New and Developing Nuclear Fusion Technologies

Eric Fell

Harvard Energy Journal Club

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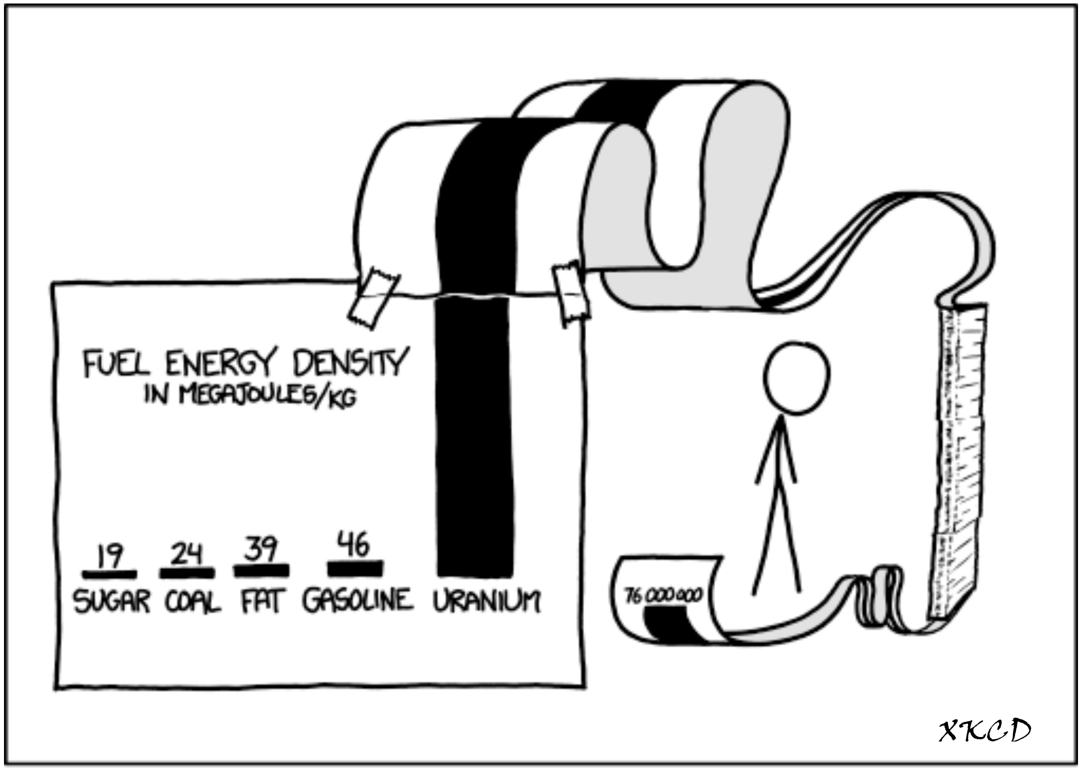
Outline

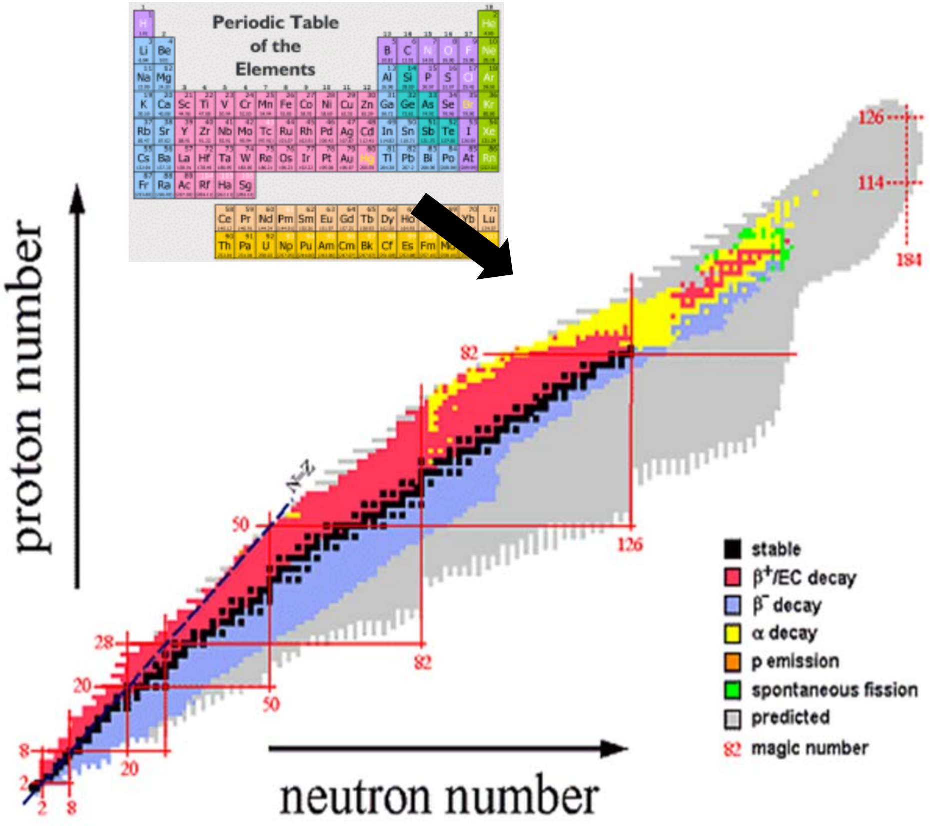
- Background
    - Nuclear reactions
    - Fission vs. fusion
    - Possible fuels
- Fusion technologies
    - Confinement methods
    - Large/small scale
    - Energy/isotope production
- Outlook



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T FIND ENOUGH PAPER TO MAKE THEIR POINT *PROPERLY.*

Fundamentals of Nuclear Reactions

- All elements have isotopes, large range of stabilities
- Radioactive decay occurs in unstable isotopes, resulting in spontaneous emission of particles and/or electromagnetic radiation
- Repulsive force between protons must be balanced by a strong attractive force for nuclei stability



http://fys246.nuclear.lu.se/topics.asp

Mass-Energy Equivalence

- In 1905 Albert Einstein identified the relation between mass and energy of an object at rest

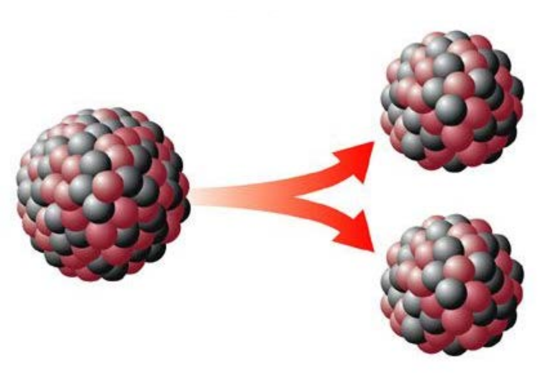
$$E_0 = mc^2$$

- Energy of nuclear decay comes from mass conversion, on the energy scale of MeV (1.6×10^{-13} J) released for every nuclear reaction
- Mass-energy conversion occurs during fission or fusion

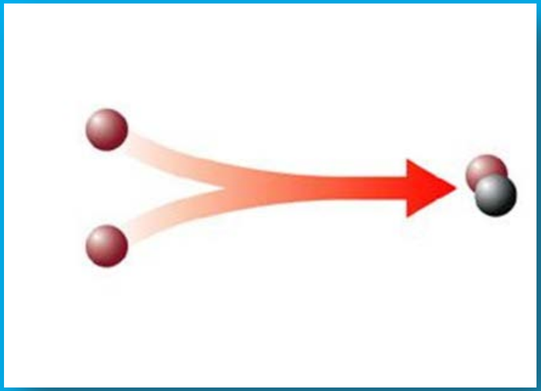
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{89}_{36}Kr + ^{144}_{56}Ba + 3\,^{1}_{0}n + 210\ MeV$$

Nuclear Reactions for Energy Production

Fission



Fusion



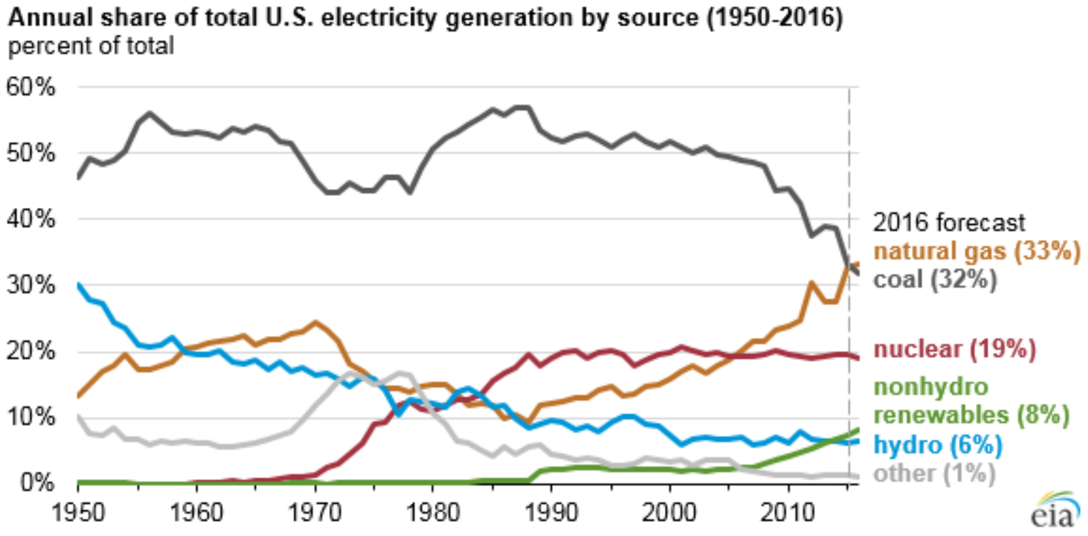
Conventional Nuclear Fission Reactor

- Uses heavy elements that are capable of nuclear fission
- Fissile material is struck by thermal neutrons, breaks apart and emits neutrons, releasing energy and continuing the self-sustaining chain reaction
- Past reactor fuels include ^{235}U, ^{239}Pu, ^{233}U

- Issues
  - Long-lived radioactivity from daughter isotopes (Pu, minor actinides)
  - How do we store wastes with half-lives >1000 yrs?
  - Decay heat from fission fragments is ~7% of total emitted energy

Nuclear Power in the U.S.

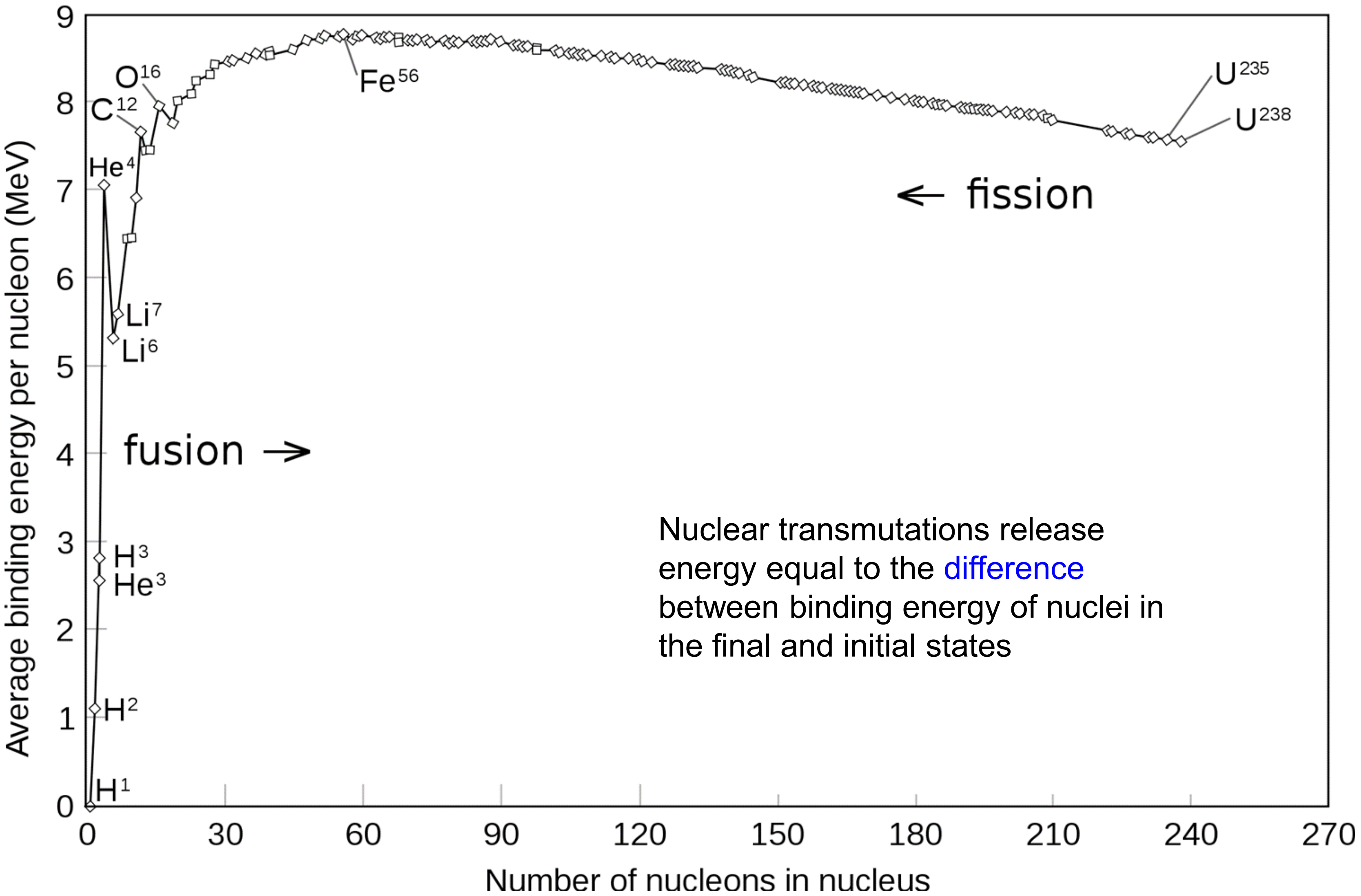
- 99 nuclear fission reactors currently operational
  - About 100 GW
- Around 20% of the nation’s total electric energy generation
- Nuclear accounts for ~60% of U.S. emission-free energy generation



(2016) US Energy Information Administration - http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0802a

Nuclear Fusion: The Essentials

- Fusion occurs when nuclei collide at high energy and are pulled together by the strong force, forming a larger nucleus
- Charged particles must overcome electrostatic potential energy barrier for fusion to occur
- Can overcome this barrier with kinetic energy
- Binding energy of the new, larger nuclide is less than the combined binding energy of the initial reactants
- Mass-energy conversion during fusion of light nuclei results in release of energy, on the scale of MeV per reaction



Nuclear transmutations release energy equal to the difference between binding energy of nuclei in the final and initial states

https://en.wikipedia.org/wiki/Nuclear_binding_energy

Possible Fusion Reactions

Neutronic • ${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6\ MeV$ • ${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.3\ MeV$ • ${}^{2}_{1}D + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}p + 18.3\ MeV$	Deuterium: abundance ~1 atom per 6500 ^{1}H atoms in sea water Tritium: abundance ~1 atom per 10^{18} ^{1}H atoms in sea water, $T_{1/2}$ = 12.3 yrs
Aneutronic • ${}^{1}_{1}p + {}^{11}_{5}B \rightarrow 3\ {}^{4}_{2}He + 8.7\ MeV$	Boron-11: 80% isotopic abundance, global production ~4 million tonnes per year

Fission vs. Fusion Energy Release

<u>Fission</u> $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{89}_{36}Kr + ^{144}_{56}Ba + 3^{1}_{0}n + 210\ MeV$

~200 MeV per ^{235}U atom = 8.2×10^{7} MJ/kg ^{235}U

<u>Fusion</u> $^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6\ MeV$

17.6 MeV per D-T reaction = 3.4×10^{8} MJ/kg D-T

Fusion can provide ~4 times more energy per gram than fission, and over 7 million times more than gasoline (46 MJ/kg)

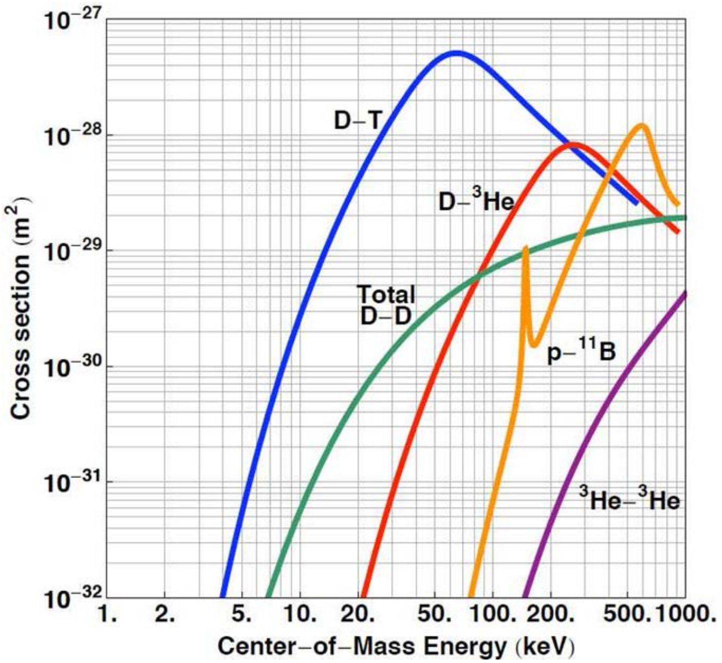
Fusion Reactor Considerations

- Energy is released in the form of kinetic energy of the products (power out)
- Charged particles must overcome electrostatic potential energy barrier for fusion to occur (power in)
- Thermal fusion reactions occur on temperature scale of keV
  - 1 keV is ~12 million Kelvin
- Goal is to produce more energy than is consumed

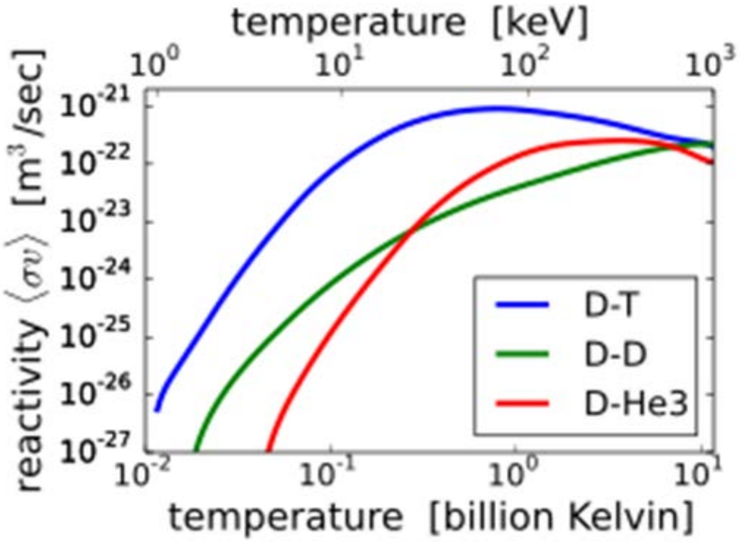
$$Q = \frac{power\ out}{power\ in}$$

Reaction Parameters

<u>Cross section</u> (σ)
Probability that a reaction will occur



<u>Averaged reaction rate</u> (σv)
Depends on cross section and speed (v) of particles



Even at temperatures lower than σ_{Max} fusion can still occur!

http://iec.neep.wisc.edu/operation.php (2007)   https://en.wikipedia.org/wiki/Nuclear_fusion

Plasma: the 4th State of Matter

- Most fusion reactor concepts using D-T designed to operate at >10 keV (120 million Kelvin)
- At these temperatures reactants are fully ionized (electrons and nuclei) in plasma state→ outward expansion
- Can estimate escape timescales using thermal velocities
  - Deuterons ~1×10^6 m/s and electrons ~7×10^7 m/s
- In a reactor of 10 m size → particles lost within 10 μs !

How can we confine plasma?

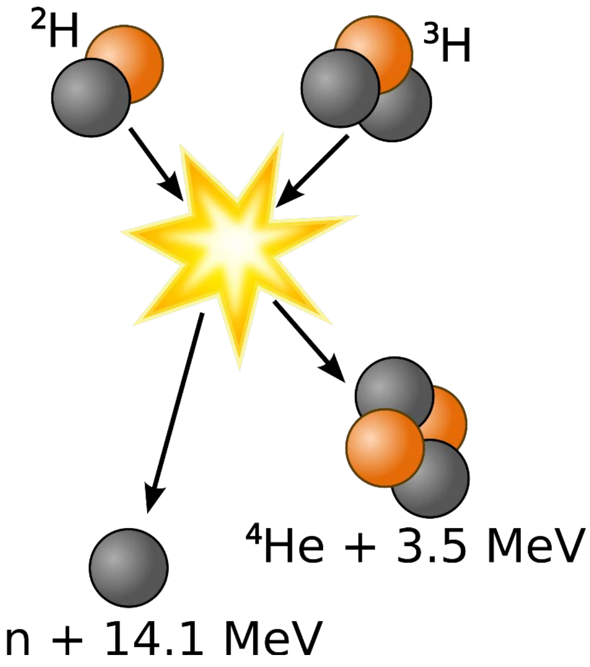
Two Approaches to Thermal Fusion

Magnetic Confinement	**Inertial Confinement**
• Use magnetic fields to confine electrically conductive plasma	• Typically use lasers to heat and compress fuel target
• Typically curved cylinder, field lines close in on themselves	• Objective is to create shockwave that can induce fusion
• Low plasma density but long confinement times	• High plasma density but very short confinement times

Large Scale Fusion Technology

International Thermonuclear Experimental Reactor (ITER)
- Magnetic confinement fusion
- Tokamak (toroidal) reactor
- International megaproject in France, still being built

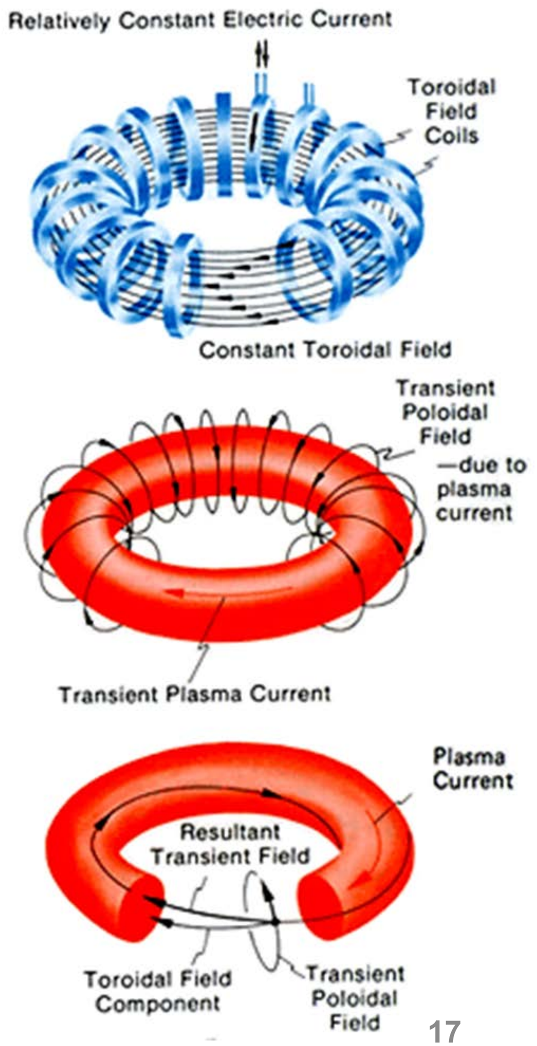
National Ignition Facility (NIF)
- Inertial confinement fusion
- Lawrence Livermore National Lab in California



www.wikipedia.org/wiki/Fusion_power

Magnetic Confinement

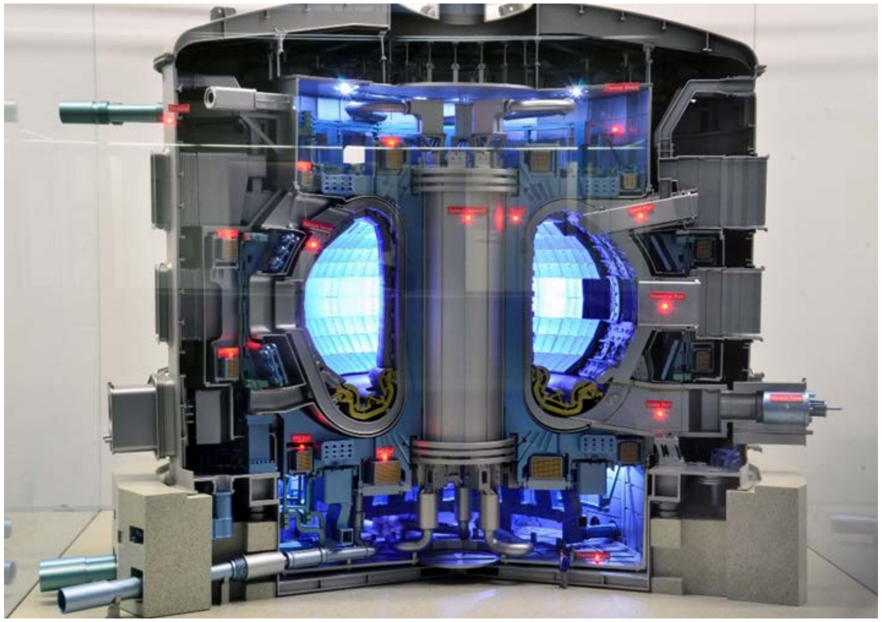
- Primary design is the Tokomak
- Toroidal field coils create toroidal magnetic field
- Moving charged particles experience perpendicular force to toroidal field coils
- Plasma current produces a poloidal field
- Resultant is a twisted, helical field around the torus, containing the plasma
- Plasma heated through Ohmic heating



www.wikipedia.org/wiki/Tokamak

ITER

- Location: Cadarache, France
- Progress: Construction ongoing
- Cost: Estimated $5 billion USD, currently over $20 billion
- Operation:
  - D-T fusion at ~10 keV
  - Designed to produce 500 MW using 50 MW to operate
  - Neutron flux will pass through a blanket of lithium to breed tritium ➡ ${}_{3}^{6}Li + {}_{0}^{1}n \rightarrow {}_{2}^{4}He + {}_{1}^{3}T + 4.8\ MeV$

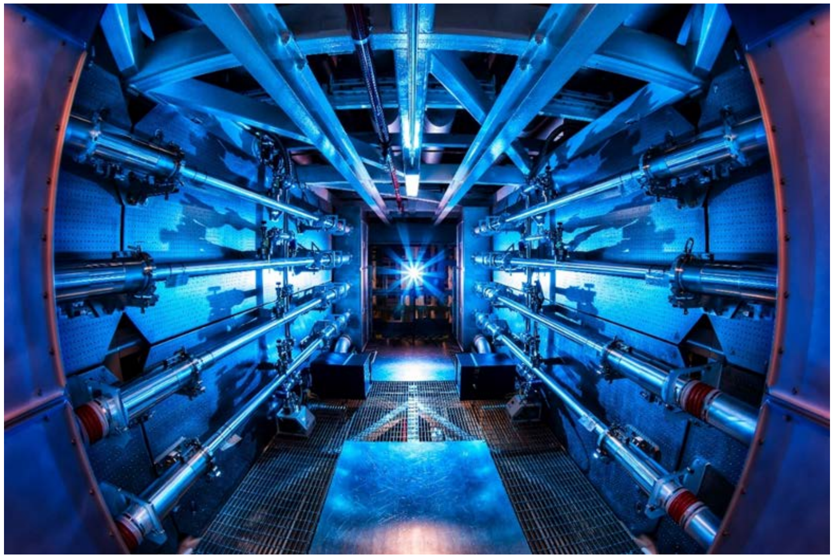


Full fusion experiments not expected until 2027

www.iter.org

Inertial Confinement: NIF

- Location: Livermore, California
- Progress: Completed in 2009
- Cost: $3.5 billion USD
- Operation
  - Uses laser systems to rapidly heat a D-T pellet and compress it
  - 192 beamlines are amplified to a total energy of 4 MJ
  - Fuel is compressed to 20 times the density of lead, ignites at ~10 keV



www.wikipedia.org/wiki/National_Ignition_Facility

Issues and Setbacks

ITER

- Neutron activation of reactor vessel
  - Replace walls every few years? Contributes radioactive waste
  - Superconducting magnets are also damaged
- Delayed and overbudget
  - Start of experiments 2016→2027, $5 billion→$20 billion

NIF

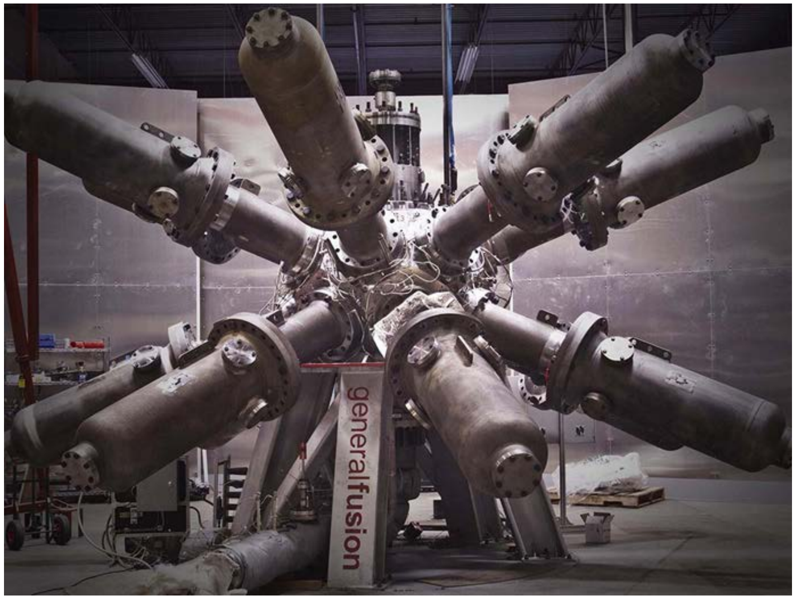
- Campaign to achieve ignition ultimately failed (Q<1)
  - Focus began to shift to materials research in 2012
- Laser cooling time only allows a few shots per day
  - Fusion power plant would require multiple shots per second to be feasible

Small Scale Fusion Technology

generalfusion **Hybrid Fusion**	HYPERV TECHNOLOGIES CORP **Hybrid Fusion**
TRI ALPHA ENERGY THE POWER OF INGENUITY **Aneutronic Fusion**	SHINE™ Medical Technologies PHOENIX NUCLEAR LABS, LLC **Fusion for Medicine**

General Fusion

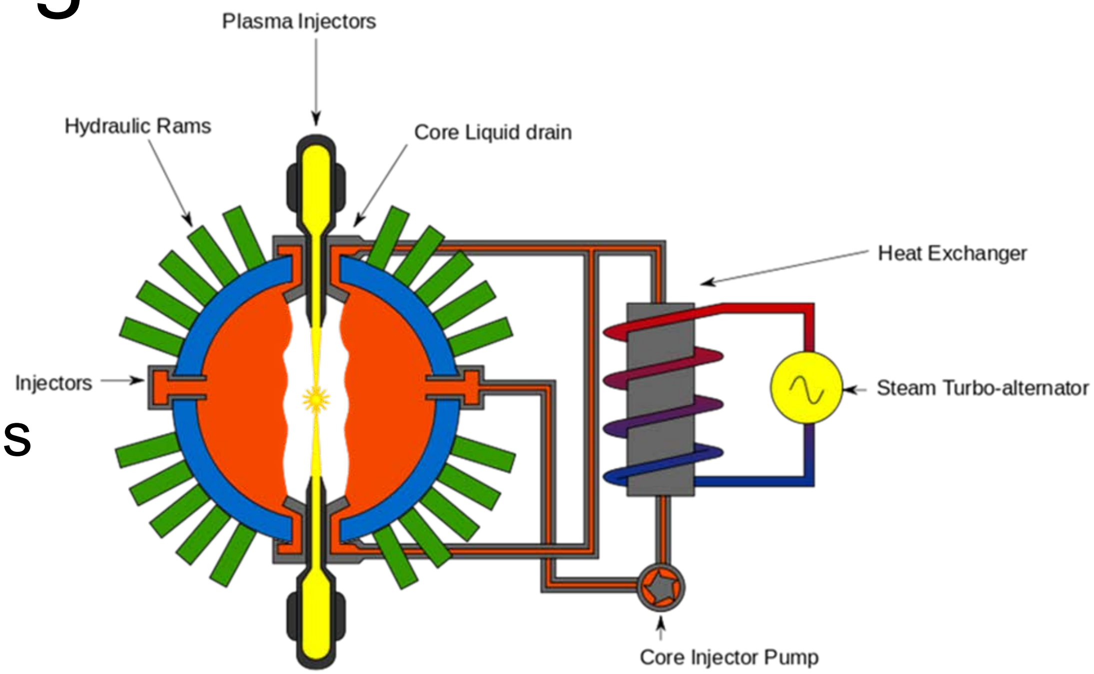
- Location: Vancouver, Canada
- Progress: Constructing prototype
- Cost: $100 million
- Operation:
  - Hybrid approach using magnetized target fusion of D-T for a 100 MW reactor
  - Gas is introduced to a liquid metal containing tank as a plasma at 0.5 keV
  - Array of pneumatic rams compresses the mixture to fusion conditions



www.generalfusion.com

General Fusion Design

- Lead-lithium liquid mixture is spun to create a cylindrical cavity in which D-T gas mixture is injected
- 300 pneumatic rams compress mixture, igniting the fuel

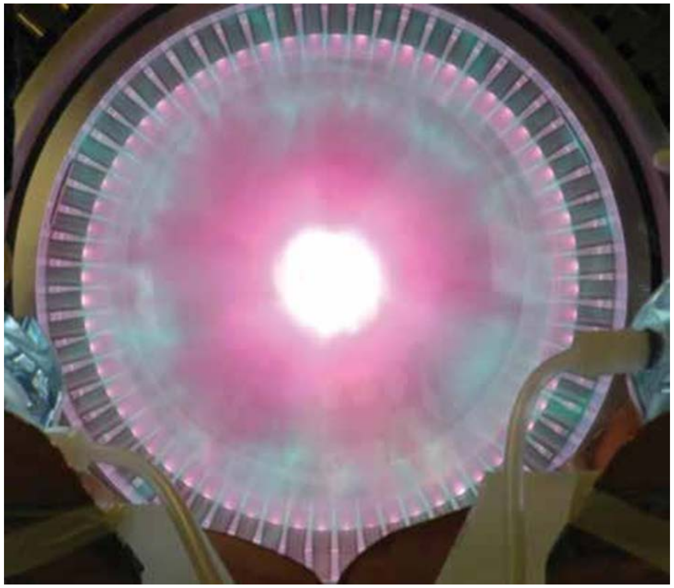


Advantage
-No need for high power lasers or superconducting magnets
Disadvantage
-High energy neutrons could still activate lead, result in radioactive products

www.wikipedia.org/wiki/General_Fusion

HyperV & The Plasma Liner Experiment

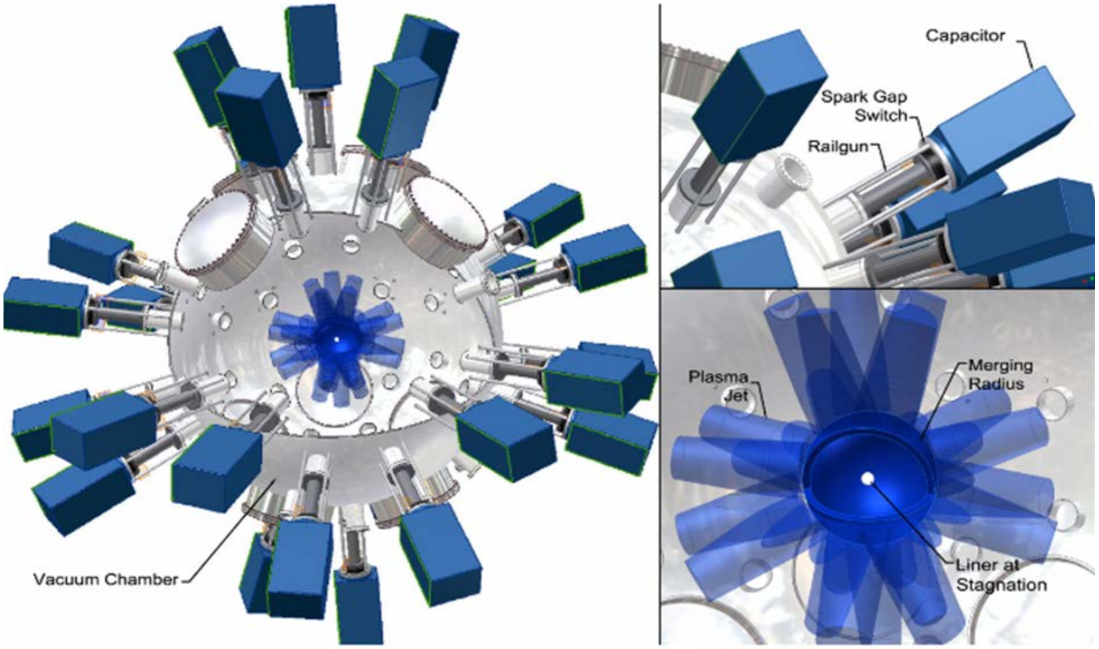
- Location: Los Alamos, New Mexico
- Progress: Constructing prototype
- Cost: $200 million
- Operation:
  - Hybrid approach using magneto-inertial fusion of D-T plasma
  - Magnetized target is compressed using plasma guns
  - Intermediate fuel density, between typical magnetic and inertial confinement



http://hyperv.com/wordpress/wp-content/uploads/2016/04/Scientia-Article-reduced-size-version.pdf

Plasma Liner Design

- Mini-railgun devices (HyperV) used to create spherically imploding plasma liner
- Accelerating liner compresses D-T plasma target to temperature and pressure required for fusion

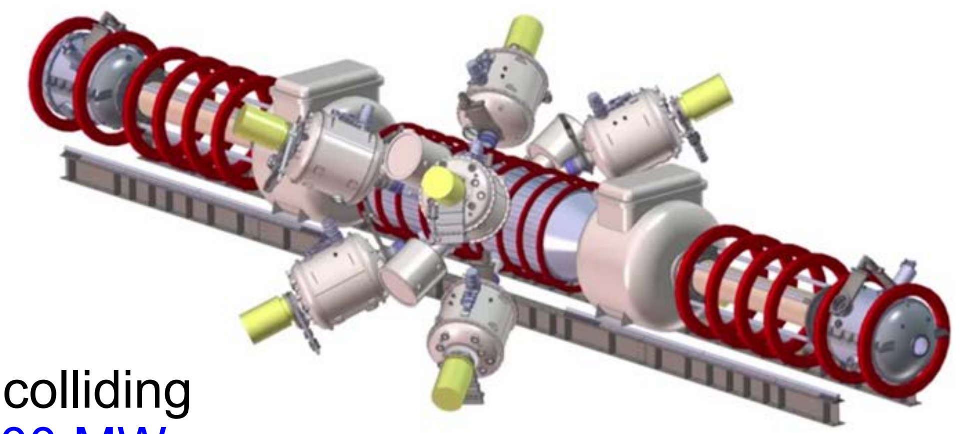


Advantage
-High temperature/plasma density not required
Disadvantage
-Plasma instabilities in liner compression still not understood properly

https://nuclearpioneers.wordpress.com/fusione-contenimento-inerziale/

Tri Alpha Energy

- Location: Irvine, California
- Progress: Testing prototype
- Cost: $500 million
- Operation:
  - Magnetic confinement of plasma in colliding beam fusion reactor, designed for 100 MW
  - Fusion at temperatures of 200-500 keV
  - Kinetic energy of charged products can be converted to a voltage by direct energy conversion techniques



$$^{1}_{1}p + {}^{11}_{5}B \rightarrow 3\ {}^{4}_{2}He + 8.7\ MeV$$

https://phys.org/news/2015-08-tri-alpha-energy-reportedly-important.html

Tri Alpha-Plasma Vortex Design

- Vortices fired towards each other, form a vortex stabilized by magnetic field
- Neutral particles are injected into plasma
  - Particles ionize and form a current ring that reverses the magnetic field→ plasma stability
- High energy α-particle fusion products are ejected past quadrupole electrodes for energy conversion

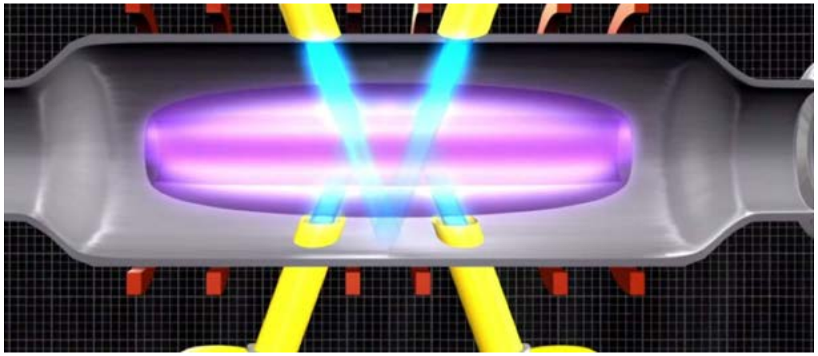
<u>Advantages</u>

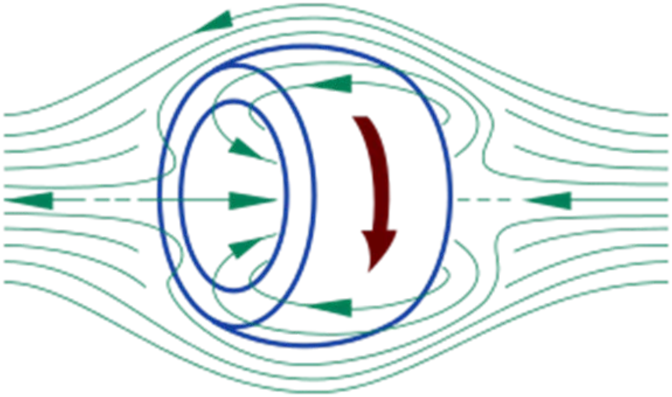
-Charged products→ direct energy conversion can be used

-Virtually no neutrons released, no radioactive waste is created

<u>Disadvantages</u>

-Direct energy conversion efficiency of ~80% is required for reactor to be feasible





www.wikipedia.org/wiki/Field-reversed_configuration www.trialphaenergy.com

Isotopes for medical diagnostics

- Over 80% of nuclear medical imaging use ^{99m}Tc
  - ~30 million procedures per year
  - $T_{1/2}$= 6 hrs, γ-emitter, good detection, eliminated from body within days
- Produced from the decay of ^{99}Mo, $T_{1/2}$= 66 hrs
  - Transport issues of ^{99m}Tc → ^{99}Mo delivered to medical facilities for onsite extraction (moly cow)
- ^{99}Mo produced in nuclear reactors, usually from enriched U
  - ~99% of world's supply from 5 reactors (Canada, Belgium, Netherlands, South Africa, Australia), but average age is 50 yrs
  - Requires processing facilities, proliferation concerns, sensitive to reactor shutdown (Chalk River: 2007, 2009 →global shortages)

Fragile ^{99}Mo supply chain requires small-scale, locally available, ^{99m}Tc generation technology

SHINE & Phoenix Nuclear Labs

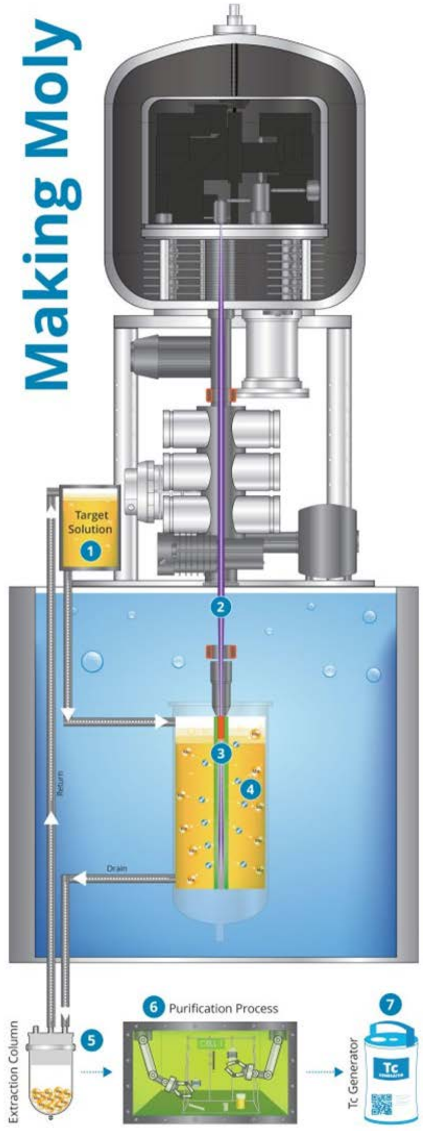
- Location: Madison, Wisconsin
- Progress: Constructing isotope production facility
- Cost: ~$125 million secured funding
- Operation:
  - Uses fusion-based neutron generation technology (Phoenix Labs) to bombard low-level enriched uranium
  - ^{99}Mo is one product of the induced uranium fission
  - In-house moly extraction and purification

http://phoenixnuclearlabs.com/

SHINE-Fusion & Fission

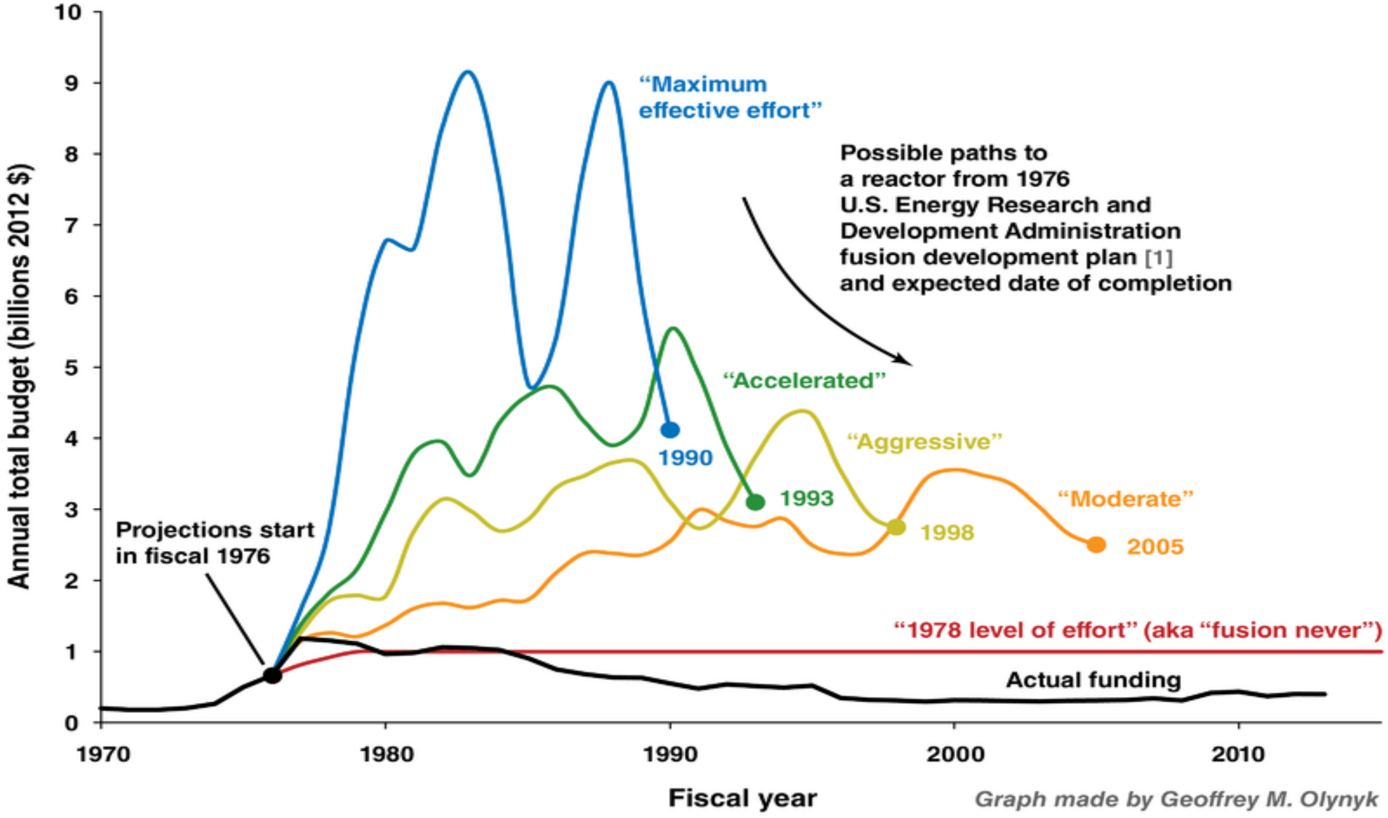
- Deuterium ions accelerated into target gas of tritium
- Fusion results in neutrons → induces fission in the surrounding uranium solution
- Solution irradiated for one week, then chemical extraction and purification (milking)

Advantage
-Reusable liquid target, no highly enriched uranium required
Disadvantage
-Other radioactive daughter products are still formed



http://shinemed.com/demonstrated-technology/

“Fusion’s always 50 years away” for a reason



Graph made by Geoffrey M. Olynyk

[1] U.S. Energy Research and Development Administration, 1976. “Fusion power by magnetic confinement: Program plan” ERDA report ERDA-76/110. Also published as S.O. Dean (1998), *J. Fus. Energy* **17**(4), 263–287, doi:10.1023/A:1021815909065

Summary and Outlook

- Benefits of fusion:
  - No greenhouse gas emissions or long-lived radioactive waste
  - No risk of uncontrolled energy release
  - Abundance of fuel
- Much research in D-T fusion, but issues still remain:
  - High energy neutrons and their effect on reactor components
  - Plasma confinement times
  - Requirement for high temperature superconductors
- Encouraging future for small scale over large scale reactors

Can we get net gain (Q>1) from a fusion reactor?

Useful references

ARPA-E's ALPHA fusion project funding list
https://arpa-e.energy.gov/?q=arpa-e-programs/alpha

Report on world production of ^{99}Mo, from the IAEA (2010)
https://www.iaea.org/About/Policy/GC/GC54/GC54InfDocuments/English/gc54inf-3-att7_en.pdf

National Academic Press report on ^{99}Mo for medical imaging (2016)
https://www.nap.edu/read/23563/chapter/6

Conceptual cost study for a fusion reactor ARPA-E (2016)
https://arpa-e.energy.gov/sites/default/files/VITTER.pdf

Introduction to Plasma Physics and Controlled Fusion, Francis F. Chen
(the first fusion textbook you should ever read)
https://abmpk.files.wordpress.com/2014/09/f-140717034619-phpapp01.pdf