - Fuel cycles, radioactive waste & storage.

- New Nukes: Advanced Nuclear Energy Technologies
  - Advanced (Gen II+, Gen IV) reactor designs,
  - U & Th breeder reactors, subcritical reactors,
  - Small modular reactors (SMR plants),
  - Closed fuel cycle (reprocessing once-through fuel elements),
  - Non-fission applications: Radioisotope Thermoelectric Generators (RTG)

- Energy from nuclear fusion reactions
  - Fusion energetics, critical
  - Principles of magnetic and inertial confinement

- Strategic Issues for Nuclear Power
  - Sustainability, reliability, scalability, safety, eco-footprint, cost

Reading Assignments

A&J; Ch. 9-10
LN 4.3

Small Modular NPPT (RF 2019)

Since 1955 1st nuclear powered *USS Nautilus*, 2024: 73 (→+?) submarines, 1960: 1st nuclear aircraft carrier *USS Enterprise* with several PWR NPPts.

Russian nuclear-powered submarines operate with lead coolant.

Spacecraft (Voyagers, Cassini,…, Rover,…) have Pu-238 nuclear thermal generators

Small Modular Reactors (SMR): Applications

Replace coal-fired power generation
- SMRs can further transition the power sector away from coal
- Even in a 2-degree scenario IEA projects 1100GWe
- Potential market **over $100B/year**

Remote island nations and off-grid communities
- Large potential in over 70k communities
- **$30B/year market**

Heat and power for mines
- SMRs powering of new mines between now and 2040 could yield total global value of **$3.5B/year market**

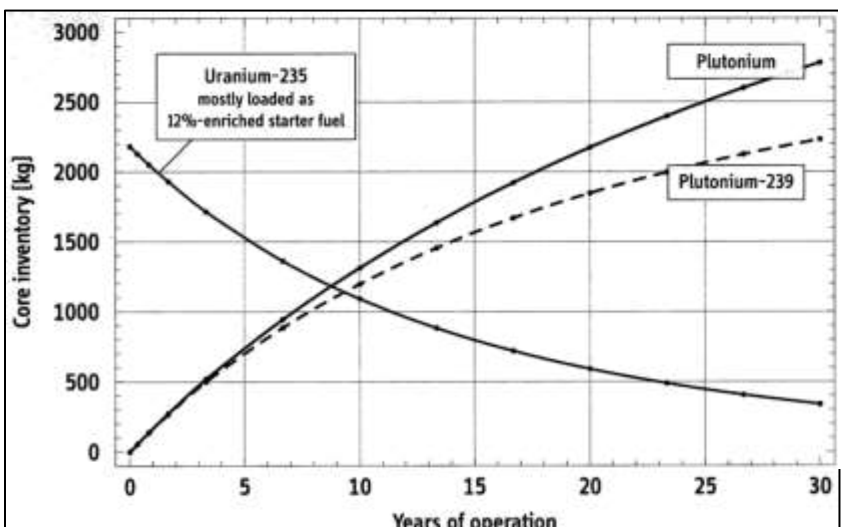
Steam for heavy industry
- Potentially **$12B per year global market.** Joint project from Idaho NL and NREL identified 850 facilities where SMRs could provide steam for US heavy industry.

Small Modular Reactors: Current Development

Lifetime cores

Design	Company	Power	Status
mPower	Babock & Wilcox	2 x 180 MWe	Detailed design
NuScale	NuScale Power	12 x 45 MWe	Testing
Vernova	General Electric	300MW	Testing
KP-X Hermes	Kairos Power	2x75 MWe	Under Construction
SMART	KAERI,S-Korea	100 MWe	Licensed
KLT-40S	OKBM, Russia	2 x 32 MWe	Operating

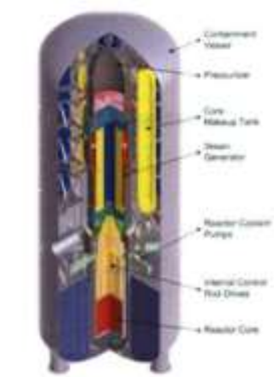
*Project currently suspended



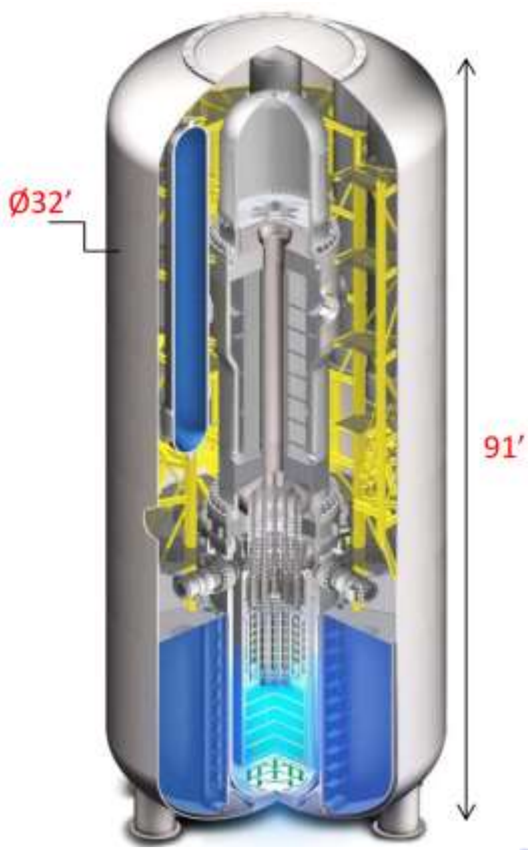

NuScale


mPower


Holtec SMR-160


Westinghouse SMR

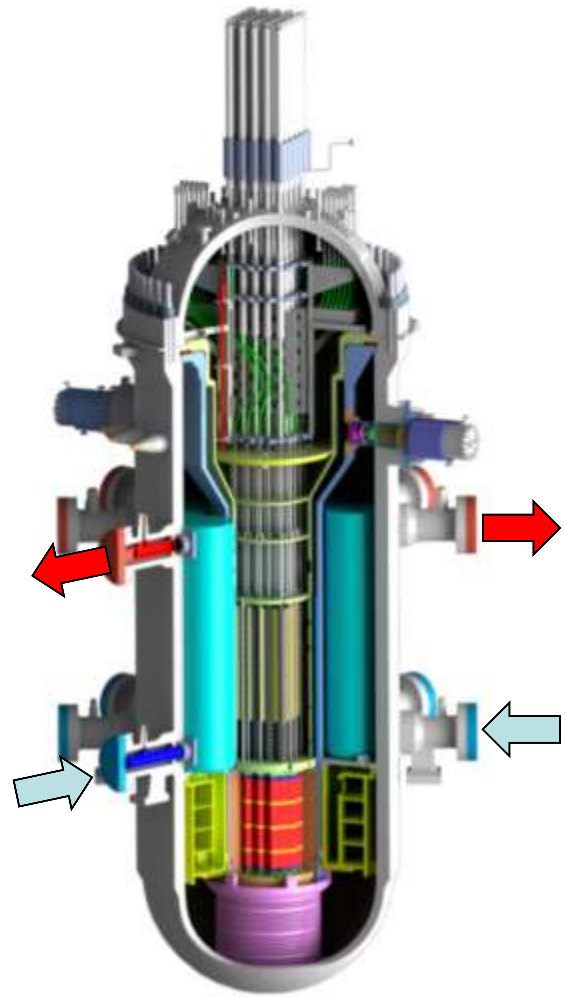
Westinghouse SMR Technology



Thermal Output	800 MWt
Electrical Output	>225 Mwe
Passive Safety Systems	No operator intervention required for 7 days
Core Design	17x17 Robust Fuel Assembly 8.0 ft. Active Length < 5% Enriched U235 89 Assemblies Soluble Boron and 37 Internal CRDMs 24-Month Refueling Interval
Reactor Vessel Size	Outer Diameter: 12 ft. Height: 81 ft.
Upper Vessel Package	280 Tons
Containment Vessel Size	Outer Diameter: 32 ft. Height: 91 ft. Fully Modular Construction
Reactor Coolant Pumps	8 External, Horizontally-Mounted Pumps Sealless Configuration
Steam Generator	Recirculating, Once-Through, Straight-Tube
Pressurizer	Integral to Vessel
Instrumentation and Control	Ovation®-based Digital Control System

Small Modular Reactor Design (Ontario Power/CND)

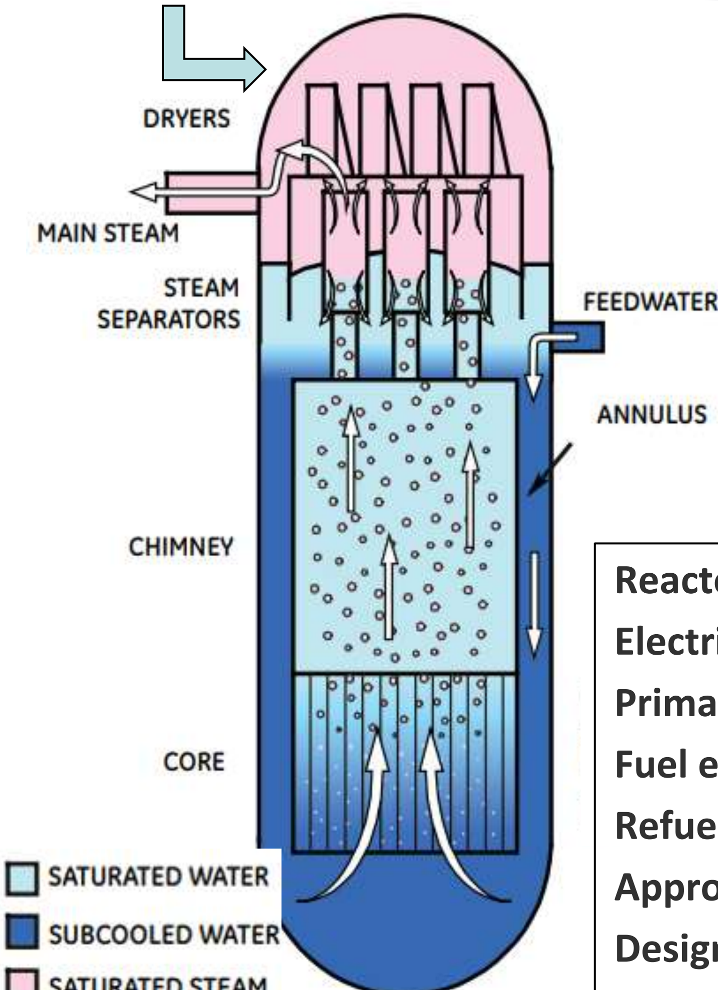
Compact "Nuclear Island" Input= feed water, Output= dry steam

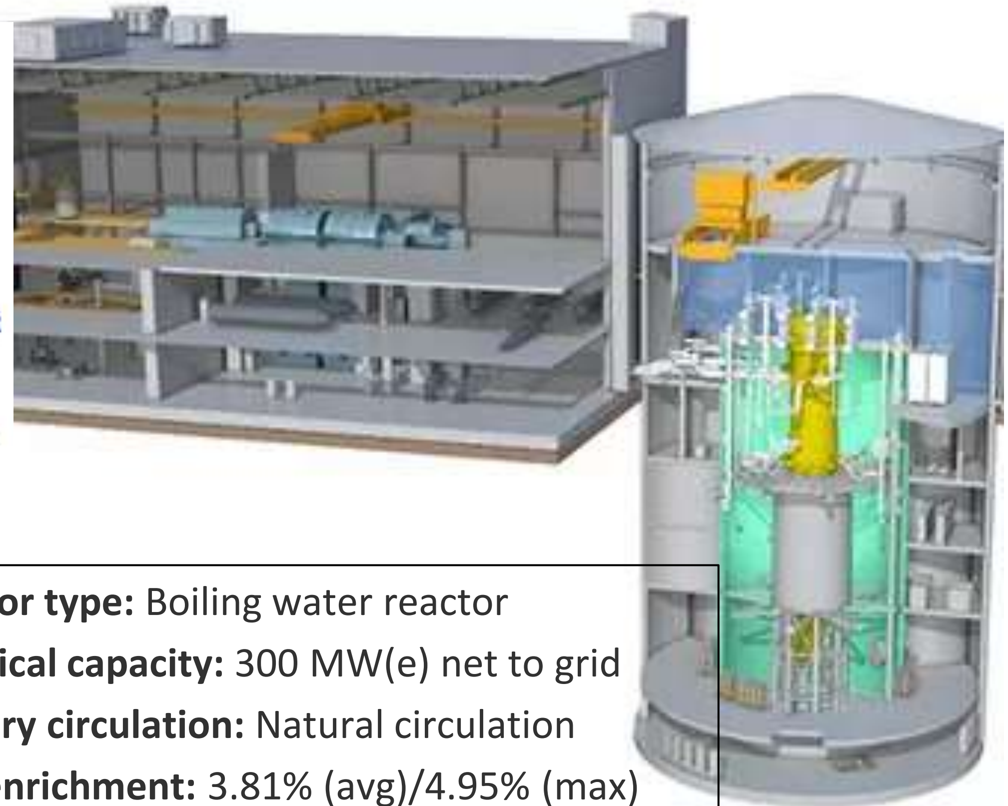


GE-Hitachi Small Modular Type BWR X-300

Under construction in Ontario/Canada, planned also by Tennessee Valley Authority

Natural coolant circulation.





Reactor type: Boiling water reactor

Electrical capacity: 300 MW(e) net to grid

Primary circulation: Natural circulation

Fuel enrichment: 3.81% (avg)/4.95% (max)

Refueling cycle: 12-24 months

Approach to safety systems: Fully passive

Design life: 60 years

Levelized Cost of Electricity (SMR vs. Rest)

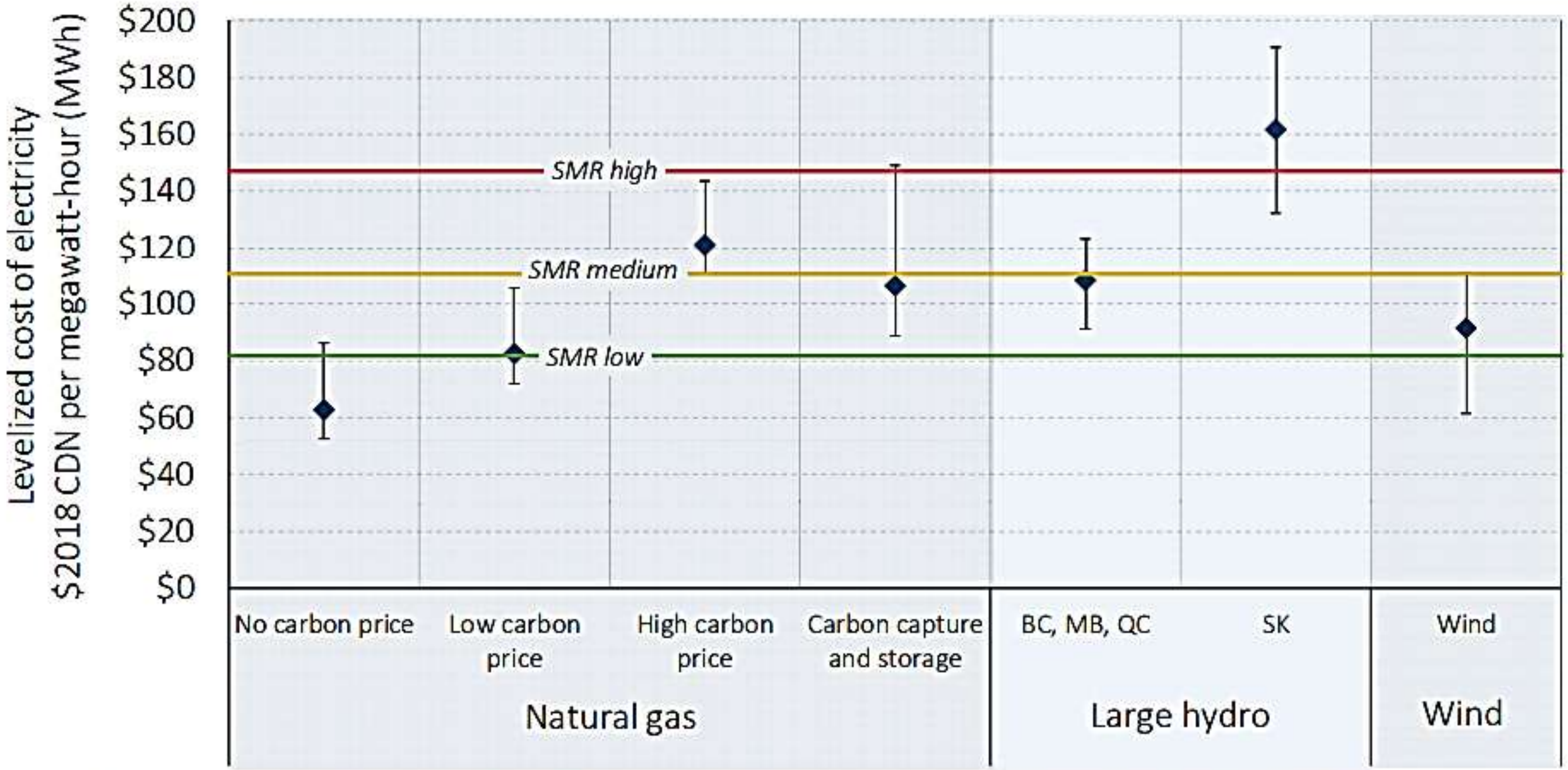
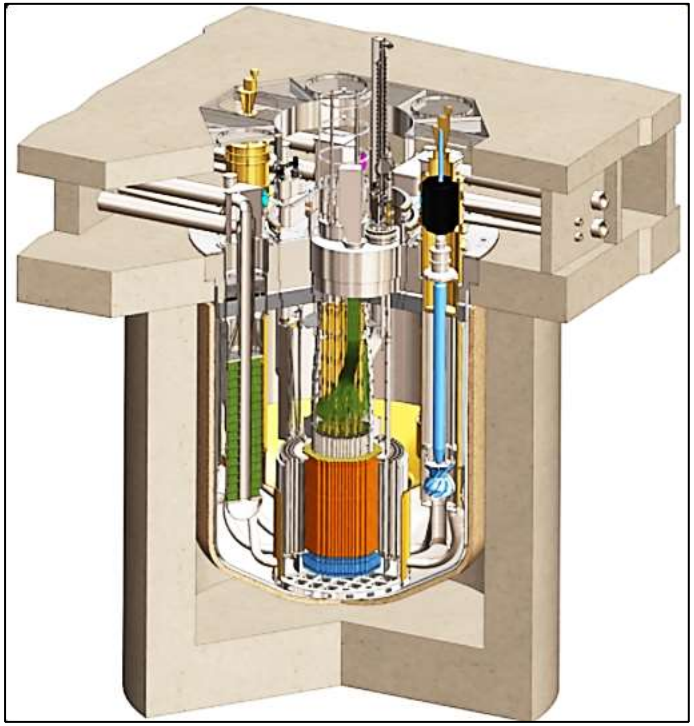


Figure 2. Comparison of levelized cost of electricity from on-grid SMRs with other options: Worst case (9% discount rate, less innovative technology)

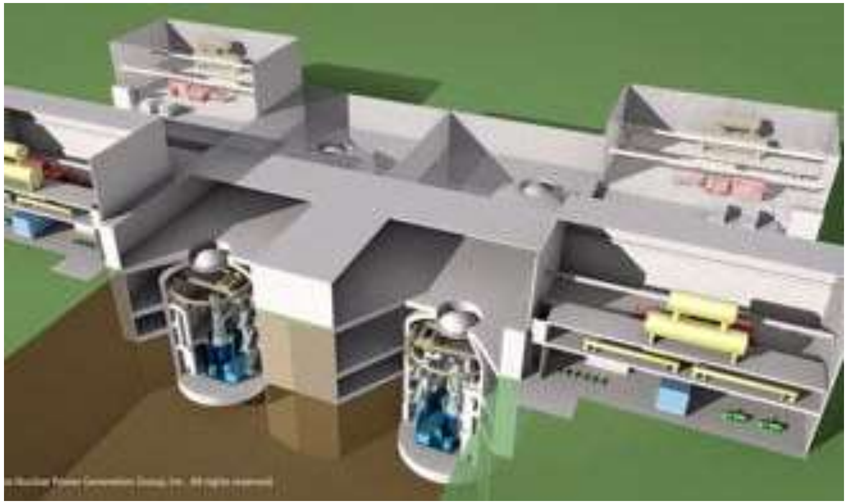
Developing: Super-Safe, Small, and Simple Modular Reactors

Prefabricated (GE A-1000 conventional PWR, comes in 300 prefab parts)
Only few standardized reactor designs.
Autonomous operation below grade without human interference,
→ self-fueling breeder (traveling wave) U/Th fuel

TerraPower Traveling-Wave



Additional companies: Hyperion 200 MW U/He
Babcock-Wilcox modular reactor



Core: enriched uranium U-235 rods surrounded by rods of depleted U-238/natural uranium. U-235 initiates a slow-moving "traveling wave" fission chain reaction delivering first neutrons for Th breeding.

Small Modular NPPT (RF 2019) w. Cogeneration

Akademik Lomonosov has now been fully commissioning (Image: Rosenergoatom)

Two 35-MW reactors KLT-40C,

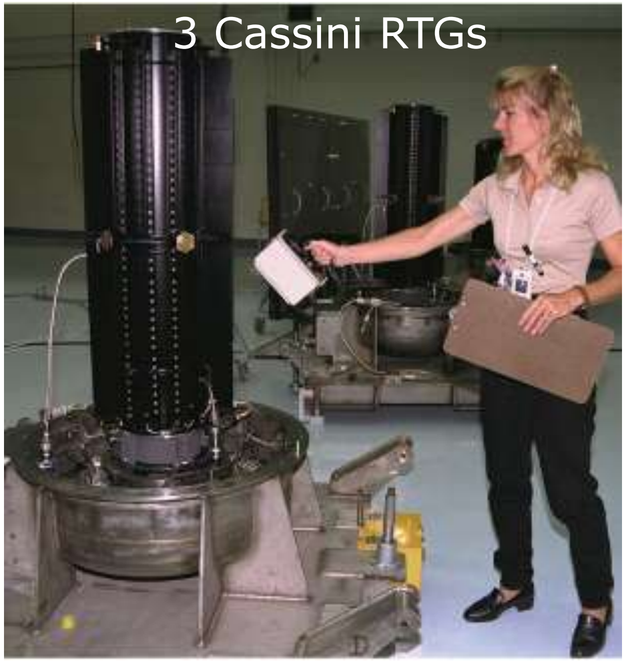
Outputs:
el. power=70 MW

Heat 50 Gcal/h (210 GJ/h)

The floating nuclear power plant (FNPP Rosenergoatom) Akademik Lomonosov has been fully commissioned in the town of Pevek (Chukotka region of Russia's Far East). Subsidiary of the state nuclear corporation Rosatom. (WNN 5/22/2020)

Russian arctic icebreakers are all nuclear powered.

Radioisotope Thermoelectric Generators (RTG)



Pu-238 ($t_{1/2} = 87.7a$) α/fission-decay (5.6MeV)→ heat

ΔT → bi-metal/SC Thermocouple → Electricity

RTG in many NASA space applications, also for remote terrestrial instrumentation (Arctic scientific or military outposts).

General Purpose Heat Source

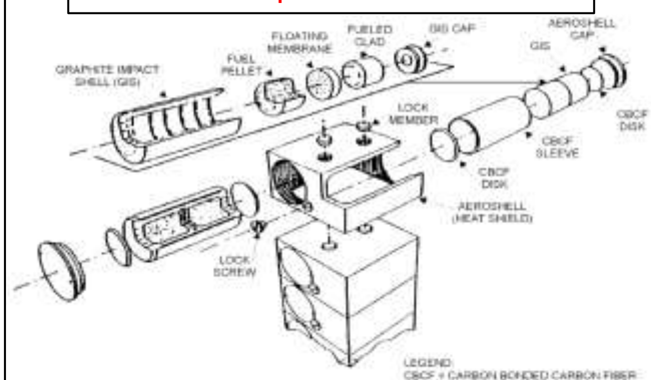
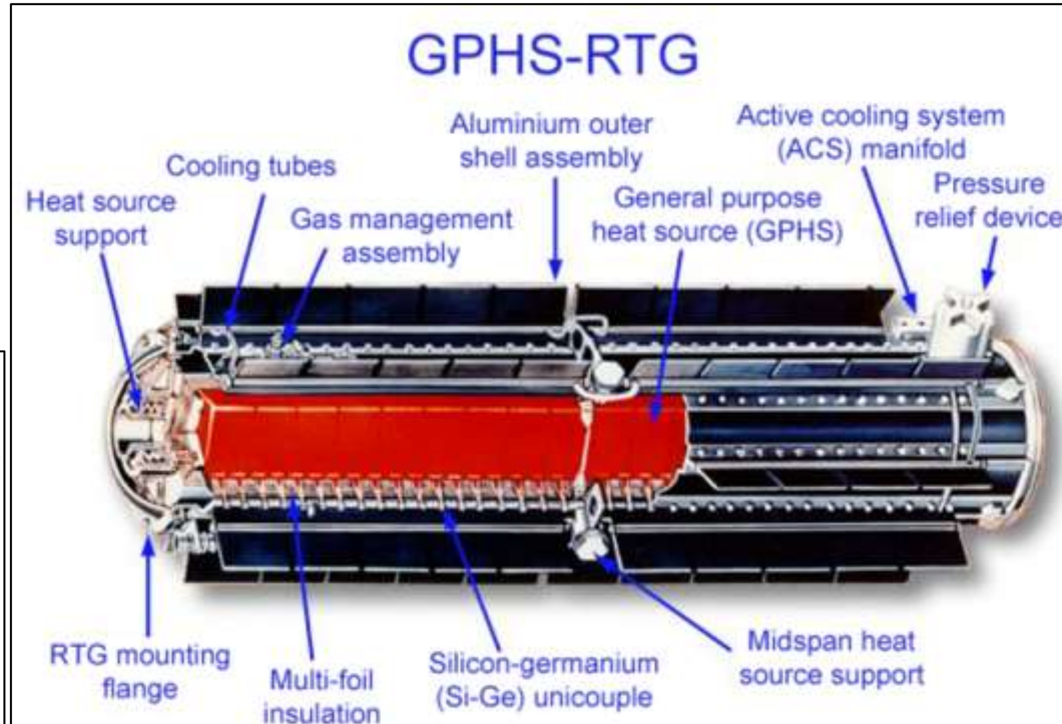


FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE



NASA Space Probes RTG Powered

$$^{238}_{92}U + ^{2}H \rightarrow ^{238}_{93}Np + 2n$$

$$^{238}_{93}Np \rightarrow ^{238}_{94}Pu + e^{-} + \bar{\nu}_e$$

A NASA Pu-238 Radioisotope Thermoelectric Generator has been in use to power space probes for many decades.

Conversion of decay heat to electricity via thermocouple.

Also:

Efficient combination with Stirling engine.

Voyager I and II, Cassini probe.

Strategic Issues of Nuclear Technology, Real and Perceived

Issues for any production technology:
Sustainability, reliability, safety, eco-footprint, cost, scalability
Specific issue for nuclear power: proliferation safety

→ Relative risk/benefit analysis, levelized lifetime analysis.

Links to sections

1. Resource limits of nuclear fuel (^{235}U/Pu, Th,…) … LNK
2. Reactor reliability ………………………………………… LNK
3. Operational reactor safety/accidents ………………… LNK / LNK
4. Ecological/resources footprint …………………………… LNK
5. Safe capture and sequestration of spent fuel ……. LNK
6. Proliferation resistance (nations, individuals) …… LNK
7. Economy (Capital plus fuel costs) ……………………… LNK
8. R&D requirements ………………………………………… LNK
9. Capability for deployment/scalability ………………… LNK
10. Public perception ………………………………………… LNK

END

Conclusion: Nuclear Fission Power in a Sustainable Future (?)

Western Gen III plants have good safety record (safest dispatchable energy).
But 3 *preventable* accidents with core damage (“melt down”), 1 accident fatal, temporary evacuation.
Gen III, III+ proven/mature technologies (PWR, U based), breeder reactors

To develop & deploy nuclear power in the U.S. (x 3 by 2050):

- Continue to improve the safety of nuclear reactors and processing plants.
- Test/construct modular nuclear reactors @ sites of existing (coal?) plants.
- Test/construct advanced breeder/incinerators → reduce radiotoxic waste.
- Import/develop closed nuclear fuel cycle technologies.
- Expand the radio-chemistry of actinides, trans actinides and fission products.
- Develop material chemistry of molten salt mixtures, molten salt reactor.
- Develop/test proliferation-safe reprocessing methods (e.g., UREX+).
- Further test/develop a closed Th/U breeder fuel cycle, advanced materials.
- Develop ADS systems, use mature current accelerator technology.
- Open a semi-permanent nuclear waste depository, flexible re-use strategy.
- Train personnel in nuclear and radiation technologies !


Fin Nuclear Fission Power
AKW Krümmel

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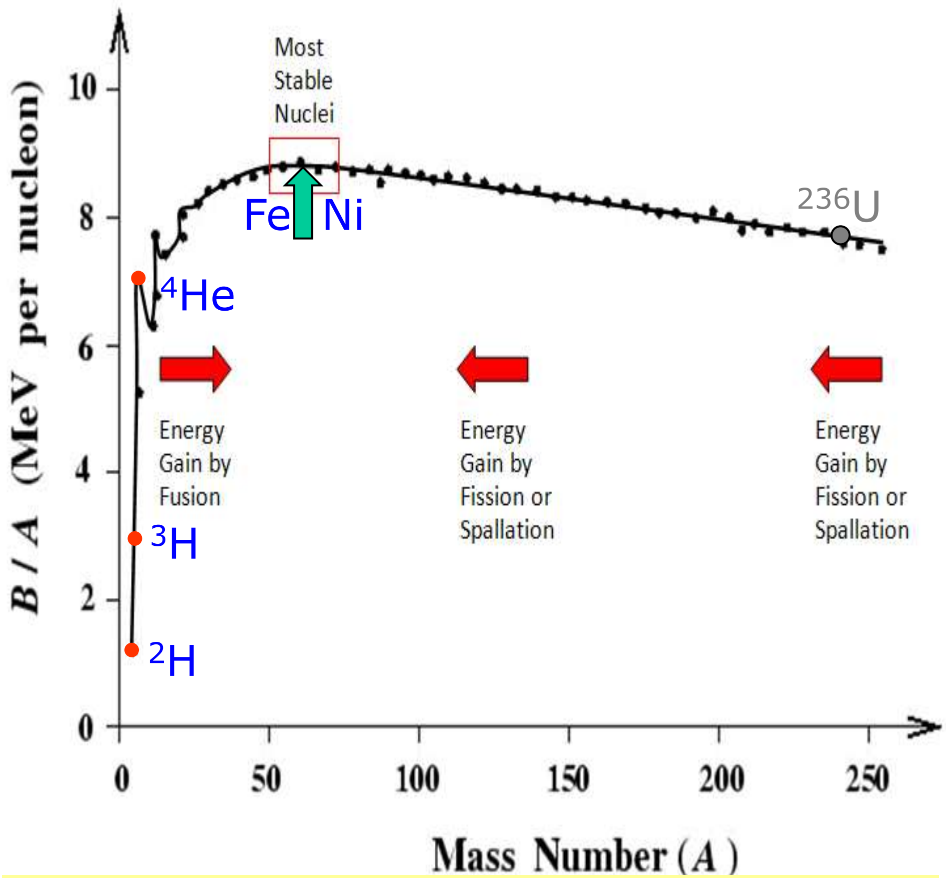
Nuclear Rearrangement Energies

$M_{(N,Z)} < N \cdot M_n + Z \cdot M_p \rightarrow \Delta M \propto B(A=N+Z)$

In formation of nucleus A: $B=\Delta Mc^2$ is released



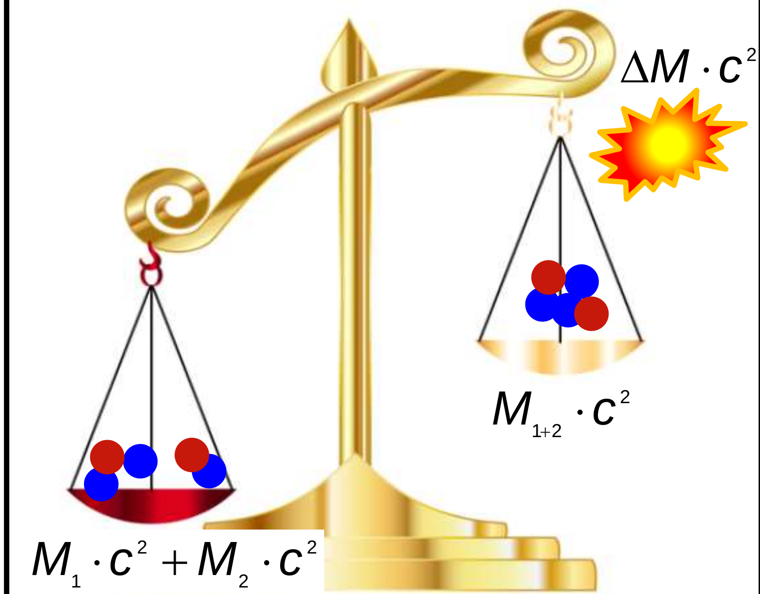
$$M\left({}^2H + {}^3H\right) = 74\,mg \xrightarrow[fusion]{\Delta M/M \sim 3.3 \cdot 10^{-3}} \Delta E = 240\,\mu g \cdot c^2 \approx 4 \cdot 10^9\,J$$

$$M(TNT) = 1t \xrightarrow[combustion]{\Delta M/M \sim 10^{-8}} \Delta E \approx 4 \cdot 10^9\,J$$

Einstein: equivalence mass = energy

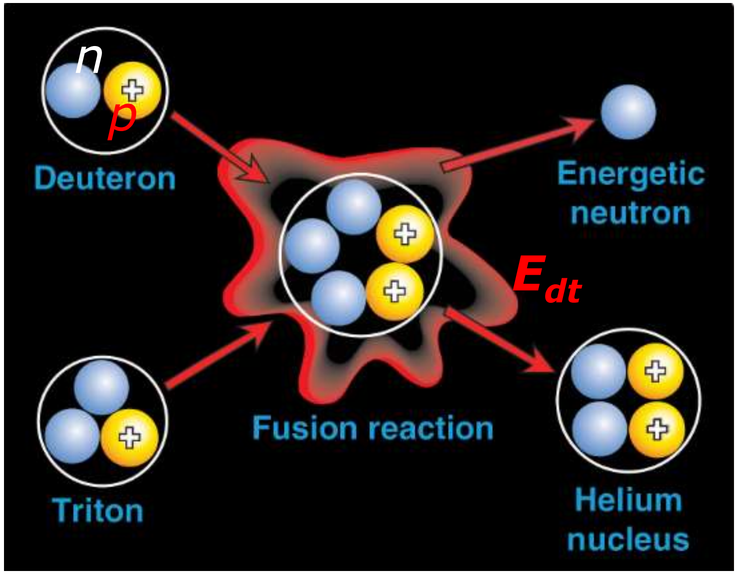
$E = M \cdot c^2$

Energy release in fusion $A_1 + A_2 \rightarrow A_{1+2}$



Fusion of light nuclei not spontaneous
→ Activation energy = Fusion Barrier
Pass for high collision velocity v_{rel}

Fusion Of Light Atomic Nuclei



Reactions between light atomic nuclei are exothermic, for example

$$d + t \rightarrow \alpha + n + \boldsymbol{E_{dt}}(17.6\text{MeV})$$

Deuterium (^{2}H or d) abundance 0.015%
Tritium (^{3}H or t) is radioactive half-life $t_{1/2}$=12.23a
Alpha particle ($^{4}He^{+}$ or α), neutron (n)

Reaction heat shows up in kinetic energy of alpha particles and neutrons.

$$E_{dt} = E_n + E_\alpha = 14.1MeV + 3.5MeV$$

power P_α

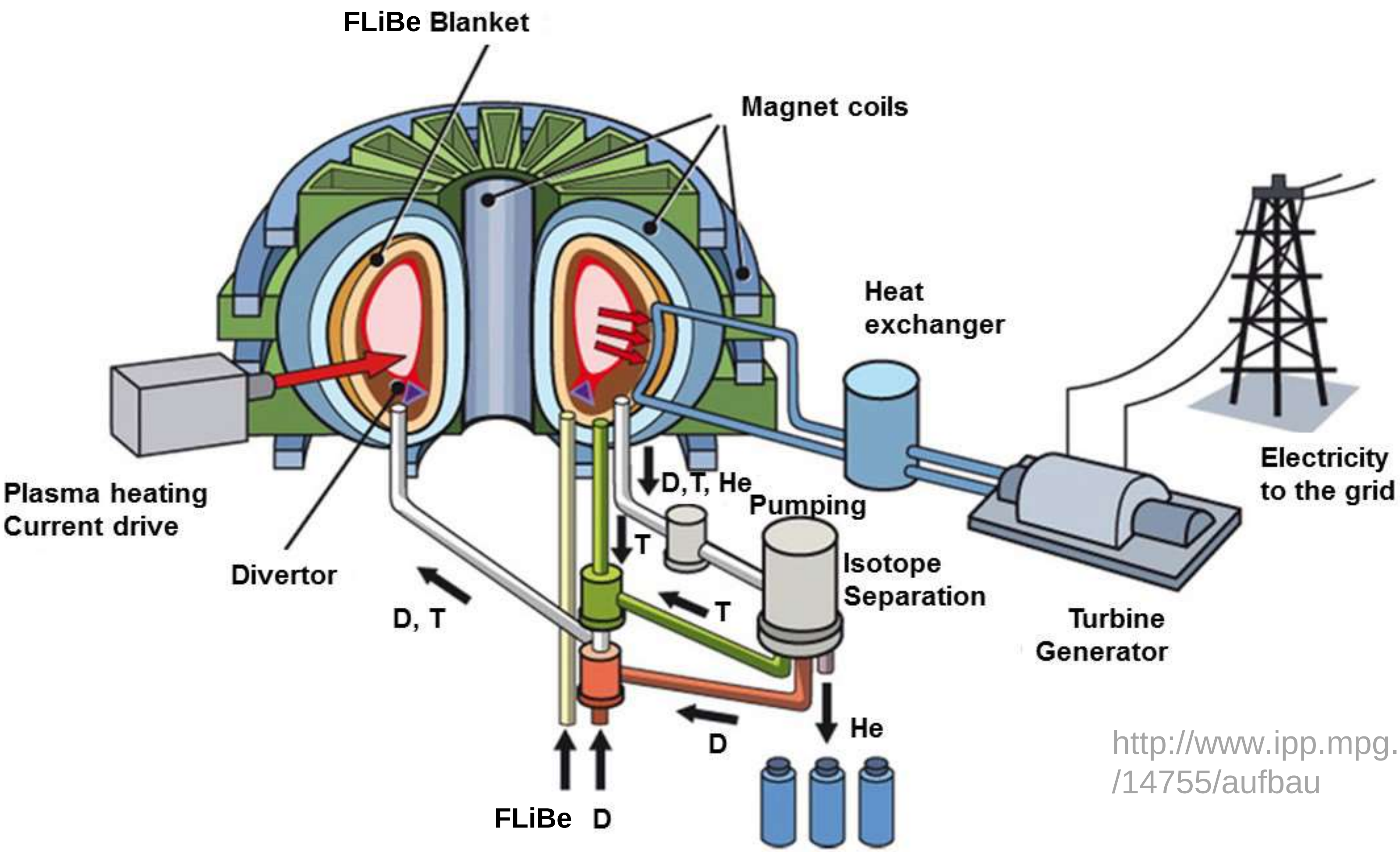
A mixture of deuterium and tritium (50:50) can undergo exothermic fusion reaction → powerful source of energy (powers our Sun!).

Fundamental Problem of Nuclear Fusion Technology:

Nuclei are positively charged → Coulomb repulsion ("Coulomb barrier")
→Reactions are not spontaneous upon contact. Need "ignition" to occur.

But energy E_{input} input yields (ideally): $Q = E_{dt}/E_{input} \gg 1$

MCF Reactor Design: Tritium Fuel Cycle

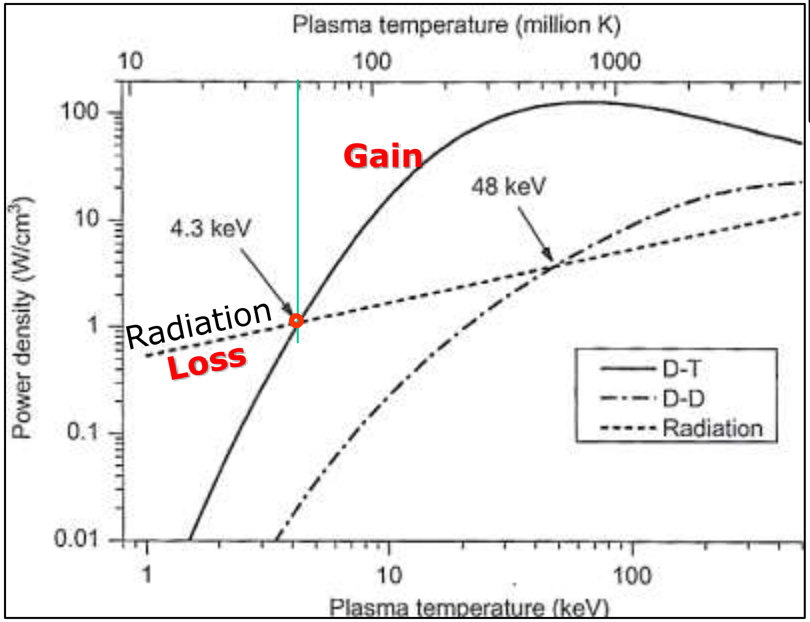


http://www.ipp.mpg.de /14755/aufbau

Not shown: fuel ash processing pumps, separators,..

FLiBe for in-situ tritium regeneration, mixture fluorides of lithium (LiF) & beryllium (BeF_2); melting point @ 459 °C, boiling point @ 1430 °C → molten salt at reactor wall T.

Plasma Ignition Temperature



After: R.L. Murray & K.E. Holbert, *Nuclear Energy*, Elsevier, BH; Cambridge MA, 2020

$$P_\alpha = \left\langle \frac{dN_{dt}}{dt} \right\rangle \cdot Q_\alpha = \rho_d \cdot \rho_t \cdot \langle \sigma_{dt} \cdot v_{rel} \rangle \cdot 3.54 MeV$$

$$\rho_d = \rho_t = \rho/2 \quad and \quad \rho = \rho_e$$

Parameterizations of σ_{dt}, MB $(dN/dE)_{d,t}$ $\rightarrow d-t$ reactivity

$$\langle \sigma_{dt} \cdot v_{rel} \rangle = 9.13 \cdot 10^{-16} \frac{cm^3}{s} \times$$

$$\times \exp\left\{ -0.5716 \cdot \left(Ln \frac{k_B T_{d,t}}{64.22 keV} \right)^{2.137} \right\}$$

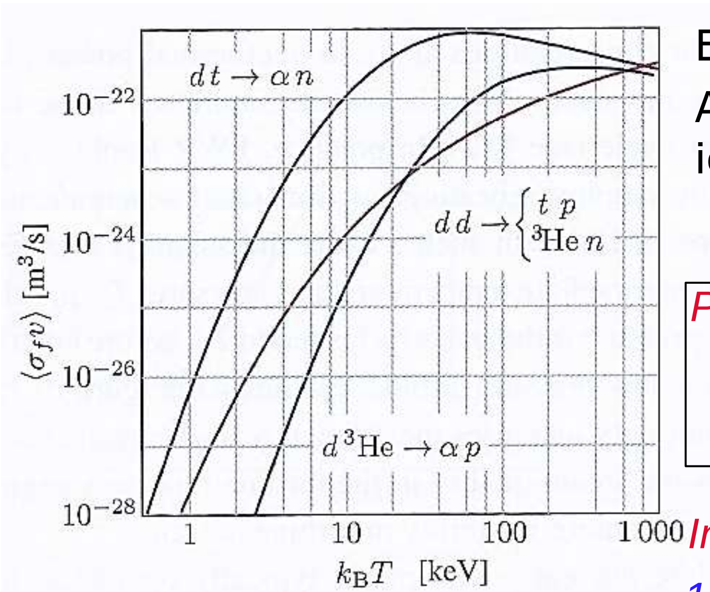
Approximate power gain-loss balance: For DT plasma @ $\boldsymbol{T}_{ign}$= 4.3keV =50 MK

No net power gain from fusion events for $T \leq \boldsymbol{T}_{ign}$ ignition temperature.
Independent of ion density of plasma.

Net power gain from fusion for $T > \boldsymbol{T}_{ign} \rightarrow$ self-sustained burn

Omitted so far: additional thermal etc. losses

Thermonuclear Plasma



Emulate in the lab reactor: d-t Sun plasma

Assumptions: thermally equilibrated gas of ions[1+] and electrons e[1-] in volume *V* at *T*

$\rho_d = \rho_t = \rho/2 \sim 10^{15}\,cm^{-3}$ → **Ideal-gas laws**

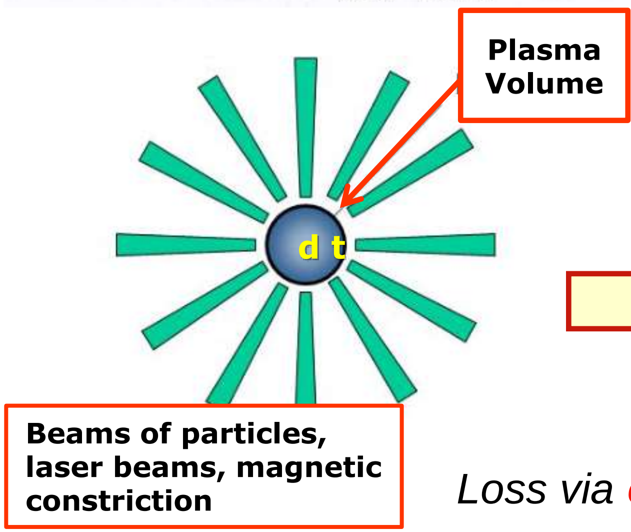
Power density (per vol) produced by fusion

$$P_{dt} = \left\langle \frac{dN_{dt}}{dt} \right\rangle \cdot E_{dt} = \frac{\rho^2}{4} \cdot \langle \sigma_{dt} \cdot v_{rel} \rangle \cdot 17.5 MeV = P_n + P_\alpha$$

Internal heating mostly by stopping fusion α particles

14 – MeV neutrons leave plasma $\xrightarrow{!!!}$ generate tritium

P_{ext} = *External heating by elm (laser, X – ray) energy, radiation, particle beam, mechanical compression*



Power loss via heat conduction (thermal radiation)

$P_C = 3/2(\rho_e + \rho_i) \cdot k_B T / \tau_E$ *to reactor walls,*

mean energy confinement time τ_E (method depend.)

Loss via electron bremsstrahlung: $P_{br} = 5.4 \cdot 10^{-31} \rho_e (\rho_d + \rho_t) \sqrt{k_B T_e}$

Hot Plasma Stability (Stationary State)

Time dependent energy balance of plasma energy content:

$$\frac{dE}{dt} = P_{gain} - P_{loss} = P_{ext} + P_{\alpha} - \left(P_{br} + P_{th}\right) \qquad (all\ densities)$$

$$P_{gain} \approx \frac{\rho^2}{4}\langle\sigma v\rangle E_{\alpha} \qquad for\ \left(\rho_d = \rho_d = \rho/2\right)$$

Loss via e-bremsstrahlung, additional loss through particle drift, collisions with reactor walls, absorption, thermal conduction.

All particles have 3 degrees of freedom $\rightarrow$ *energy density* $E(0) = \left(\rho_e + \rho_d + \rho_d\right)\cdot\frac{3}{2}k_BT$

Heat to ignition conditions: $\langle\sigma v\rangle_{T_{ign}} = 10^{-17}\,cm^3/s;\ k_BT = k_BT_{ign} = 4.3keV$

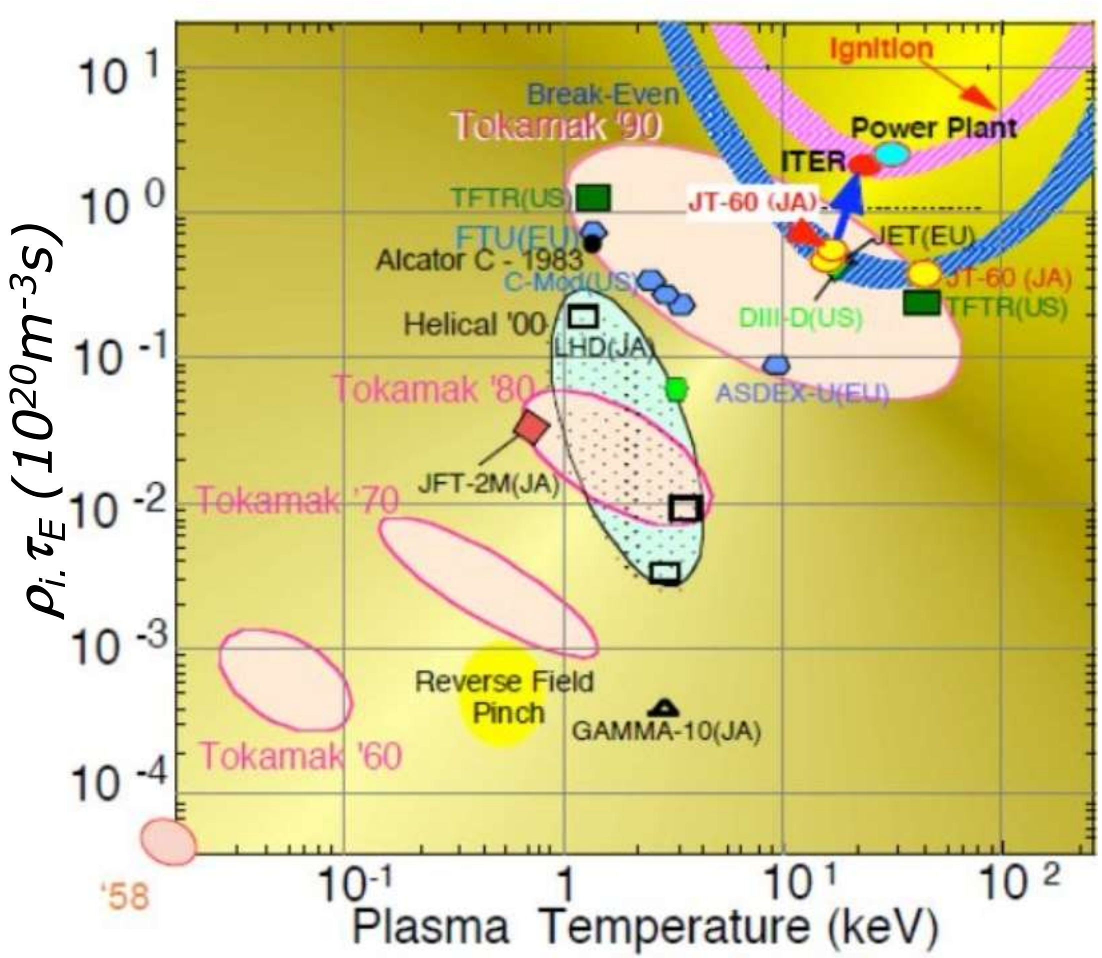
Cools down within "containment time" $\Delta t = \tau_E \rightarrow$ *power loss* $P_{loss} = \frac{\Delta E}{\Delta t} = 3\rho\frac{k_BT}{\tau_E}$

Require $P_{gain} = P_{loss} \rightarrow \rho\tau_E = \frac{12k_BT}{\langle\sigma v\rangle E_{\alpha}}$

@Balance: $\rho\tau_E = \frac{12k_BT_{ign}}{\langle\sigma v\rangle_{T_{ign}} E_{\alpha}} = 3\cdot10^{20}\,\frac{s}{m^3}$

Lawson Criterion $\rho\cdot\tau_E > 3\cdot10^{20}\,\frac{s}{m^3}$

Lawson Fusion Criterion



Technological progress:
1958-2021:
Actual LC $\rho_i \tau_E$ increased by 10^7

Several new U.S. startup companies design and test fusion demonstrators.

Commonwealth: SPARC
Expected demo in 2025/6

Helion: Different fuel,
a-neutron fusion
$p + {}^{11}B \rightarrow 3\alpha + 8.7\text{MeV}$