Nuclear fusion: dream of plenty or evanescent Morgane?

Franco COZZANI
SEII - Château St. Anne
April 28, 2023

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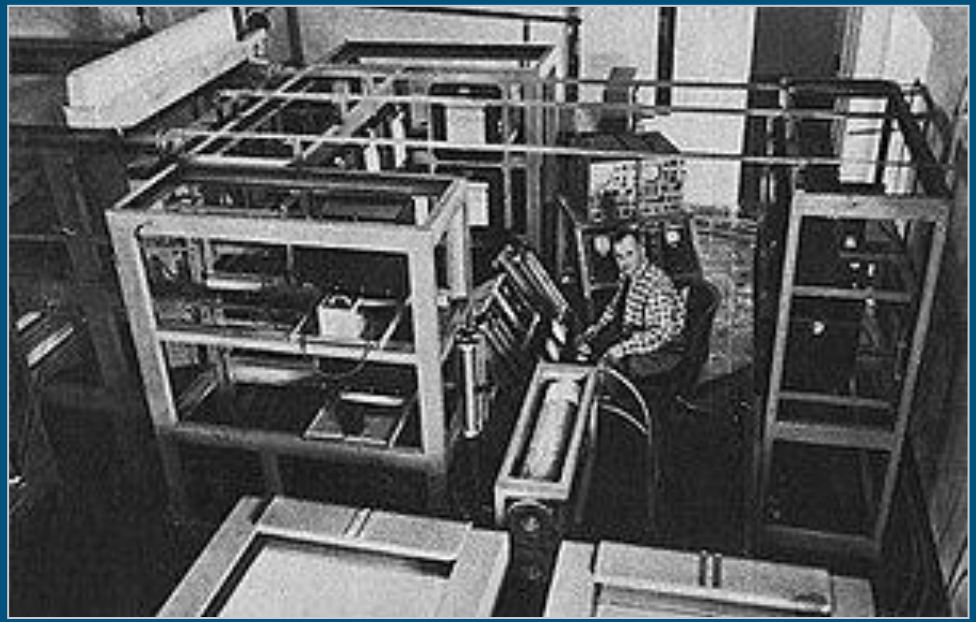
For what relates to inertial confinement and non-proliferation aspects of fusion energy, this conference conforms to the prescriptions regarding “born secret” content, in accordance with United States Atomic Energy Act of 1954, and successive legal rulings of the U.S. Department of Energy.

1951: Proyecto Huemul

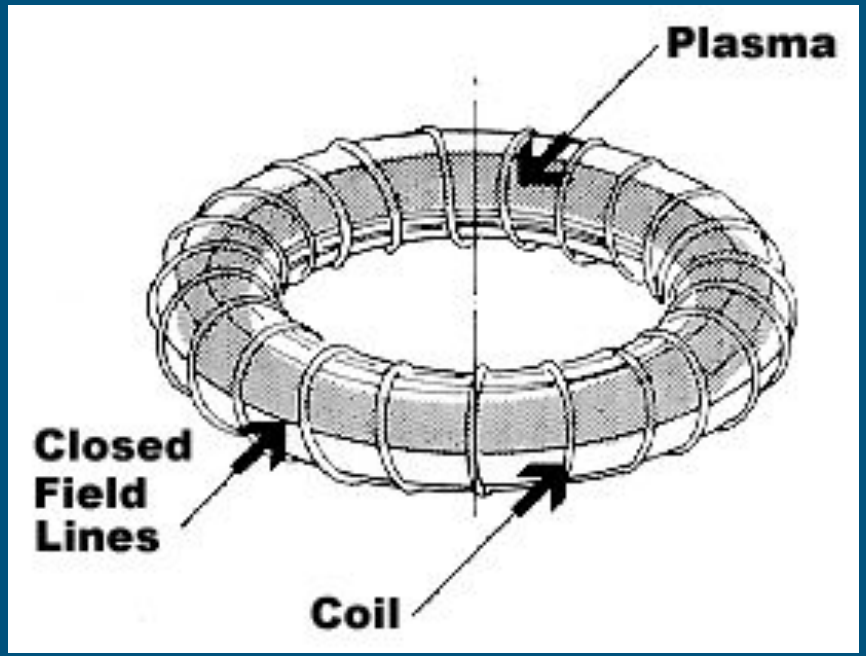
“El resultado obtenido es, pues, que el enorme número de choques sufridos por el átomo de Li, en las condiciones que se opera, imposibilita la realización de cualquier dispositivo de contralor basado en el principio mencionado por el doctor Richter.

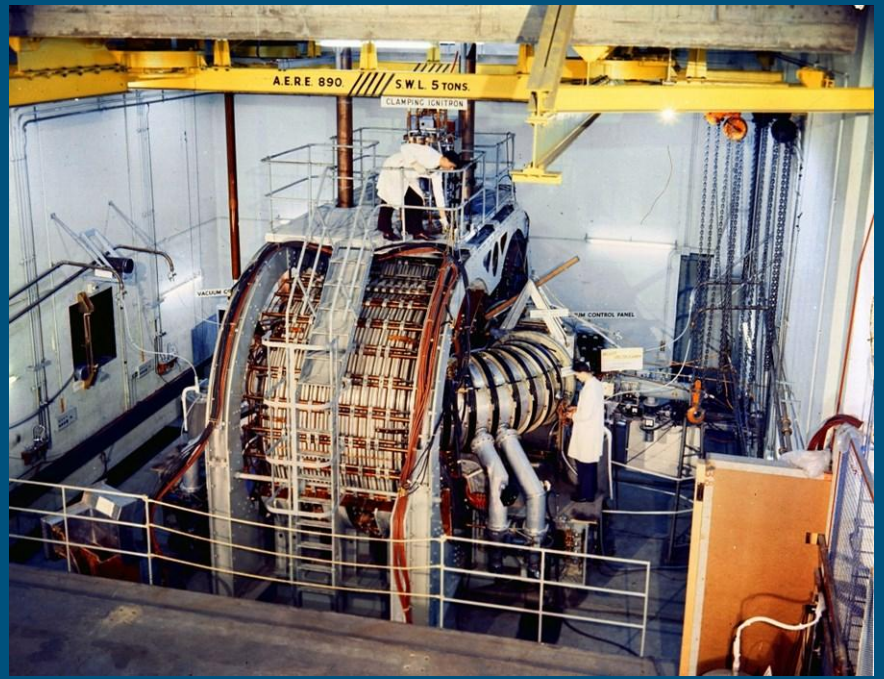
El Dr Richter ha mostrado un desconocimiento sorprendente sobre el tema.”

Government Commission, dr Balseiro, 1952



First Toroidal machines: Zeta 1958





Zeta: late January 1958

DAILY SKETCH 2½d
SATURDAY, JANUARY 25, 1958
© 1958, by the Daily Sketch

OUR SCIENTISTS SPUTNIK THE RUSSIANS—FOR PEACE

P-S-S-T!

A SUN OF OUR OWN / AND IT'S MADE IN BRITAIN •

By PETER STEWART
HARWELL, BERKS, Friday

BRITISH scientists revealed their stupendous ZETA secret officially to-night. They have built a man-made sun on earth.

It is a peaceful, safe sun which promises limitless cheap power for all mankind.

The news made even the Space Age Russians sit up.

Moscow Radio gave a long report on our success, but—true to form—claimed it was based on a discovery made by Russian scientists in 1950.

ZETA is a 120-ton yellow and black painted reactor standing behind foot-thick walls in a hangar here.

THE HEAT FROM 10 TONS OF COAL FOR 2s

● MUCH HOTTER

TO-NIGHT the biggest flashes man has made are exploding every 6th second at more than 5,000,000 degrees Centigrade—a third of the temperature at the centre of the sun.

IN A YEAR, scientists hope, ZETA will be working at temperatures far beyond those of the sun.

AND IN 10 YEARS, with luck, ZETA will herald in the beginning of a social millennium for mankind.

That will be commercial application of the fast-speed H-Bomb thermonuclear reaction, giving power from the oceans, ZETA-style, like this:

● From every five gallons of sea-water scientists can now obtain one gramme of Deuterium gas.

● Via ZETA, the energy stored in that gramme of gas could do the work of ten tons of coal—all for 2s.

The importance of the discovery for which the U.S., Russia and Britain have raced neck-and-neck for ten years is this:

● Coal and oil resources could run out in 50 years.

● Uranium and thorium for atomic fission reactor power stations will only last 300 to 400 years.

● With ZETA the whole world has enough energy stored in the oceans for more than 1,000 million years.

The secret of ZETA—code for long energy thermonuclear assembly — was given free to the world by Sir John Cockcroft, outgoing boss of the Atomic Energy Authority.

● SO SHY

ZETA was produced by a team of grammar school and scholarship boy workers on a makeshift reactor built partly from Admiralty scrap.

Cost: Less than £250,000.

Shifting slyly from one foot to another on the darkened stage of a lecture hall named in his honour, Sir John revealed that:

While the Russians were perfecting Sputniks and inter-continental ballistic missiles the Commonwealth has been building quietly for the benefit of every nation.

"To have achieved temperatures a third of those

➡ Page 9

P-S-S-T!

WHAT'S the hush-hush girl got to do with ZETA? Just that she illustrates the tell-nobody attitude of the authorities over this stupendous discovery. See: Shall We Suck Dr. Hill? on Page 2.*

* And Berrotty Melcher is pretty, too.

… a controlled fusion experiment recreates the processes occurring inside a star, 'A Sun of our own' and 'Britain's H-men make a Sun'

In response to the media fiasco, chief scientist at Harwell, Sir George Thompson commented that a viable nuclear fusion reactor could be developed in around 20 years : commonly shared scientific joke that 'Viable nuclear fusion is always 20 years away'.

The biggest promise to come from Project Zeta has yet to be realised. Nuclear fusion has the potential to provide virtually limitless amounts of energy without releasing any environmentally harmful byproducts. And the fuel for the nuclear fusion process, deuterium, can be extracted from seawater, a virtually limitless supply.

https://edu.rsc.org/opinion/remembering-project-zeta/2021040.article (2008)

NIF (LLNL & Washington, D.C.)

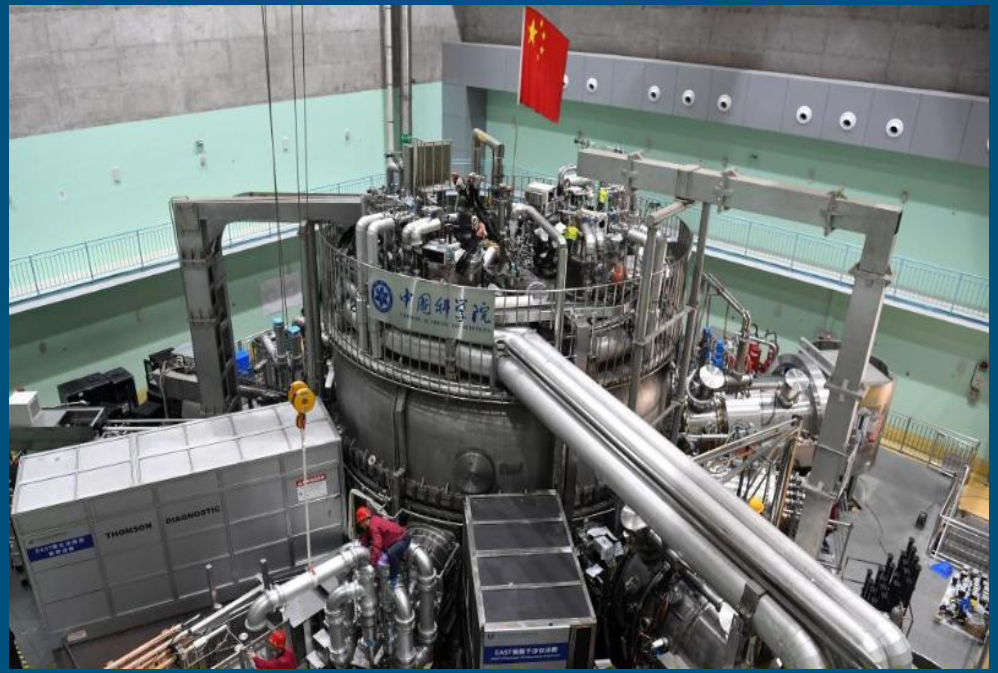
This historic, first-of-its kind achievement will provide unprecedented capability to support NNSA's Stockpile Stewardship Program and will provide invaluable insights into the prospects of clean fusion energy, which would be a game-changer for efforts to achieve President Biden's goal of a net-zero carbon economy.

U.S. Secretary of Energy Jennifer M. Granholm, press conference, December 13, 2022

403 seconds! Chinese 'artificial sun' sets new world record in sustaining steady-state high-confinement plasma, Global Times, Apr 13, 2023

China's "artificial sun" achieves breakthrough, key step toward fusion reactor, updated: April 14, 2023 Xinhua (EN.GOV.CN)

比太阳还热！



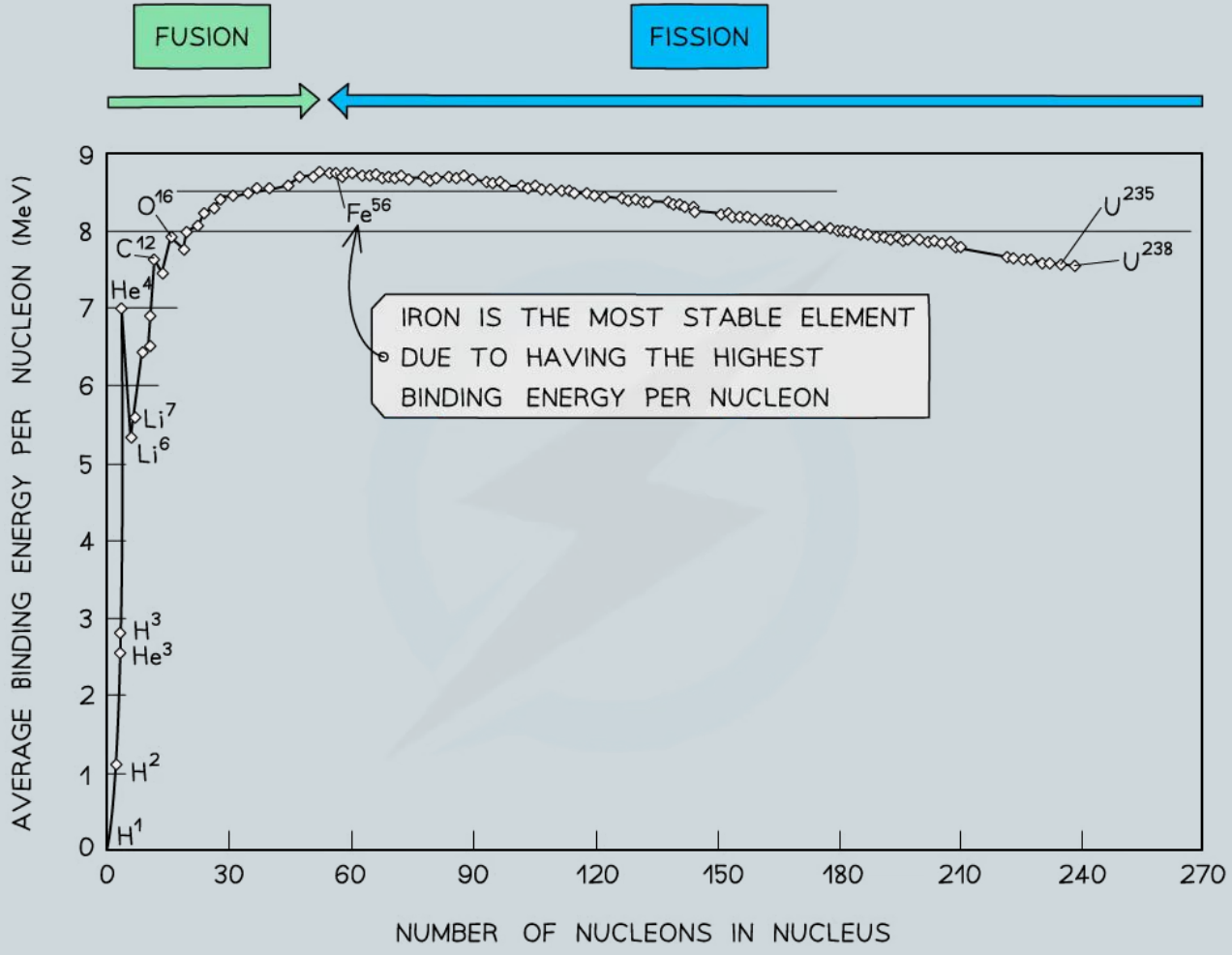
… and the joke now is…

Homi Bhabha: fusion in about 20 years (1955)

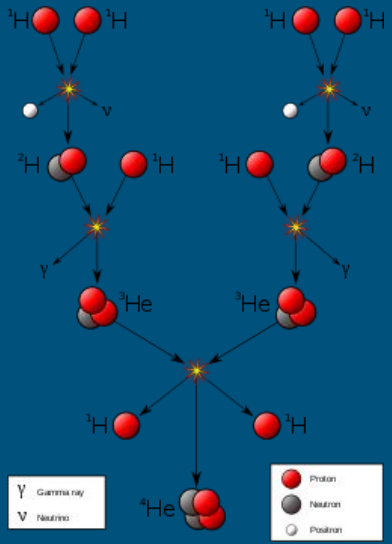
Fusion is always 20 years in the future (joke among fusion scientists in the U.S., 1982-85)

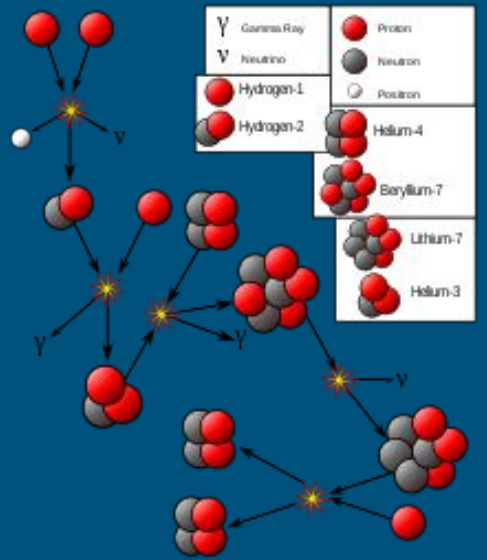
Fusion is always 30 years in the future 😅… 😭

The power of the Sun

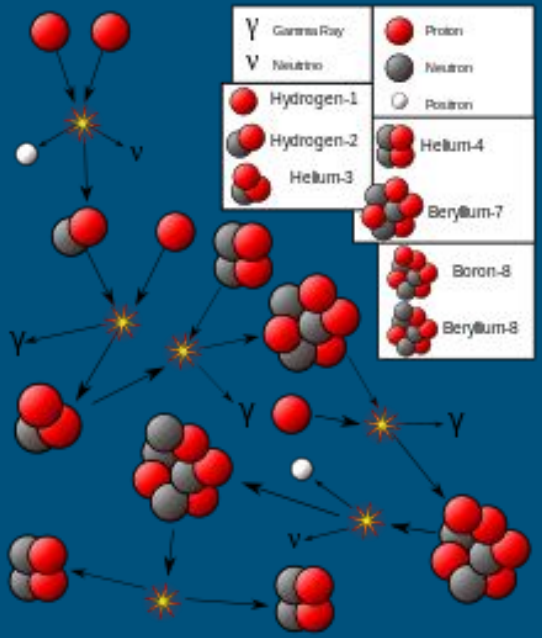


p-p cycle, branch I and II





p-p cycle, branch III



NB: some precision in the language:
the p-p cycle does fuse H-1 into He-4, but some intermediate reactions in branch II and III are light nuclei fission!

Nuclear reactions for fusion on Earth: the D-T cycle

$$D + T \dashrightarrow \text{He-4 (3.52 MeV)} + n \text{ (14.1 MeV)}$$

Energy released = 94,000 kWh (thermal) per gram of reacting nuclei

T - breeding reactions are:

$$\text{Li-6} + n \dashrightarrow T + \text{He-4} + 4.8 \text{ MeV},$$

$$\text{Li-7} + n \dashrightarrow T + \text{He-4} + n - 2.5 \text{ MeV}$$

The overall reactions for D -T fusion are therefore:

$$D + \text{Li-6} \rightarrow \text{He-4} + \text{He-4} + 22.4 \text{ MeV (75,000 kWh (th)/ g reactants)}$$

$$D + \text{Li-7} \rightarrow \text{He-4} + \text{He-4} + n + 15.1 \text{ MeV (45,000 kWh (th)/ g reactants)}$$

Nuclear reactions for fusion on Earth: the D-D cycle

D + D --› He-3 (0.82 MeV) + n (2.45 MeV) (22,000 kWh (th)/ g reactants)

D + D --› T (1.01 MeV) + H (3.02 MeV) (27,000 kWh (th)/ g reactants)

D will react with He-3 and also with T as before

D + He-3 → H (14.67 MeV) + He-4 (3.67 MeV) (98,000 kWh (th)/ g reactants)

Accordingly, burning deuterium to completion would give:

6 D → 2 He-4 + 2 H + 2 n + 43.2 MeV (96,000 kWh (th)/ g reactants)

Nuclear reactions in Castle Bravo

Start: a little (classified!) D + T from boosted fission
→ He-4 + n + 17.6 MeV,
+ fission neutrons from the primary (NB: spectrum of fast fission neutrons)

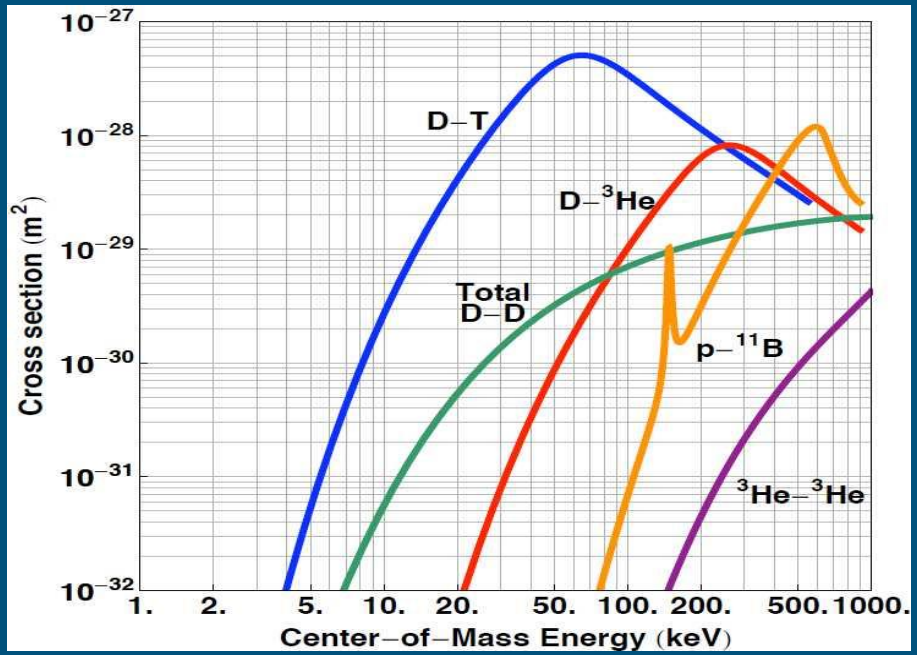
Li-6 + n --› T + He-4 + 4.8 MeV,
Li-7 + n --› T + He-4 + n - 2.5 MeV (the same breeding reactions for peaceful fusion energy)

D + T --› He-4 + n + 17.6 MeV,
T + T --› He-4 + 2 n + 11.27 MeV,
D + D --› T + H + 4.04 MeV,
D + D --› He-3 + n + 3.27 MeV,
D + He-3 --› He-4 + H + 18.34 MeV,

but also: Li-7 + n --› Li-6 + 2 n --> more Li-6 (exothermic, more T)--> more D-T --> more n's (well above 5 MeV) --> more U-238 fast fission in the tamper:

Bravo predicted yield: 5-6 MT; it ran away to 15 MT

Typical reactions for MFE and IFE



Similarities with the Sun

- Fusion – Fission curve (binding energy curve)
- Coulomb barriers, tunneling and potential cliffs
- Why nuclear fusion must be “thermo”-nuclear?

Differences with the Sun

- MFE and ICE rely on other reactions than the Sun's
- Stars don't mess with neutrons… until they collapse 😄
- D-T fusion relies on Li reaction = « mini » fission
- « H-bombs » have really little to do with the Sun
- Stars have an advantage over MFE in their Hamiltonian
  → Instabilities in MFE

Why Fusion?

A Nuclear –friendly World (1951 to the early 1960's)

Generation I: PWR's: they work
Generation II: FBRs (Fast reactors work like the Bomb)
Generation III: Fusion-Fission hybrids: they will work like the H-Bomb
Generation IV: Pure Fusion reactors: they will work like the Sun

 Fusion Power is Prometeus' dream.

NB: different « generations » w.r.t. present-day roadmap for fission reactors!
NB2: 1958: Project Orion; EURATOM; the Brussels Atomium

The big Resources Scare

Club di Roma: The Limits to Growth (1972)
Yom Kippur (1973)
Iranian Revolution (1979)
Fusion Act (Sen. Mc Cormick, 1980)

- Plentiful and cheap:

Fusion Power will run on Seawater!

Resources: the D-D case

Deuterium has a natural abundance in Earth's oceans of about one atom in 6420 of hydrogen. Thus, deuterium accounts for approximately 0.0312% by mass of all the naturally occurring hydrogen in the oceans.

recall burning deuterium to completion: 96,000 kWh (th) / g reactants

recall: World electricity consumption
25,343 TWh (el) (2021);
23,966 TWh (el) (2020);
23,921 TWh (el) (2019).
source https://www.statista.com/statistics/280704/world-power-consumption/

Resources: the D-T case

The total lithium content of seawater is estimated as 230 billion tonnes, where the element exists at a relatively constant concentration of 0.14 to 0.25 ppm.

Lithium constitutes about 0.002 percent of Earth's crust. At 20 mg lithium per kg of Earth's crust, lithium is the 25th most abundant element.
source: https://en.wikipedia.org/wiki/Lithium

NB: **Beryllium** is widely distributed in Earth's crust and is estimated to occur in Earth's igneous rocks to the extent of 0.0002 percent. The United States has about 60 percent of the world's beryllium and is by far the largest producer of beryllium; other major producing countries include China, Mozambique, and Brazil.
source: https://www.britannica.com/science/beryllium

Resources: the D - He-3 case

Moon's surface contain helium-3 at concentrations between 1.4 and 15 ppb in sunlit areas, and may contain concentrations as much as 50 ppb in permanently shadowed regions.
Because of the low concentrations of helium-3, any mining equipment would need to process extremely large amounts of regolith (over 150 tonnes of regolith to obtain one gram of helium-3).
source: https://en.wikipedia.org/wiki/Helium-3

NB: millions of tons of He-3 might be found in the Gas Giants in our Solar System.

Divorce from Fission

→ Three Mile Island, 1976

→ « A whole lot better than Fission »
Airline passenger in front of a stand surmounted by a banner reading:
« Develop laser fusion or learn Russian »,
DFW domestic terminal, 1984

→ Chernobyl, 1986

A dangerous experiment with the Earth's Climate

ESECOM (Environmental, Safety and Economic Aspects of Magnetic Fusion Energy), J. Holdren Chair, 1987
EEF (Environmental and Economic prospects of Fusion), S. Pease Chair, 1989
SEAFP (Safety and Environmental Assessment of Fusion Power), 1994-1996
SERF (Socio-Economic Research on Fusion), 1997-1999

Fusion Power: cheap, clean, and safe ☐ *Fusion has the potential to become a carbon-free source for baseload electricity production / has the potential to contribute significantly to carbon-free generation of…*

Why Fusion_nuclear safety

Suicidal safety Chernobyl

Active safety Three Mile Island, Fukushima

Passive safety Advanced Fission, Fusion

Intrinsic (inherent) safety Fusion

Absolute safety quote Gandhi

Why Fusion_nuclear safety_2

The good:

- An engine, not a pile
- Not enough energy to break container (cfr. Chernobyl)
- Tritium is a moderate beta-emitter

The bad:

- DTO is 25,000 x radiotoxic than gaseous T
- Divertor LOCA?
- Li is reacted, but blankets and first wall are noy exactly healthy enviroments
- And… materials, materials, materials!!!

☐ (D-T) fusion still will need a containment building

Why Fusion_non proliferation

The good:

- Building / Operating a Tokamak will not teach you how to build a bomb
- There are / there ought to be ZERO fissile / fertile materials on-site a fusion plant

The bad:

- Details of pellet design and—especially—radiation-plasma coupling codes for ICF/ICE should not be posted on Instagram

Why Fusion_non proliferation_2

The ugly

- A D-T fusion (and a D-D reactor) with fertile materials in the blanket would be a dream to produce weapon-grade Pu-239 and U-233

☐ (D-T and D-D) fusion will still need to fall under IAEA safeguards

source: UKAEA study under SEAFP (but also known in IIASA study by Holdren et al., 1976-77.

Risk vs Perceived Risk = a problem with all things nuclear!

Please rate the following (alphabetically-ordered) accidents in terms of number of fatalities

Bhopal	man-made
Fukushima (Daichi meltdown)	nature-initiated, man-related
Japan (tsunami), at the time of Fukushima	natural
Three Mile Island	man-made
Vajont Dam	nature-initiated, man-related

Risk vs Perceived Risk_2

And the winner is…

Japan (tsunami), at the time of Fukushima ☐ *over 19,000 died*

Bhopal ☐ *3,787 died (official estimate by Madha Pradesh government; one can finds 2x estimates)*

Vajont Dam ☐ *1,917 died*

Fukushima (Daichi meltdown) ☐ *0 died from radiation, reportedly 34 to 50 died for loss of medical care after evacuation*

Three Mile Island ☐ *0 died*

The trust ladder: a bit of sociology

Tell them is good for them

Tell them the key numbers

Tell them all the numbers

Tell them what the numbers mean

Listen to them

Make them partners

The Porto Torres Experiment (SERF)

What would you say if we (EURATOM) build a thermonuclear reactor near you and your daughter falls in love with a Japanese scientist?

The Porto Torres Experiment (SERF)

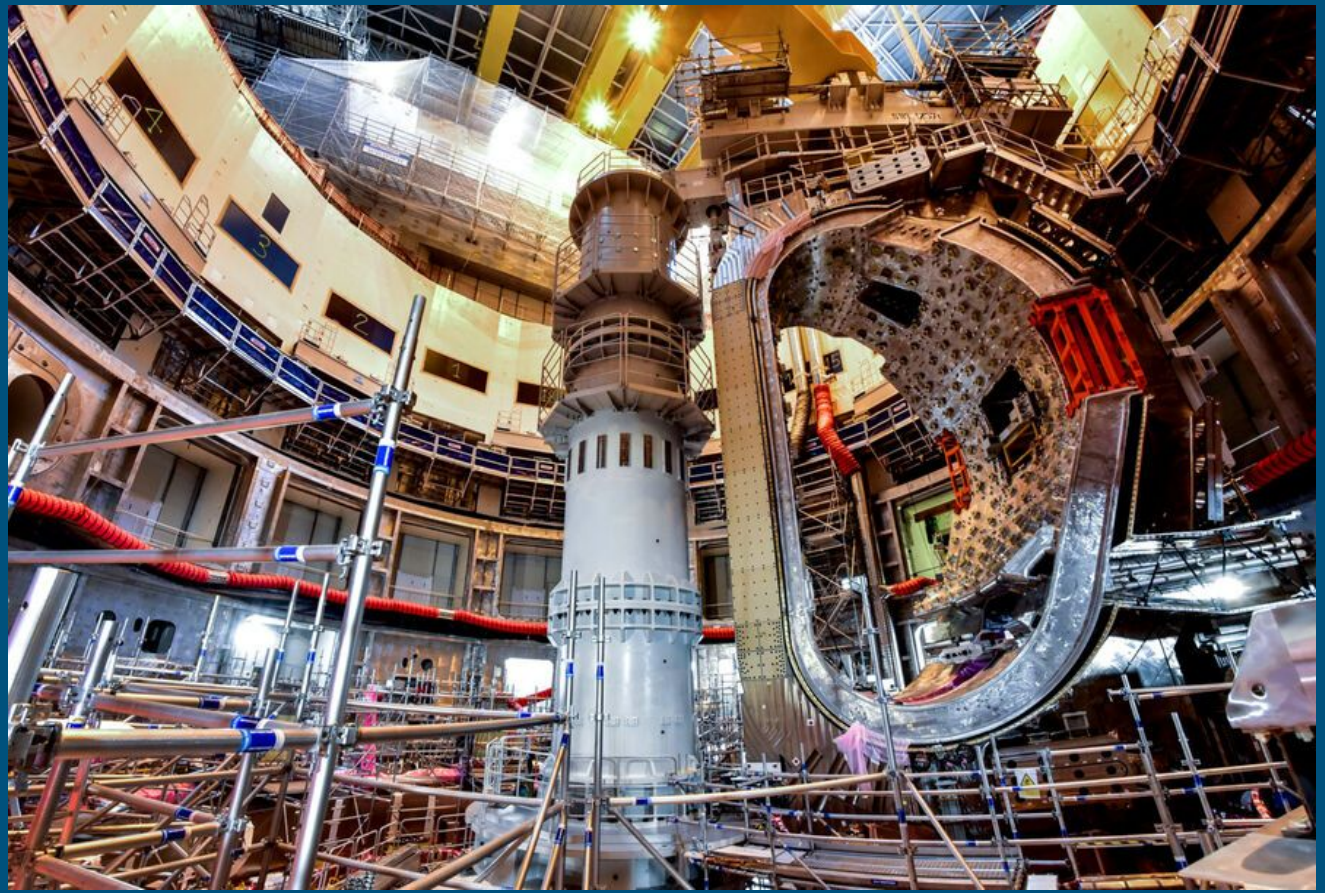
The fair breeze blew, the white foam flew,
The furrow followed free
We were the first that ever burst
Into that silent sea

Samuel Taylor Coleridge
The Rime of the Ancient Mariner

ITER:

EURATOM (incl. CH and UK), China, India, Japan, South Korea, Russian Federation, United States.

Partners: Australia, Canada, Kazakhstan, Thailand



Always 30 years in the future… 

I shall drink to the Pope, if you please

John Henry Newman