When Will We Get Energy From Nuclear Fusion?

Progress in Nuclear Fusion from 1950 to 2050

By Steven B. Krivit

New Energy Times

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Version with video clips here: https://youtu.be/Jy3mN3fL9qE

"Every profession has, at its core, a group of terms and knowledge that are shared and understood by its practitioners."*

Fusion research is no exception.

Although we see a constant stream of exciting design concepts, claims of breakthroughs, and wonderful-sounding future results, the fusion research industry and its scientists have not helped the rest of us to clearly understand fusion terms, actual progress, and the facts. This presentation aims to bridge this gap.

* Steve Bunting

Fusion scientists told us in 1975 that we would have electrical power from fusion by 1995.

Congressional Record, May 5, 1993

Congressman Walker noted, "I remember coming here as a relatively new Member (17 years ago) and listening to some of these hearings and being told at that time that we were ten years away from success back in the last seventies, and the time line always seems to be ten years. Now I must admit that today we're maybe becoming a little more honest. It sounds to me more like 20 years today."

Progress in nuclear fusion can be measured in three ways:

1. Overall net reactor power output
2. Net nuclear reaction power output
3. Triple-product performance

Overall Net Reactor Power Output

This refers to the overall rate of power output of the fusion reactor and accounts for and subtracts the input power required to operate the reactor.*

Overall net reactor power output is the only measurement the public cares about.
If positive, it would directly show that fusion *is possible as an energy source*.

No fusion reactor has produced net energy or even net power.
The overall ITER reactor, if it works correctly, will not produce net energy or power.

* For accurate comparisons, thermal values are normalized to electric values for "apples-to-apples" comparisons.

Net Nuclear Reaction Power Output

This refers to the rate of thermal power produced by nuclear reactions compared with heating power injected into and used to heat the fuel for those reactions.

Net nuclear reaction power output does not account for the power required to operate the reactor.

This is the only type of power measurement fusion scientists seek to measure in ITER.
A net positive *reaction output* is a prerequisite to a net positive *reactor output*.

No fusion reactor has produced a net positive *reaction output*.
Therefore, no fusion reactor has come close to producing a net positive *reactor output*.

Net Nuclear Reaction Power Output (ITER Example)

The International Thermonuclear Experimental Reactor (ITER), if it works correctly, will have a net positive *reaction*, a tenfold thermal power gain.

But the net *reactor* output power rate will be equivalent to less than zero Watts.

The Facts:

Heating power that will be injected into the fuel: 50 MW

Peak thermal power expected from fusion: 500 MW

Minimum electrical power expected to be consumed by the reactor: 300 MW

Minimum equivalent thermal input power expected to be consumed by the reactor: 750 MW

These values are simplified. For more precise values, and for all sources, please see:
http://news.newenergytimes.net/iter-fusion-reactor-technical-references/

Therefore, when fusion scientists are asked about their progress,
they show the "triple-product" value.

Before we define triple-product, we need to define some other terms.

The following terms apply to only *controlled magnetic confinement* fusion.

"Fusion Power" Definitions

Meaning for the Public

Usable rate of power (in thermal or electric form) produced by a fusion reactor.

Meaning for Fusion Scientists

A physics measurement, indicating the thermal power of the produced fusion particles.

"Triple Product" Definition

In a nuclear reactive plasma, combined concomitant* value of plasma temperature,** plasma density, and plasma confinement time.

* Happening at the same time and multiplied together.
** Although this value is commonly identified as "plasma temperature," the reported values are, more precisely, values of ion temperature.

Definition of Scientific Breakeven

The hypothetical condition when fusion reactions produce the same rate of power that is injected into the fuel to produce those reactions.

Does not directly apply to overall reactor power.

Fusion scientists define this more concisely as when the power input in the plasma (heating) is equal to the fusion power produced.

Fusion Research Has Three Sequential Breakeven Terms

Scientific → Engineering → Commercial

After 70 years, fusion scientists have failed to achieve the first level: scientific breakeven.

"Engineering Breakeven" and "Commercial Breakeven"

Engineering Breakeven: "When sufficient electrical power can be generated from the fusion output to supply power for the reactor and auxiliary systems."[1,2]

Commercial Breakeven: "Requires a sufficient net surplus of power output whose sale will pay off the costs of building and operating the power plant."[2]

1. Basu, Dipak K., "Dictionary of Material Science and High Energy Physics," 2001, CRC Press.
2. Direct communication with Daniel Jassby.

Fusion Pioneer John D. Lawson

The work of John D. Lawson formed the initial basis for the triple-product concept. He published his concept in 1957 in a paper called "Some Criteria for a Power-Producing Thermonuclear Reactor."

Fusion scientists use the triple-product value as a way to mark their progress. According to their hypothesis, the achievement of specific temperatures, plasma densities, and plasma confinement time will provide the required conditions to demonstrate the "scientific feasibility" of fusion on Earth.

For Fusion, "Scientific Feasibility" Has At Least Two Meanings

Typical Meaning for the Public

When a fusion reactor can show scientific evidence that it is capable of producing useful power.

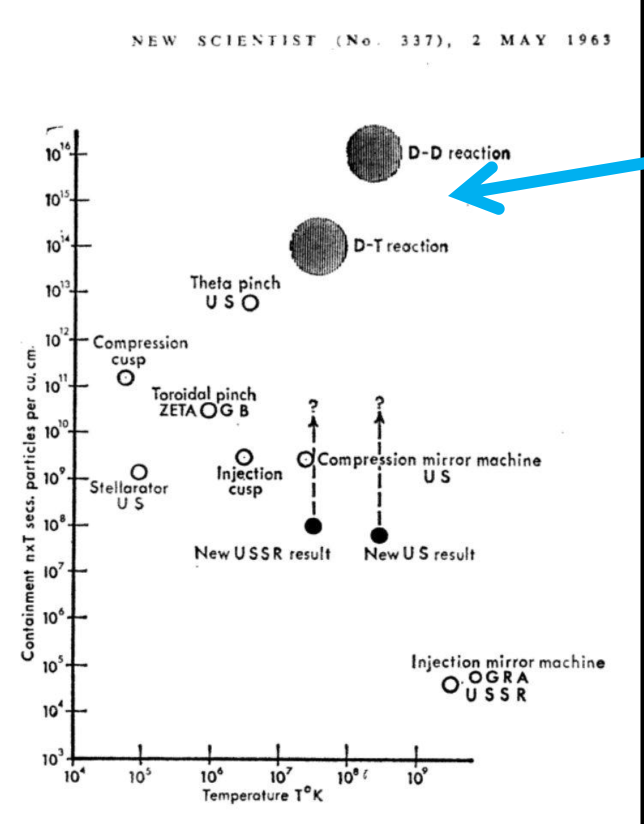
Typical Meaning for Scientists

When fusion reactions can produce power at a greater rate than required to produce those reactions.

Does not directly apply to overall reactor power. Thus, even a zero-net Watt reactor like ITER can "demonstrate the scientific feasibility of fusion."

See Appendix for detailed definition.

The Three Values Determine a Minimum Target Operating Regime

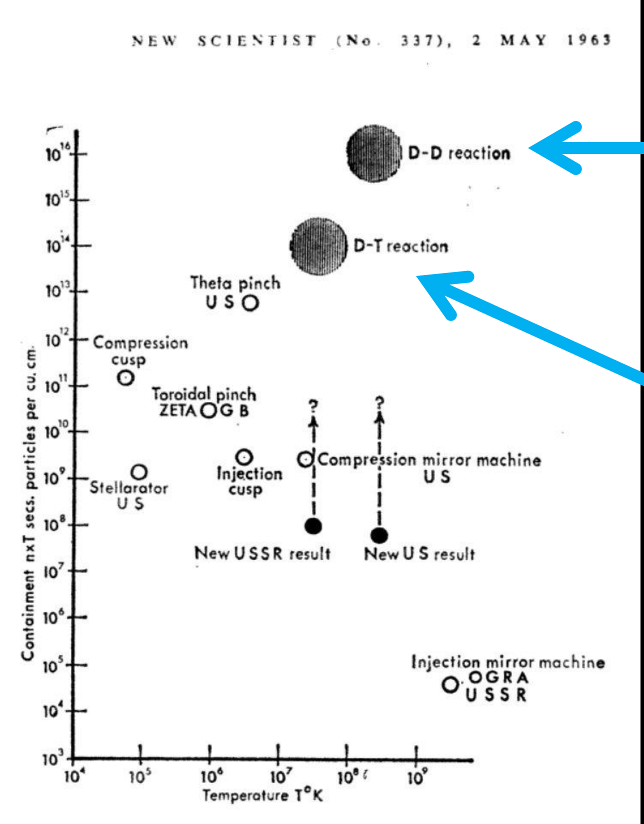


The two circles to the left indicate where the plasma density, plasma confinement time, and temperature need to be, based on the triple-product hypothesis, to reach scientific feasibility.

The vertical axis is the combined concomitant value of plasma density and plasma confinement time.

The horizontal axis is not time but temperature.

Scientific Feasibility Depicted as a Circular Area (1963)



The upper circle depicts the approximate triple-product values necessary to achieve "scientific feasibility" for DD fusion. DD fusion has never been considered a viable approach to practical fusion energy because the fusion reaction rates are too low.

The lower circle depicts the same parameters for DT fusion. When DD testing in ITER is finished, perhaps by 2035, it will begin using DT fuel for the real experiments.

The circles imply a circular bound, but in later years, scientists depicted the target regime more accurately, with a curve.

Scientific Feasibility Depicted as a Lower Bound (1971)

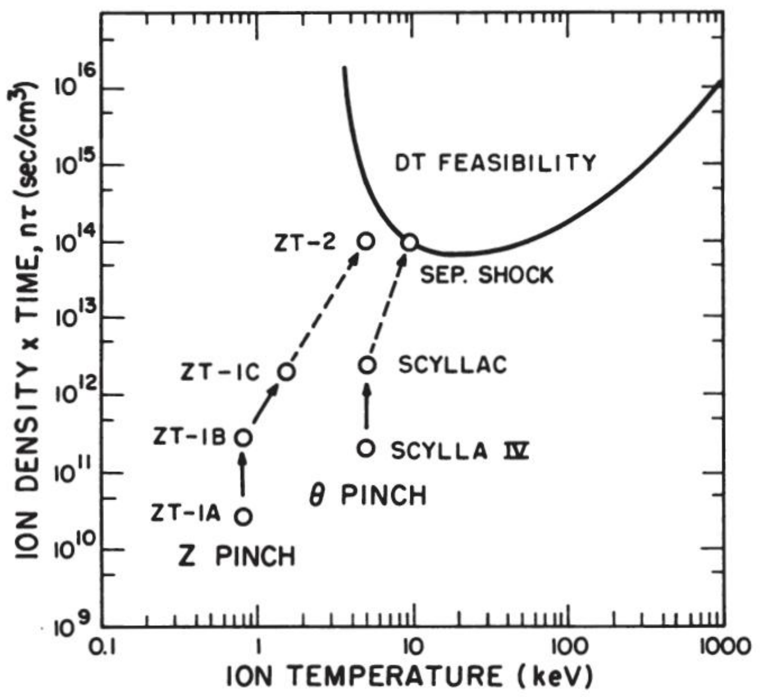


FIGURE 9.—Graph of the Lawson criterion for scientific feasibility, showing the relationship of present and projected θ- and Z-pinch experiments.

CONTROLLED THERMONUCLEAR RESEARCH

HEARINGS

BEFORE THE

SUBCOMMITTEE ON RESEARCH, DEVELOPMENT, AND RADIATION

OF THE

JOINT COMMITTEE ON ATOMIC ENERGY

CONGRESS OF THE UNITED STATES

NINETY-SECOND CONGRESS

FIRST SESSION

ON

THE CURRENT STATUS OF THE THERMONUCLEAR RESEARCH PROGRAM IN THE UNITED STATES

NOVEMBER 10 AND 11, 1971

Here's What Scientific Feasibility of Fusion Looks Like on a Graph

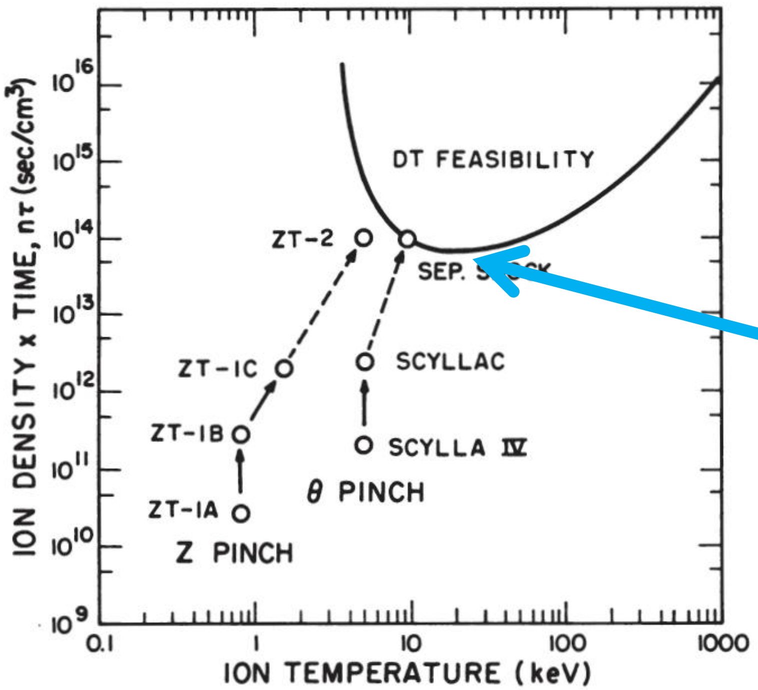


FIGURE 9.—Graph of the Lawson criterion for scientific feasibility, showing the relationship of present and projected θ- and Z-pinch experiments.

Here, scientists drew a curve, above which, are the minimum hypothetical parameters needed for "scientific feasibility" of DT fusion.

Note that the lowest part of the curve represents the intersection of the lowest values of temperature, density, and confinement time.

Achieving "scientific feasibility" in fusion does not mean that fusion is scientifically proven to be an energy source. It means only that one scientific prerequisite for fusion as an energy source has been accomplished.

Higher Temperature Does Not Necessarily Mean Greater Success

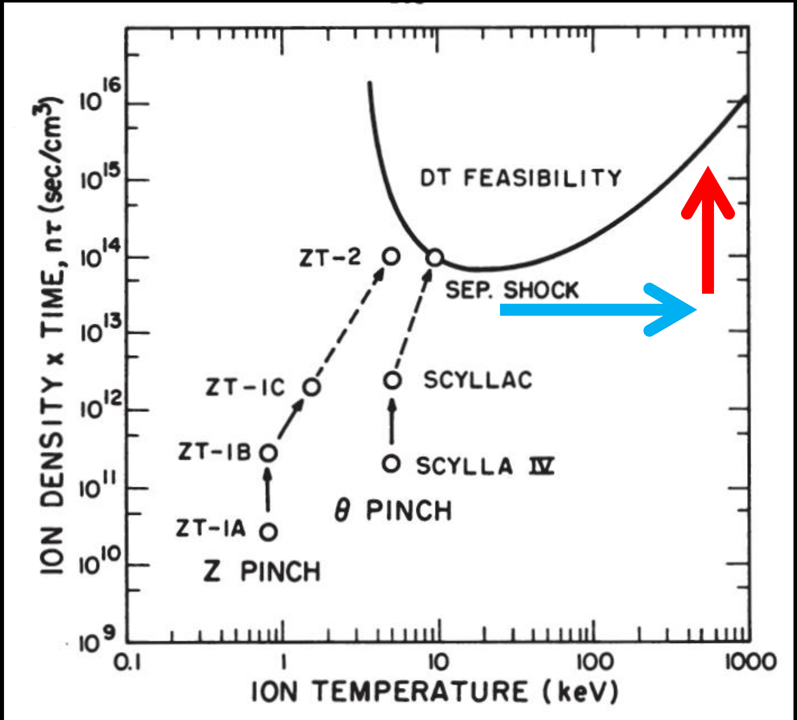


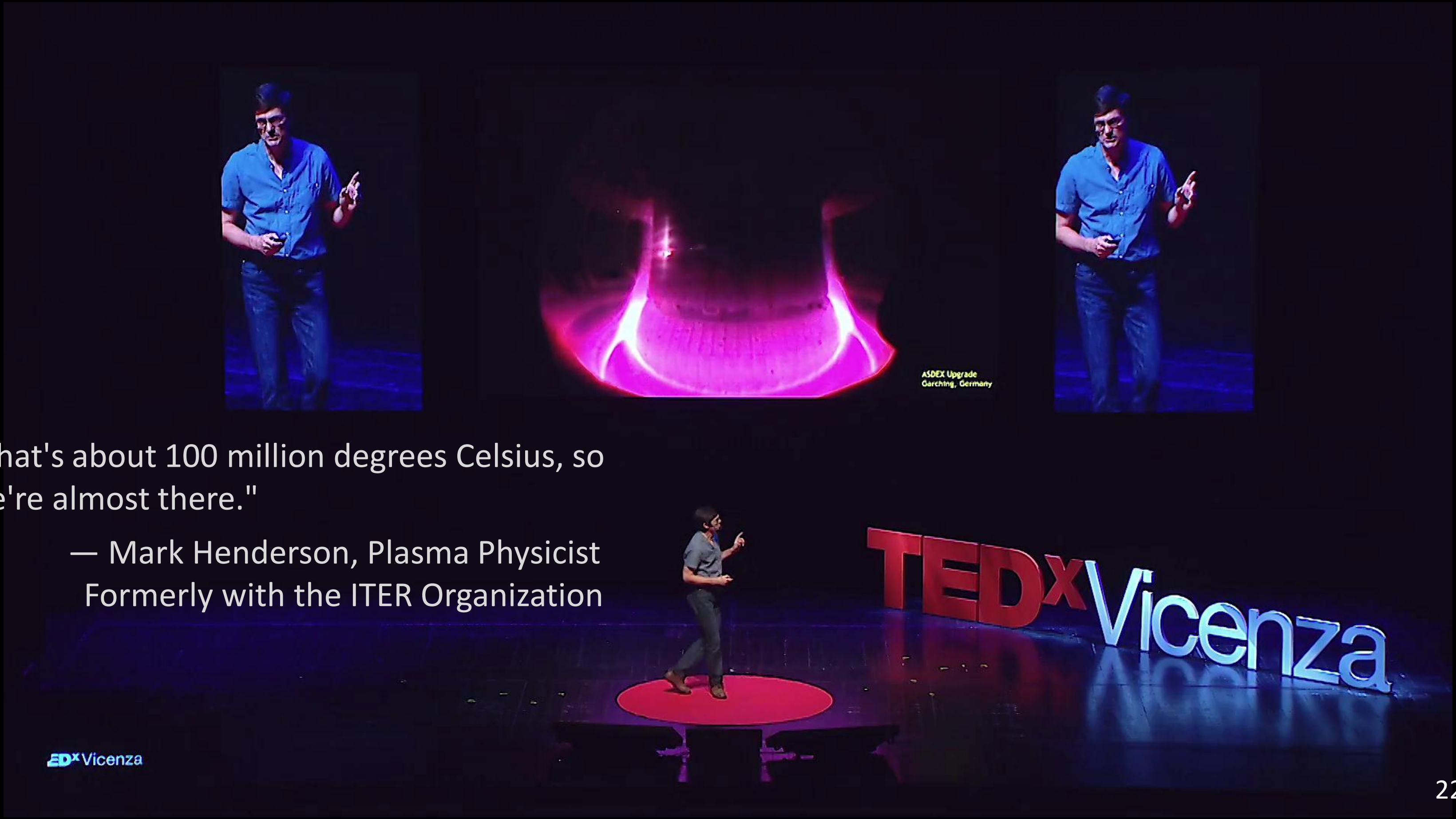
FIGURE 9.—Graph of the Lawson criterion for scientific feasibility, showing the relationship of present and projected θ- and Z-pinch experiments.

Another way to describe the bottom of this curve is a "sweet spot." An increase in temperature beyond the bottom of the curve is not helpful and is, in fact, counterproductive.

As temperature increases (blue arrow) beyond the bottom of the curve, the other two reaction parameters (red arrow) must be greater.

In other words, higher temperature does not necessarily mean greater success.

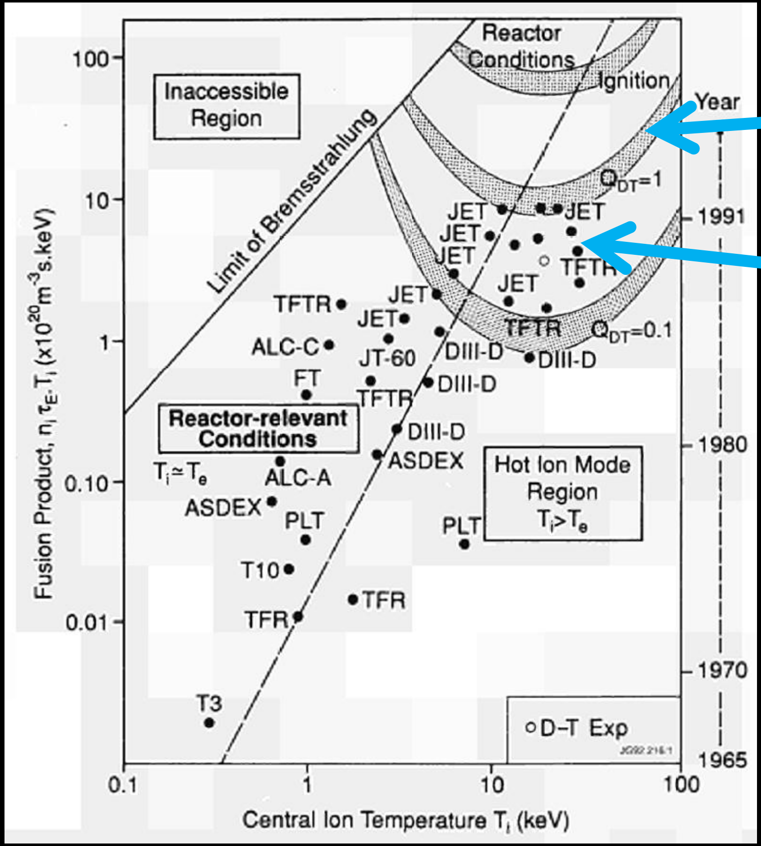
High Temperature Is Not Sufficient to Get There



"That's about 100 million degrees Celsius, so we're almost there."

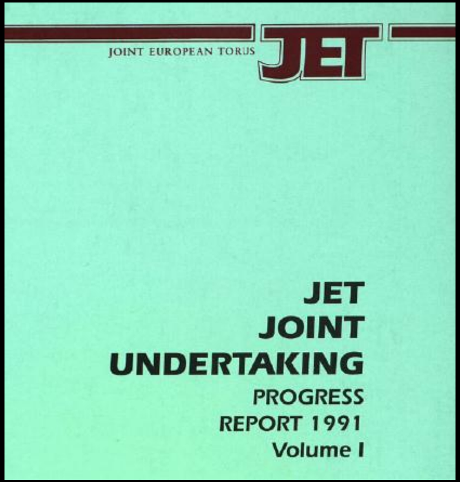
— Mark Henderson, Plasma Physicist
Formerly with the ITER Organization

Highest Triple-Product Results: TFTR and JET

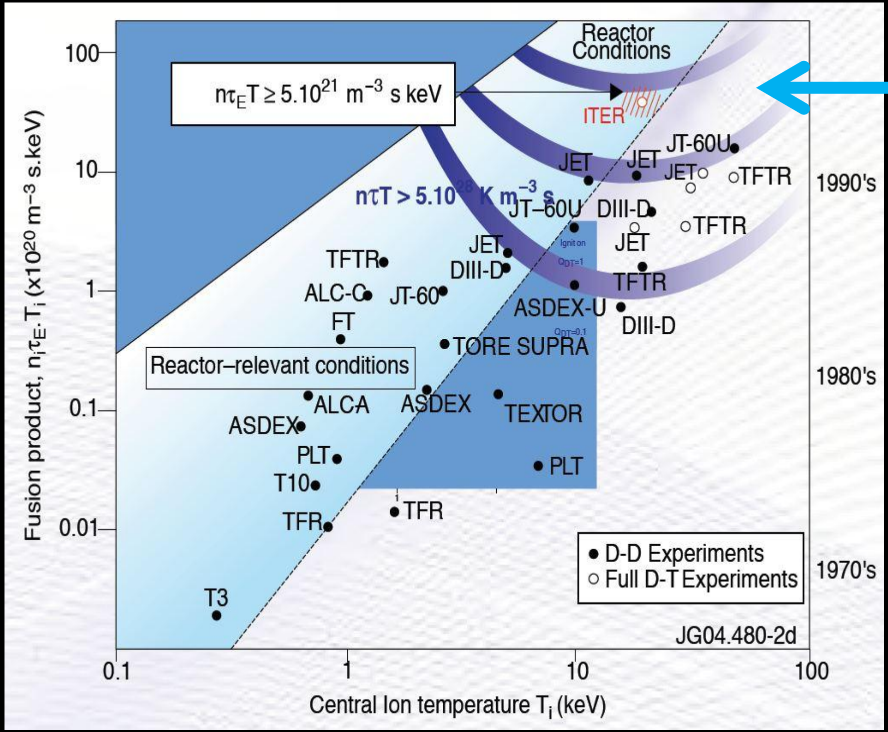


The confinement regime above the middle band is loosely correlated to 100% of scientific breakeven.

In the 1990s, scientists conducted experiments at TFTR and JET that came close to scientific breakeven.

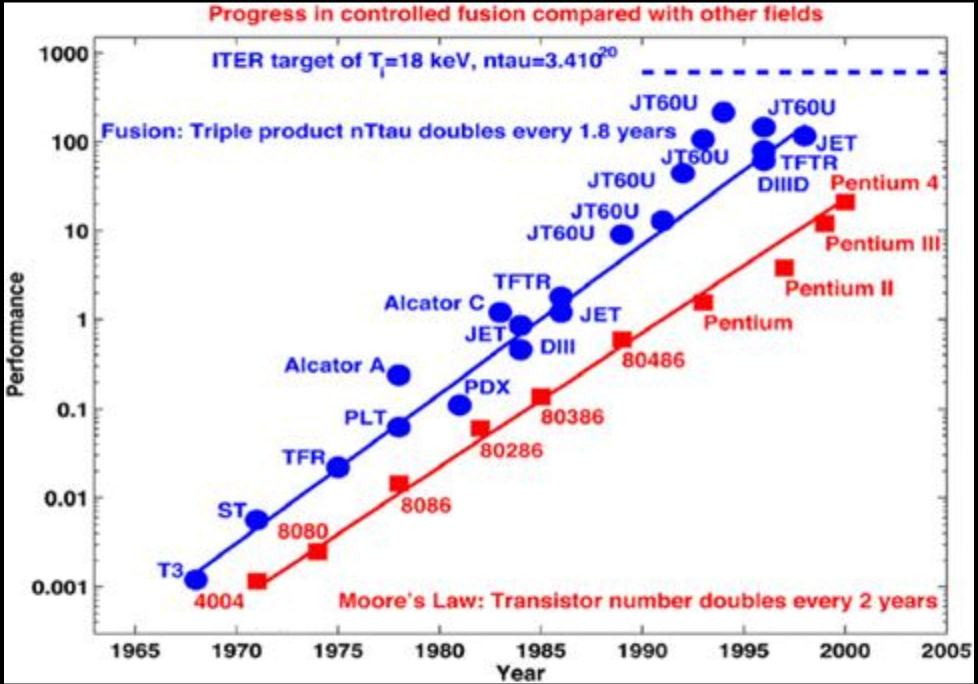


ITER Is Designed To Achieve and Exceed Scientific Breakeven



ITER is designed to go beyond scientific breakeven, up to 10 times scientific breakeven.

Comparison to Microprocessor Progress, Over Time



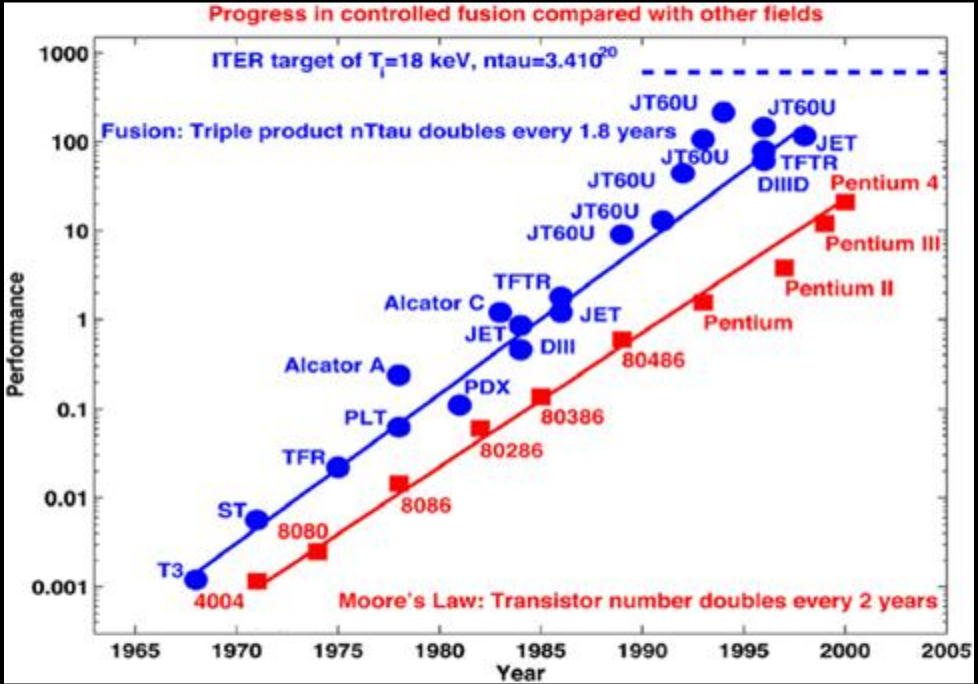
To show people the progress fusion scientists have made, they portray similarity in fusion progress to computer chip development.

This graph shows, for triple-product performance, a proportional increase in the increase of transistors on a single chip in semiconductors.

Note that all three fusion values are now combined on the vertical axis.

There are five problems with this comparison.

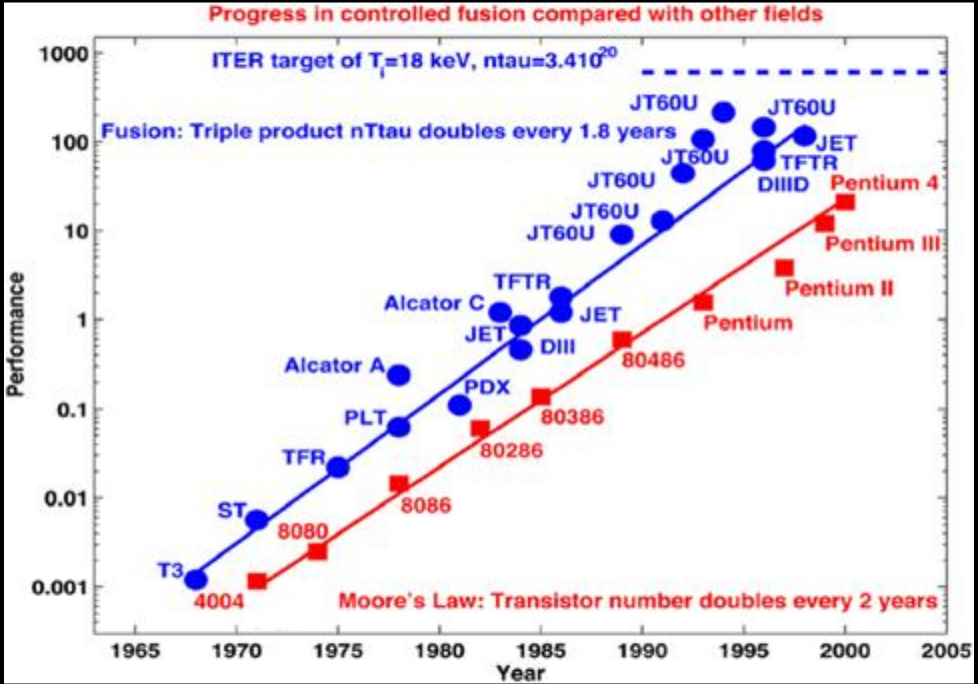
1. Microprocessors Do Something Useful



The first computer chip listed on this graph, the Intel 4004 CPU chip, was working technology and did something useful.

No fusion reactor has ever left the realm of science and entered the realm of technology, let alone doing something useful.

2. Triple-Product Values Do Not Measure Reactor Power Output

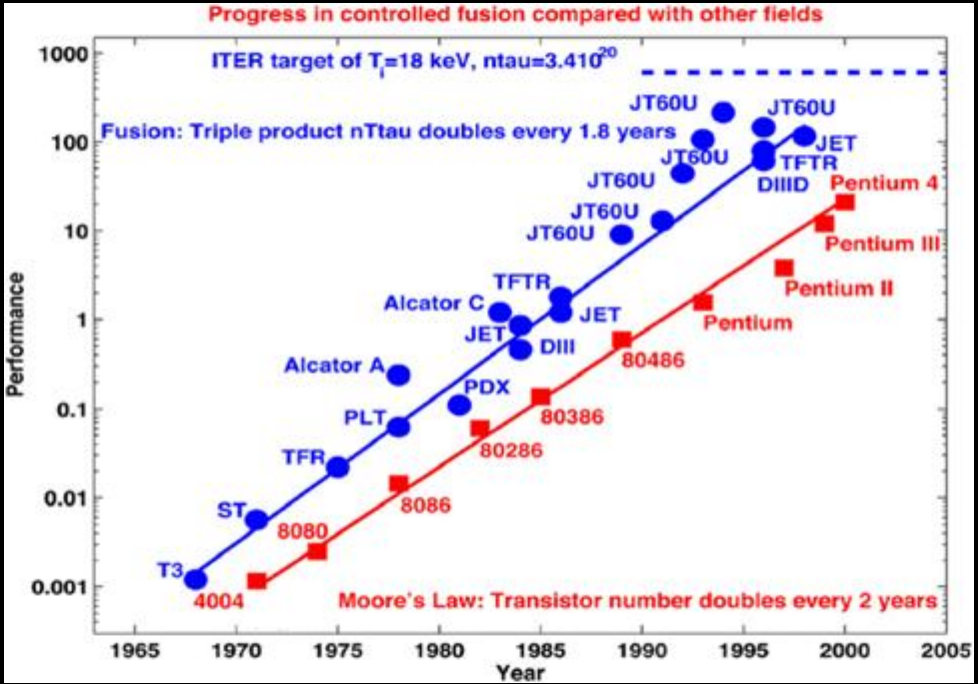


The triple-product components — temperature, plasma density, and confinement time — are measurements of the experimental parameters that have been achieved.

None of these is a measurement of reactor thermal output power.

The triple-product hypothesis may turn out to be predictive, but it is not evidence of reactor thermal output power.

3. Triple-Product Values Do Not Consider Reactor Power Input

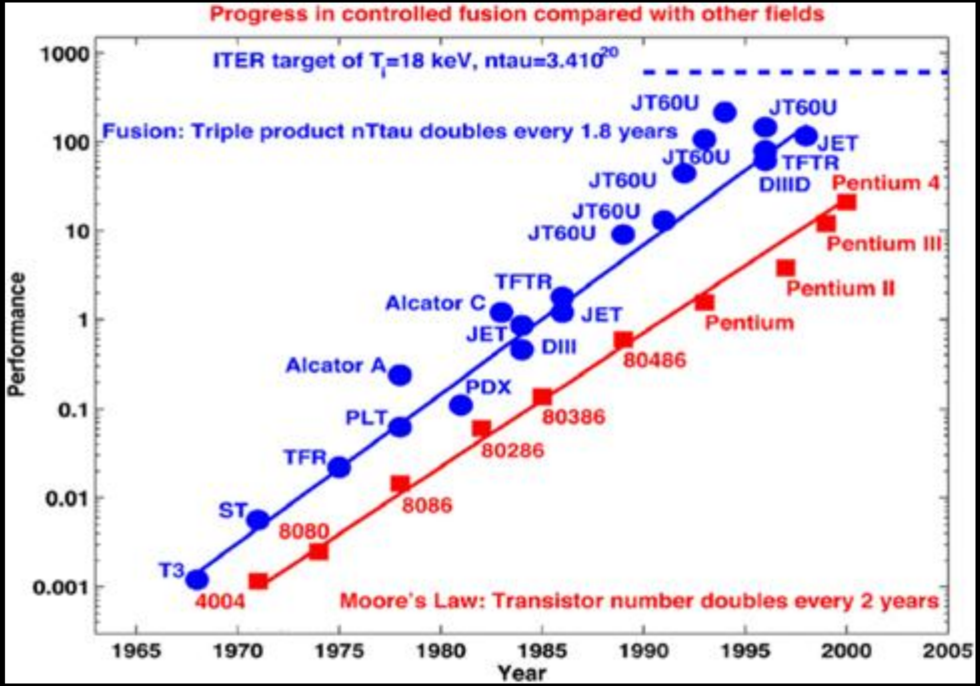


We want and expect useful rates of net power output from fusion reactors. This means we need to know the cost, in terms of input power, to the reactors.

Fusion scientists never compare triple-product values with reactor input values.

They do, however, compare triple-product values with gross reactor output power values, measured by the neutron flux. But without a correlation to *net reactor output*, triple-product values are not correlated to practical fusion energy.

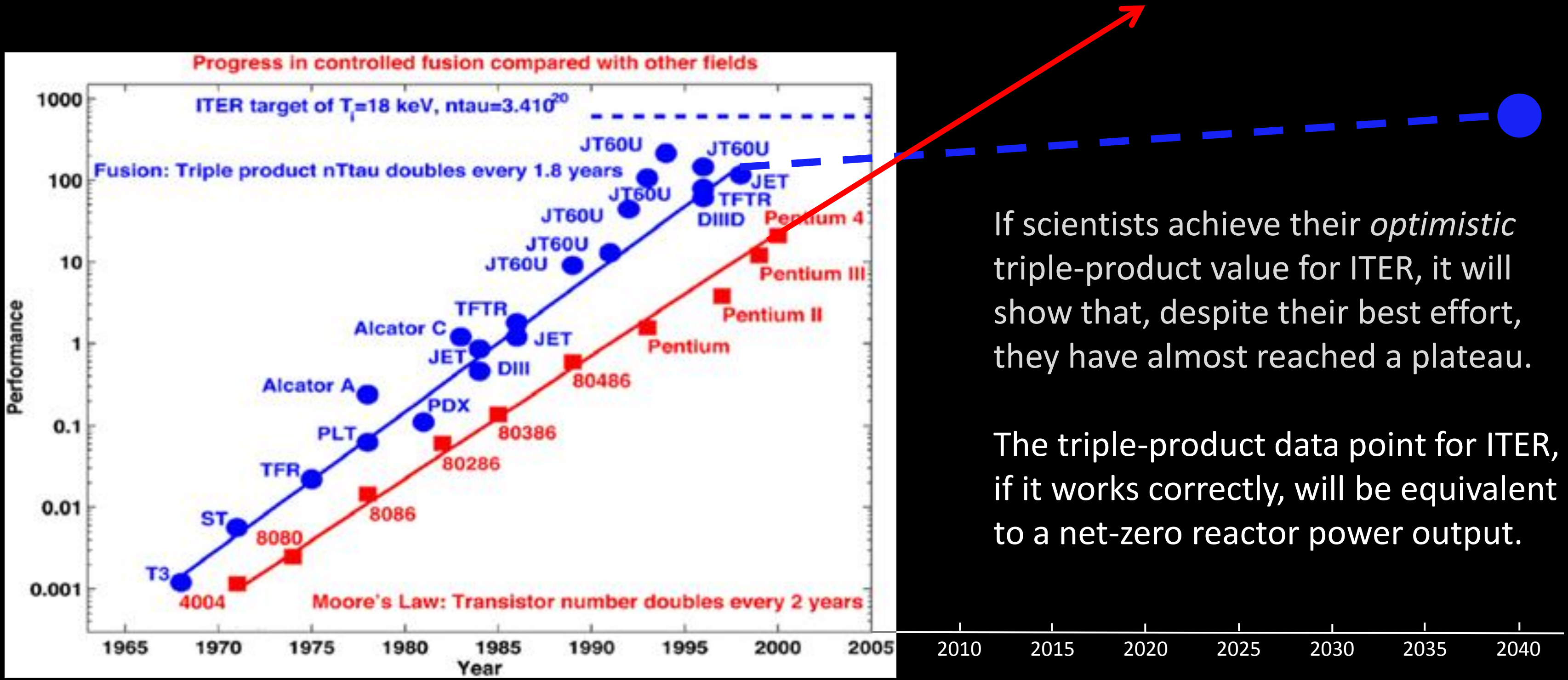
What's Missing?



There's something missing on this and other similar triple-product graphs.

Can you figure it out before seeing the next slide?

4. The Plateau



If scientists achieve their *optimistic* triple-product value for ITER, it will show that, despite their best effort, they have almost reached a plateau.

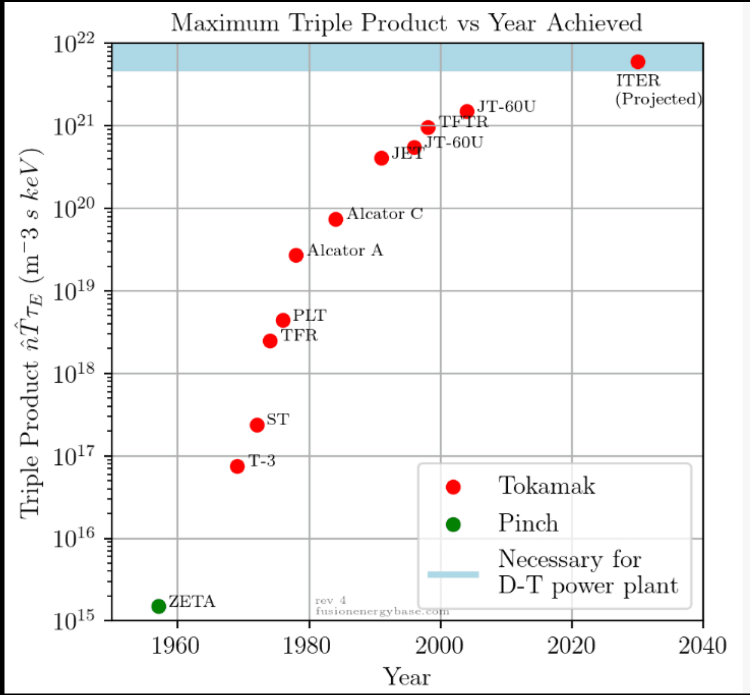
The triple-product data point for ITER, if it works correctly, will be equivalent to a net-zero reactor power output.

5. Lawson Said His Criteria Weren't Valid for Reactor Performance

The triple product value is just a prerequisite. Fusion scientists often forget a key phrase in Lawson's criteria:

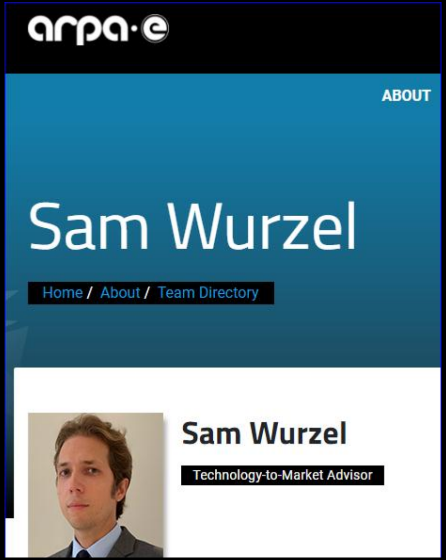
"The assumptions made are in all cases optimistic, so that the criteria established are certainly necessary, though by no means sufficient, for the successful operation of a thermonuclear reactor." — John D. Lawson

Wurzel's Omission: "Necessary [but Not Sufficient] for D-T Power Plant"



Instead of writing "reactor conditions" in the top corner of their graphs, some fusion advisors are describing this region as "Necessary for a DT Power Plant."

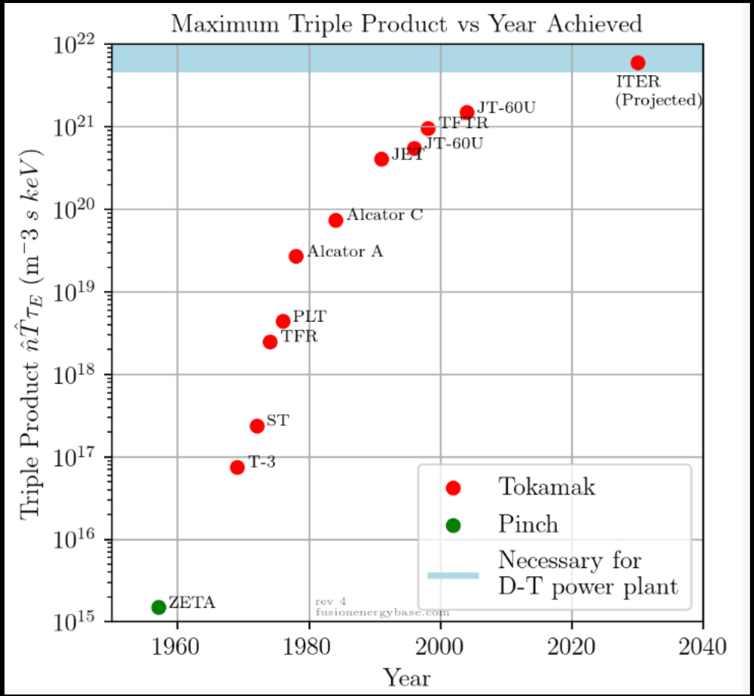
But ITER, as a zero-net-Watt reactor design, is not quite sufficient for a DT power plant.



There's another reason why this graph is likely to cause misunderstandings, particularly for investors —

Graph source: Sam Wurzel's Web site: fusionenergybase.com
"unbiased information to those, especially private investors, interested in fusion energy." (https://arxiv.org/abs/2105.10954v1)

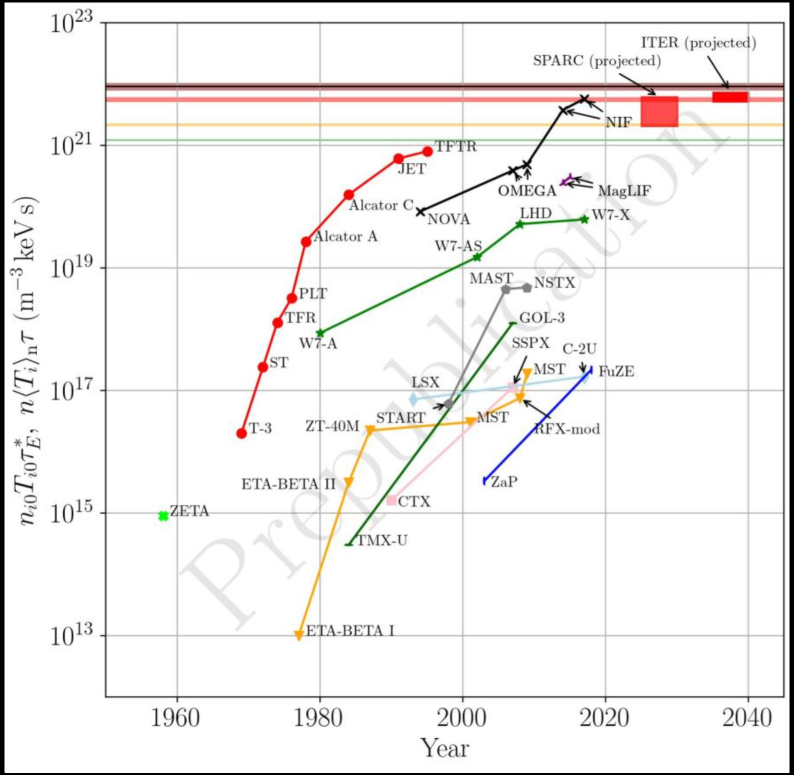
Wurzel Picked Only the Highest Values



The 10 data points on Wurzel's graph for tokamak reactors are not broadly representative of the fusion triple-product values.

Wurzel selected these points to represent only the highest values from 1970 to 1995 to show a trend line of *peak values*.

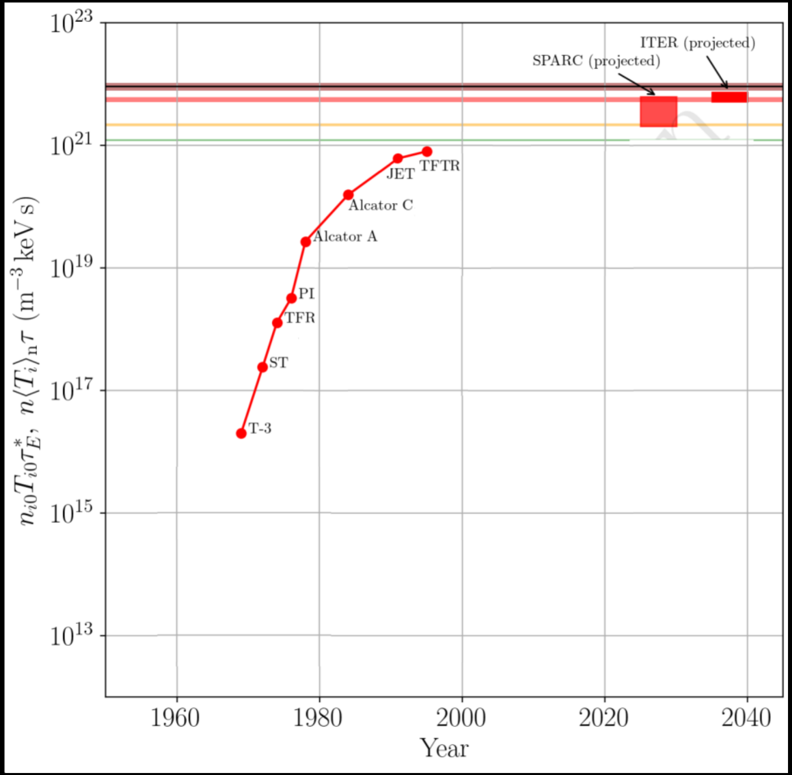
Wurzel Picked Only the Highest Values, Again



On May 23, 2021, Wurzel published a preprint of peak triple-product values from many fusion reactor types. The caption of his graph explains that these are values "that set a record for a given [reactor] concept vs. year achieved."

Wurzel, Samuel E., and Hsu, Scott C., https://arxiv.org/abs/2105.10954v1

A Closer Look at Wurzel's Triple-Product Graph



Each time an experiment is performed in a fusion reactor, it's called a plasma shot.

I removed all the shots from Wurzel's 2021 graph except those from tokamak reactors.

In his preprint, Wurzel lists 30 tokamak plasma shots from 1969 to 2019. But he chose to display only eight here.

These eight plasma shots span the years from only 1969 to 1995.

The following slide, a table from Wurzel's preprint, contains a more complete list of values from 1969 to 2019.

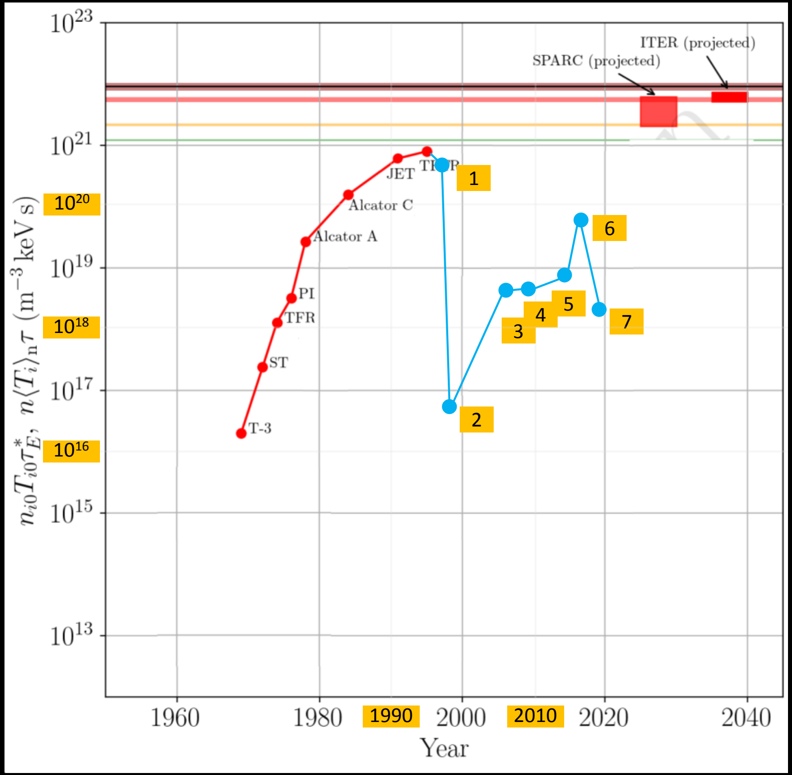
Table 2 Data for tokamaks, spherical tokamaks, and stellarators.

Project	Concept	Year	Shot Identifier	Citation	T_{i0} (keV)	T_{e0} (keV)	n_{i0} (m^{-3})	n_{e0} (m^{-3})	τ_E^* (s)	$n_{i0}\tau_E^*$ ($\mathrm{m}^{-3}\,\mathrm{s}$)	$n_{i0}T_{i0}\tau_E^*$ ($\mathrm{keV\,m}^{-3}\,\mathrm{s}$)
T-3	Tokamak	1969	Unknown	[19,20,21]	0.3	1.05	$2.25 \times 10^{19\ddagger}$	2.25×10^{19}	0.003	6.8×10^{16}	2.0×10^{16}
ST	Tokamak	1972	Unknown	[22]	0.4	0.8	$6 \times 10^{19\ddagger}$	6×10^{19}	0.01	6.0×10^{17}	2.4×10^{17}
TFR	Tokamak	1974	Molybdenum limiter	[23]	0.95	1.8	$7.1 \times 10^{19\ddagger}$	7.1×10^{19}	0.019	1.3×10^{18}	1.3×10^{18}
PLT	Tokamak	1976	22149-231	[24]	1.54	1.86	$5.2 \times 10^{19\ddagger}$	5.2×10^{19}	0.04	2.1×10^{18}	3.2×10^{18}
Alcator A	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.7 \times 10^{19}$
W7-A	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.6 \times 10^{17}$
TFR	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.2 \times 10^{18}$
TFR	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.1 \times 10^{18}$
Alcator C	Tokamak	1984	Unknown	[27]	1.5	1.5	2×10^{21}	2×10^{21}	0.052	1.0×10^{20}	1.6×10^{20}
JET	Tokamak	1991	26087	[28]	18.6	10.5	4.1×10^{19}	5.1×10^{19}	0.8#	3.3×10^{19}	6.1×10^{20}
JET	Tokamak	1991	26095	[28]	22.0	11.9	3.4×10^{19}	4.5×10^{19}	0.8#	2.7×10^{19}	6.0×10^{20}
JET	Tokamak	1991	26148	[28]	18.8	9.9	2.4×10^{19}	3.6×10^{19}	0.6#	1.4×10^{19}	2.7×10^{20}
JT-60U	Tokamak	1994	17110	[29]	37.0	12.0	4.2×10^{19}	5.5×10^{19}	0.3#	1.3×10^{19}	4.7×10^{20}
TFTR	Tokamak	1995	83546	[30]	43.0	12.0	6.6×10^{19}	8.5×10^{19}	0.28#	1.8×10^{19}	7.9×10^{20}
TFTR	Tokamak	1995	80539	[30]	36.0	13.0	6.7×10^{19}	1.02×10^{20}	0.17#	1.1×10^{19}	4.1×10^{20}
TFTR	Tokamak	1995	68522	[30]	29.0	11.7	6.8×10^{19}	9.6×10^{19}	0.18#	1.2×10^{19}	3.5×10^{20}
TFTR	Tokamak	1995	76778	[30]	44.0	11.5	6.3×10^{19}	8.5×10^{19}	0.19#	1.2×10^{19}	5.3×10^{20}
JT-60U	Tokamak	1996	E26949	[31]	35.5	11.0	4.3×10^{19}	5.85×10^{19}	0.28#	1.2×10^{19}	4.3×10^{20}
JT-60U	Tokamak	1996	E26939	[31]	45.0	10.6	4.35×10^{19}	6×10^{19}	0.26#	1.1×10^{19}	5.1×10^{20}
JET	Tokamak	1997	42976	[32]	28.0	14.0	3.3×10^{19}	4.1×10^{19}	0.51#	1.7×10^{19}	4.7×10^{20}
DIII-D	Tokamak	1997	87977	[33]	18.1	7.5	8.5×10^{19}	1×10^{20}	0.24#	2.0×10^{19}	3.7×10^{20}
JT-60U	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.6 \times 10^{20}$
START	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.1 \times 10^{16}$
W7-AS	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.5 \times 10^{19}$
HSX	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	$.8 \times 10^{14}$
MAST	Spherical Tokamak	2006	14626	[38]	3.0	2.0	$3 \times 10^{19\ddagger}$	3×10^{19}	0.05	1.5×10^{18}	4.5×10^{18}
LHD	Stellarator	2008	High triple product	[39]	0.47	0.47	$5 \times 10^{20\ddagger}$	5×10^{20}	0.22	1.1×10^{20}	5.2×10^{19}
NSTX	Spherical Tokamak	2009	129041	[40]	1.2	1.2	$5 \times 10^{19\ddagger}$	5×10^{19}	0.08	4.0×10^{18}	4.8×10^{18}
KSTAR	Tokamak	2014	7081	[41]	2.0	–	$4.80 \times 10^{19\ddagger *}$	–	0.1	4.8×10^{18}	9.6×10^{18}
EAST	Tokamak	2015	41079	[42]	$1.2^{\dagger}$	1.2	$2 \times 10^{19\ddagger}$	2×10^{19}	0.04	8.0×10^{17}	9.6×10^{17}
ASDEX-U	Tokamak	2016	33237	[43]	$0.6^{\dagger}$	0.6	$1.3 \times 10^{20\ddagger}$	1.3×10^{20}	0.072	9.4×10^{18}	5.6×10^{18}
C-Mod	Tokamak	2016	1160930042	[44]	$6.0^{\dagger}$	6.0	$2 \times 10^{20\ddagger}$	2×10^{20}	0.054	1.1×10^{19}	6.5×10^{19}
C-Mod	Tokamak	2016	1160930033	[44]	$2.5^{\dagger}$	2.5	$5.5 \times 10^{20\ddagger}$	5.5×10^{20}	0.054	3.0×10^{19}	7.4×10^{19}
W7-X	Stellarator	2017	W7X 20171207.006	[45,46,47]	3.5	3.5	$8 \times 10^{19\ddagger}$	8×10^{19}	0.22	1.8×10^{19}	6.2×10^{19}
Globus-M2	Spherical Tokamak	2019	37873	[48]	1.2	–	$1.19 \times 10^{20\ddagger *}$	–	0.01	1.2×10^{18}	1.4×10^{18}

Wurzel Selected 8 Plasma Shots From Among These

Wurzel Selected No Plasma Shots From Among These

If Wurzel Continued Picking the Highest Yearly Values —



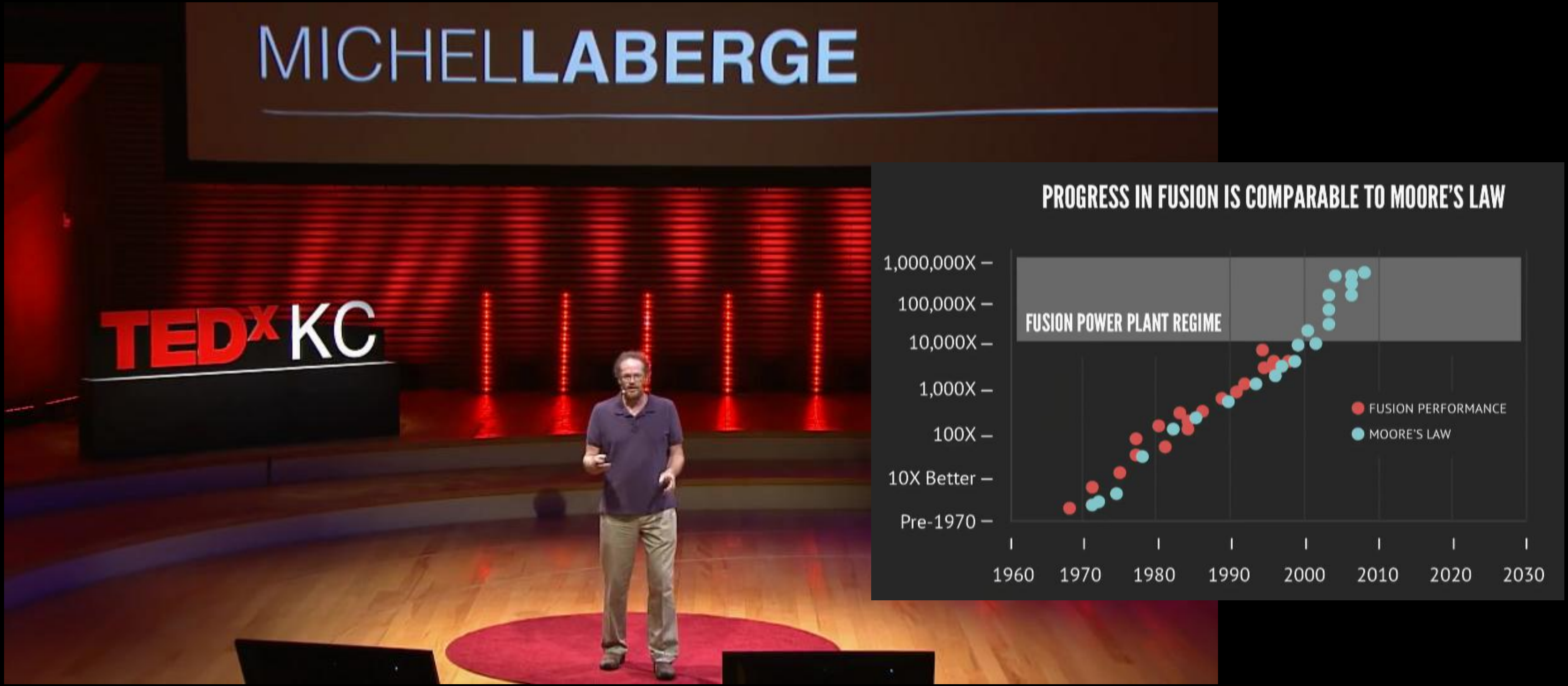
— this is what the data would look like.

RED: Wurzel's values and curve.
BLUE: Values and curve added by Krivit.
ORANGE: Labels added by Krivit
SOURCE DATA: Wurzel's preprint:
https://arxiv.org/abs/2105.10954v1

1. 1997 (JET) / SHOT 42976 / TP 4.7 × 10^20
2. 1998 (START) / SHOT 35533 / TP 6.1 × 10^16
3. 2006 (MAST) / SHOT 14626 / TP 4.5 × 10^18
4. 2009 (NSTX) / SHOT 129041 / TP 4.8 × 10^18
5. 2014 (KSTAR) / SHOT 7081 / TP 9.6 × 10^18
6. 2016 (C-Mod) / SHOT 1160930033 / TP 7.4 × 10^19
7. 2019 (Globus-M2) / SHOT 37873 / TP 1.4 × 10^18

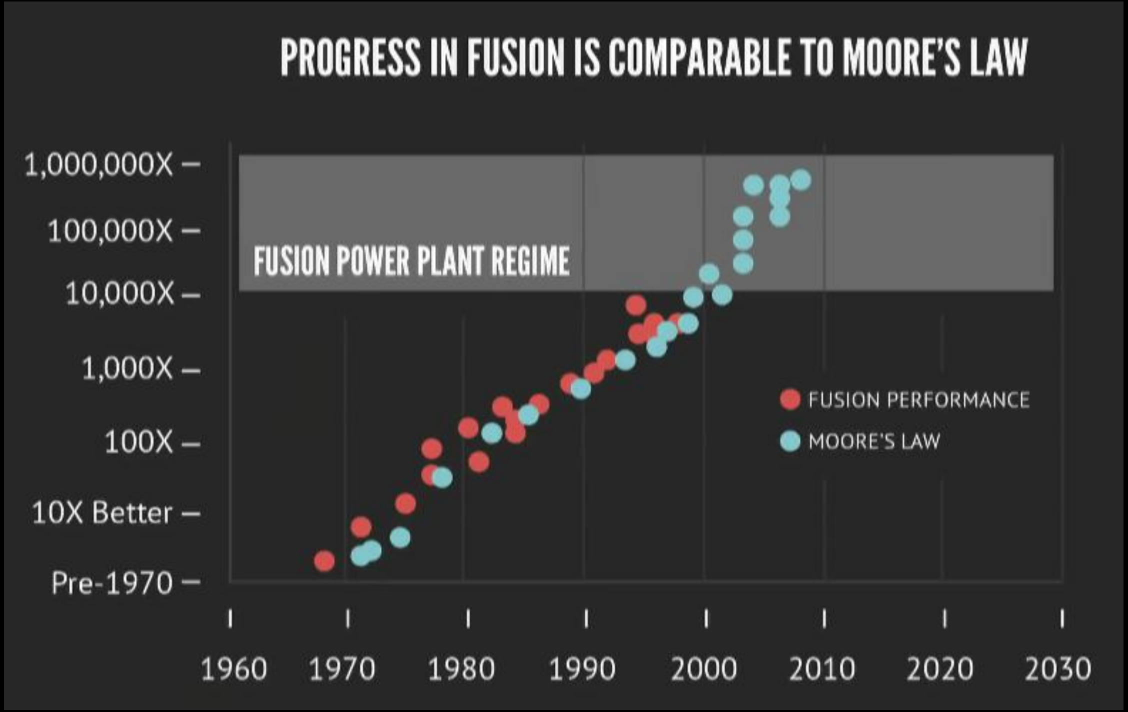
There were additional values for some years, but I couldn't put them in without overlapping data points.

Michel Laberge, Founder of General Fusion Inc.



No, Triple Product Value Alone Is Not Sufficient "To Do Energy."

No, ITER will not really make power.



Laberge: "As you can see, we improved the fusion by 10,000, so we're almost there. We're pretty close to this sort of big square at the top. That is enough to do energy. When [ITER] comes online, it will produce 500 megawatts of power with only 50 megawatts of heating, so this one will really make power."

His statement was likely to cause misunderstandings, particularly among his investors.

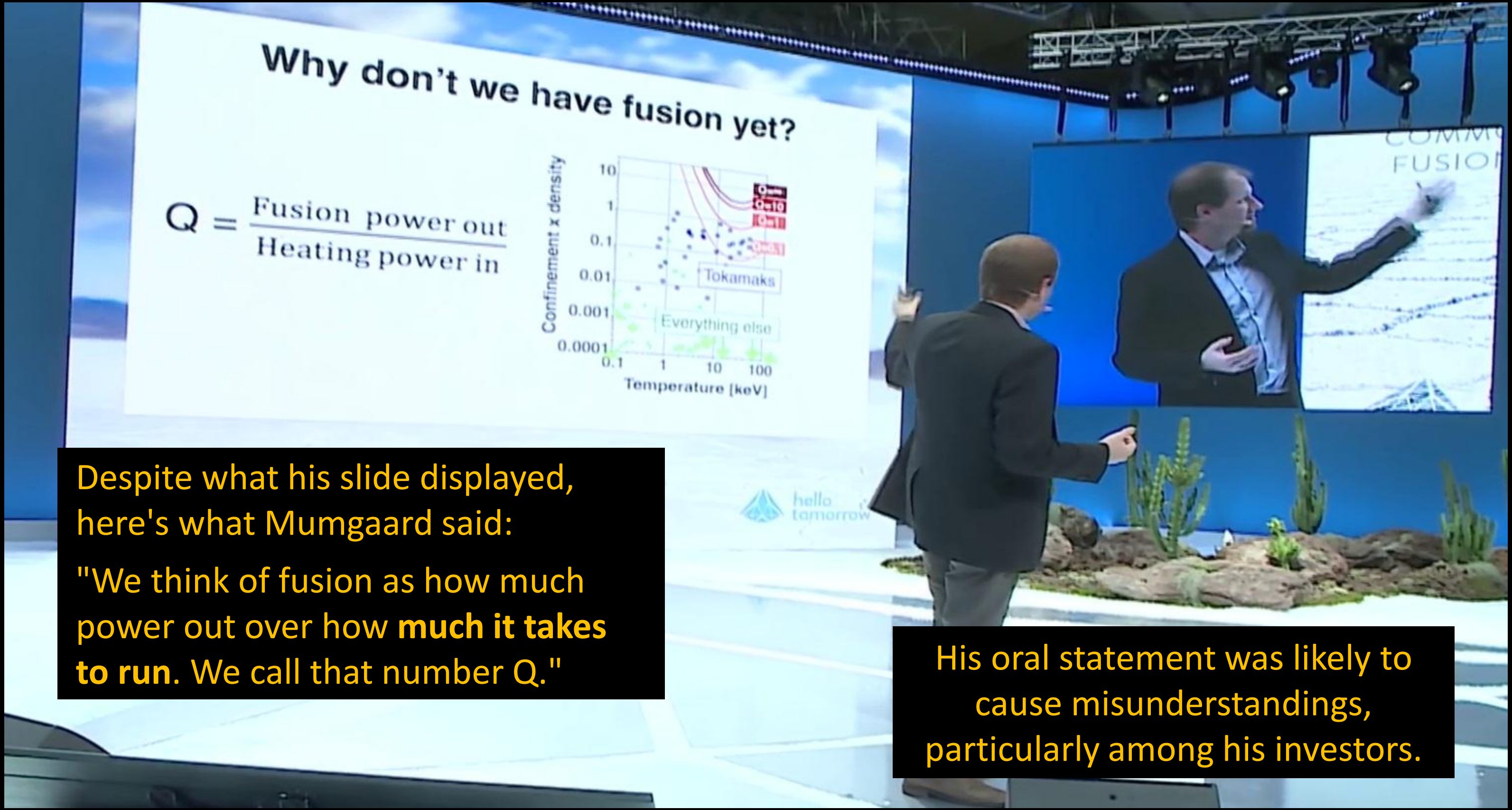
ITER will require at least 300 MW of electricity, which is equivalent to 750 MW of thermal power. Thus, the net reactor output will be equivalent to less than zero Watts.

Bob Mumgaard — CEO of Commonwealth Fusion Systems

After 43 years of fusion research at the Massachusetts Institute of Technology on its Alcator series fusion reactors, the U.S. government terminated funding in 2016, and MIT was unable to continue operating an experimental fusion reactor.

To stay in the fusion game, the MIT fusion group formed a partnership with CFS, which brought in private investors.

What Mumgaard Said vs. What He Showed

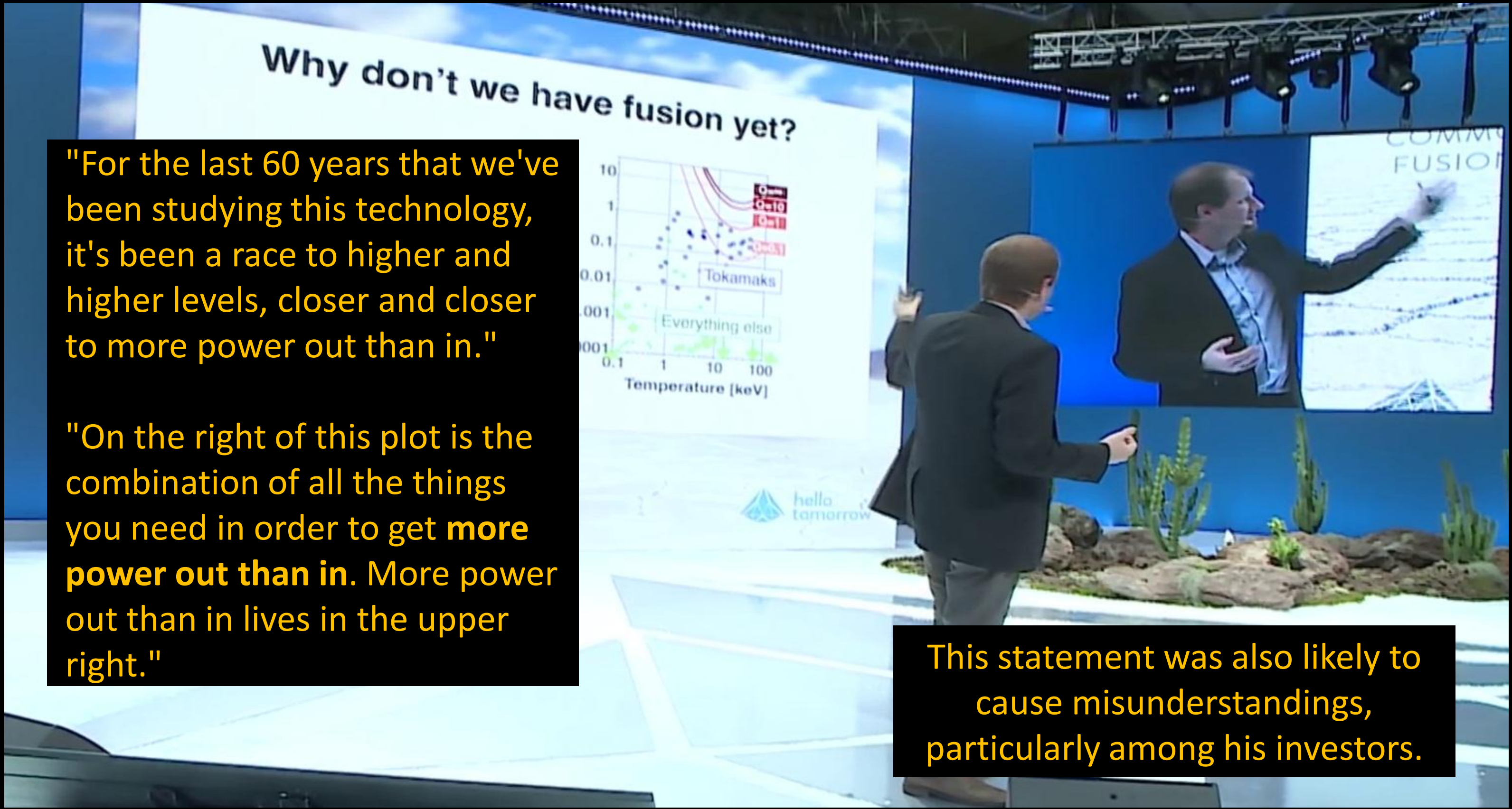


Despite what his slide displayed, here's what Mumgaard said:

"We think of fusion as how much power out over how **much it takes to run**. We call that number Q."

His oral statement was likely to cause misunderstandings, particularly among his investors.

Mumgaard Omitted Operating Power Requirements



"For the last 60 years that we've been studying this technology, it's been a race to higher and higher levels, closer and closer to more power out than in."

"On the right of this plot is the combination of all the things you need in order to get **more power out than in**. More power out than in lives in the upper right."

This statement was also likely to cause misunderstandings, particularly among his investors.

Fusion Energy Progress As Reported By the U.S. Dept. of Energy's Princeton Plasma Physics Laboratory

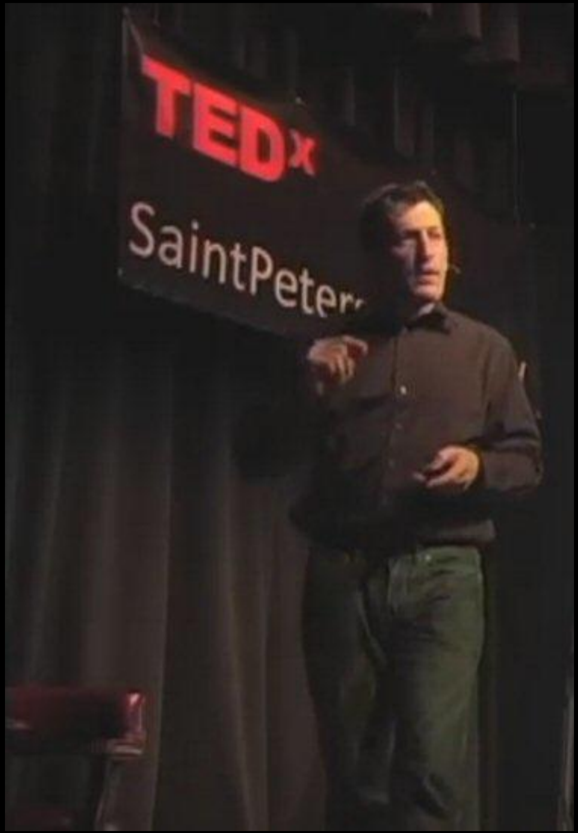
Representatives of the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL), operated by Princeton University, have their own, unique method of describing progress in nuclear fusion research.

I have not listed this method of measuring progress with the other methods because the Princeton method suffers from a complete lack of scientific credibility and scientific integrity.

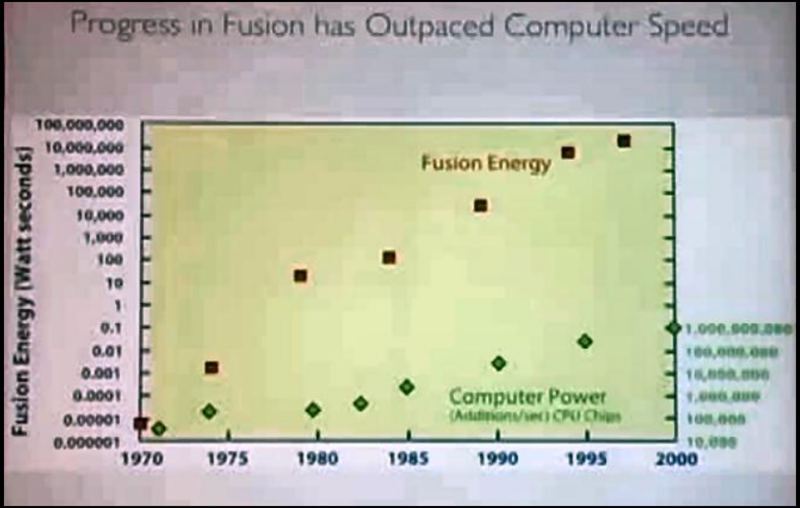
Fusion Energy Progress — According to Andrew Zwicker

In 2013, physicist Andrew Zwicker gave a TED talk at Saint Peters' University, in New Jersey. At the time, he was the head of the Science Education Department at Princeton Plasma Physics Laboratory.

He is now also the head of public relations for PPPL and a New Jersey state senator.



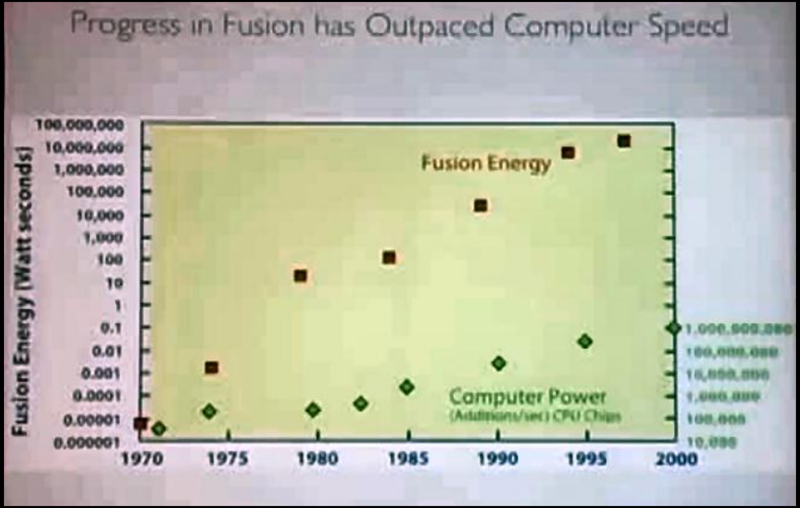
Fusion Energy Progress — According to Andrew Zwicker



Here's what Zwicker said:

"If we look at how much fusion energy we're making, with all of these machines, not just the ones that I'm showing you but all the other machines that are being built that have experiments running all over the world, what you see is that the amount of fusion energy over time has increased by 100 billion times. And I've compared that to how fast our computers are going. You see that fusion is proceeding at a pace even faster than how fast all of our computer chip manufacturing is going."

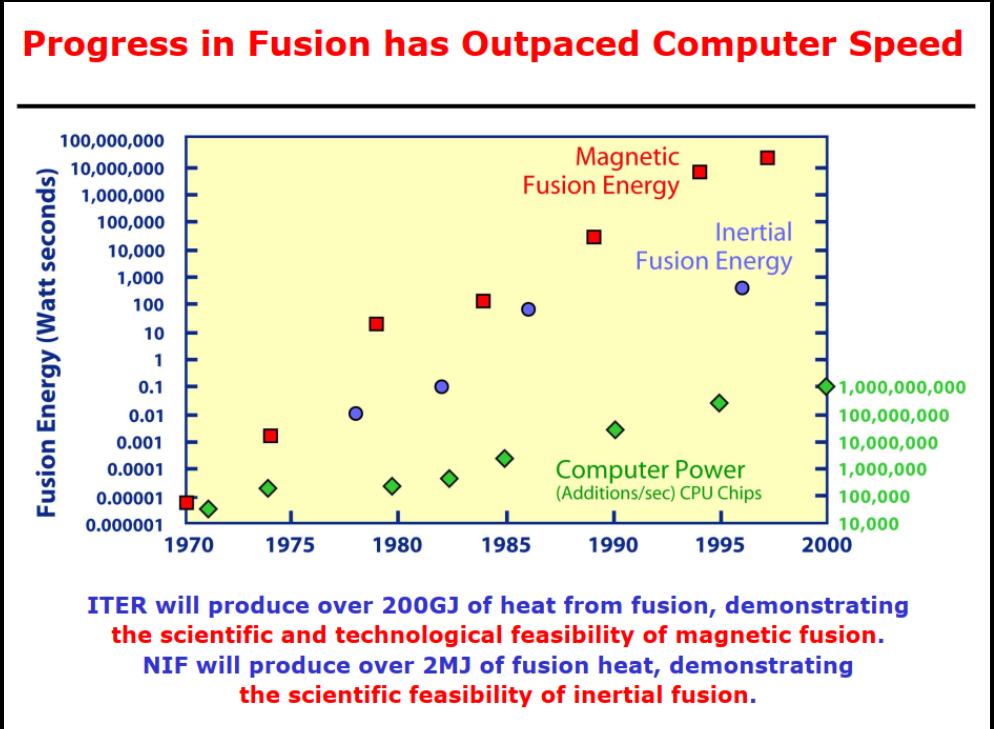
Fusion Energy Progress — According to Princeton Lab Representatives



This graph has been used repeatedly by executive-level representatives of the Princeton laboratory.

A quick Internet search turns up two such instances, along with higher-quality versions of the graph.

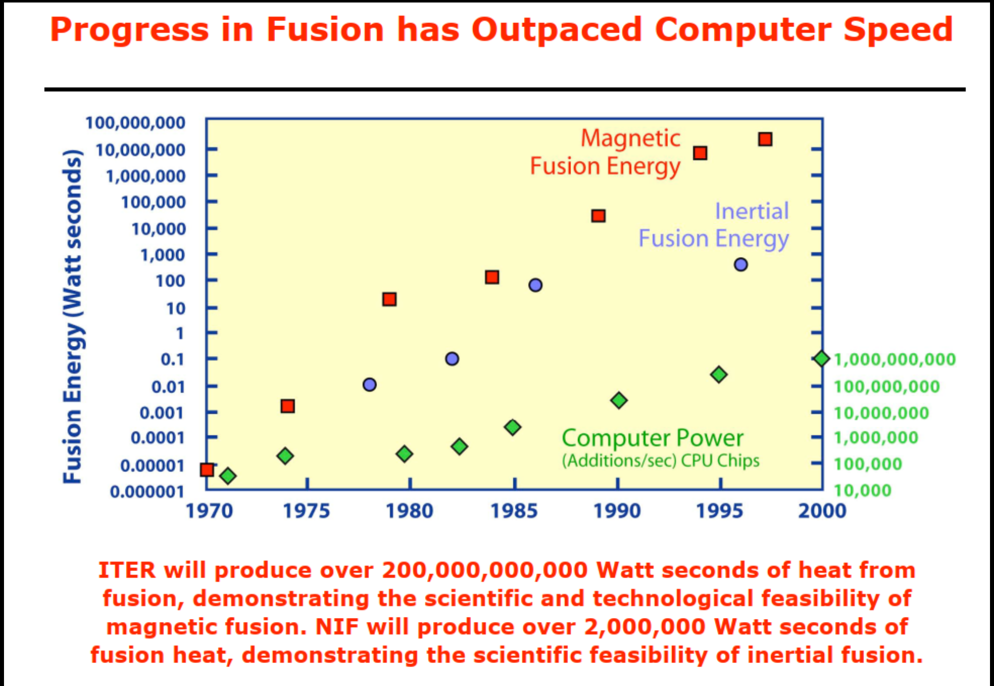
Fusion Energy Progress — According to Richard Hawryluk



Richard Hawryluk, the deputy director of the lab, used the graph in 2006 when he made a presentation at the NERSC Users' Group.

The National Energy Research Scientific Computing Center (NERSC) users' group is developed and maintained under the auspices of the Office of Science, U. S. Department of Energy.

Fusion Energy Progress — According to Robert Goldston

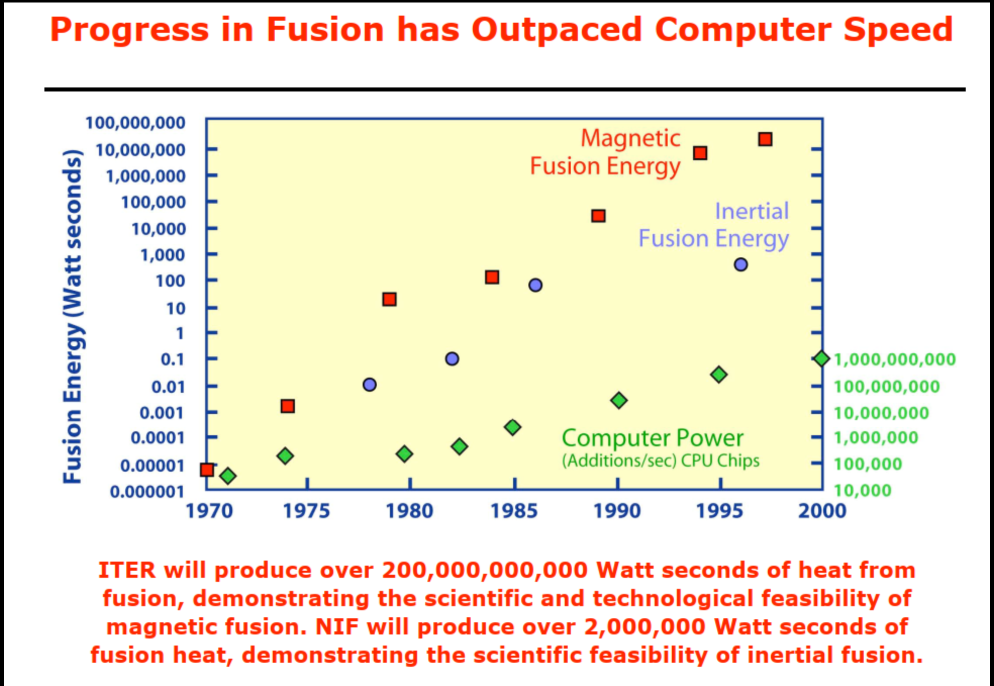


But the metadata on Hawryluk's file, as well as another instance of the graph, indicate that the author was Robert Goldston, the sixth director of the Princeton laboratory.

On Dec. 7, 2005, Goldston displayed the graph to attendees at a U.S. Congressional Research and Development Caucus meeting.

By doing so, Goldston had the opportunity to guide the fusion messaging provided to members of Congress.

Fusion Energy Progress — According to Robert Goldston



But what are the data points on Goldston's graph for magnetic fusion energy research?

What do the two red squares in the upper-right corner, appearing at 1994 and 1997, represent?

It's easy to figure out by looking at a graph presented by Stewart Prager.

Fusion Energy Progress — According to Stewart Prager

The path to magnetic fusion energy

from physics to energy

Stewart Prager

Princeton Plasma Physics Laboratory

U.S. DEPARTMENT OF ENERGY

PRINCETON UNIVERSITY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Stewart Prager was the seventh director of the Princeton laboratory.

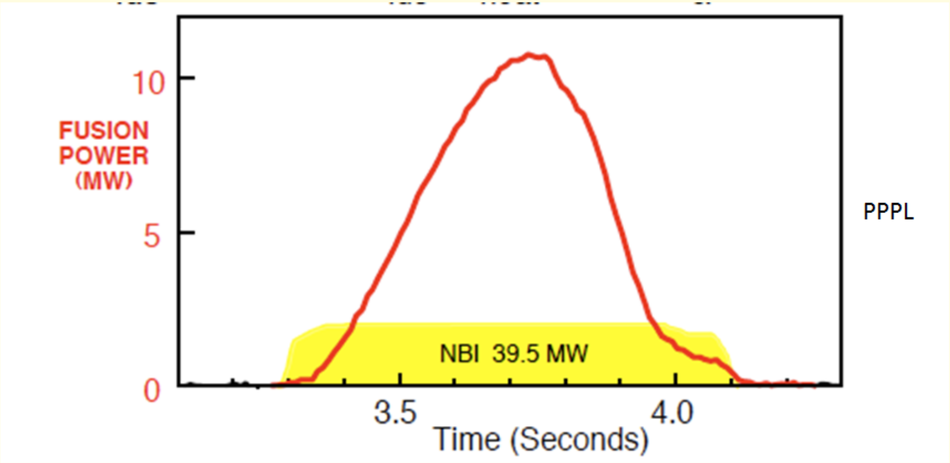
He displayed a graph on Aug. 3, 2011, at a meeting of the American Security Project in conjunction with the U.S. House Research and Development Caucus.

It provided another opportunity to guide the fusion messaging going to members of Congress.

Fusion Energy Progress — According to Stewart Prager

We have produced fusion energy

10 MW in 1994



1997: 16 MW produced in JET (UK)

Prager told the meeting attendees, "We have produced fusion energy."

He said that the Princeton TFTR reactor produced 10 megawatts in 1994 and the Joint European Torus (JET) reactor produced 16 megawatts in 1997.

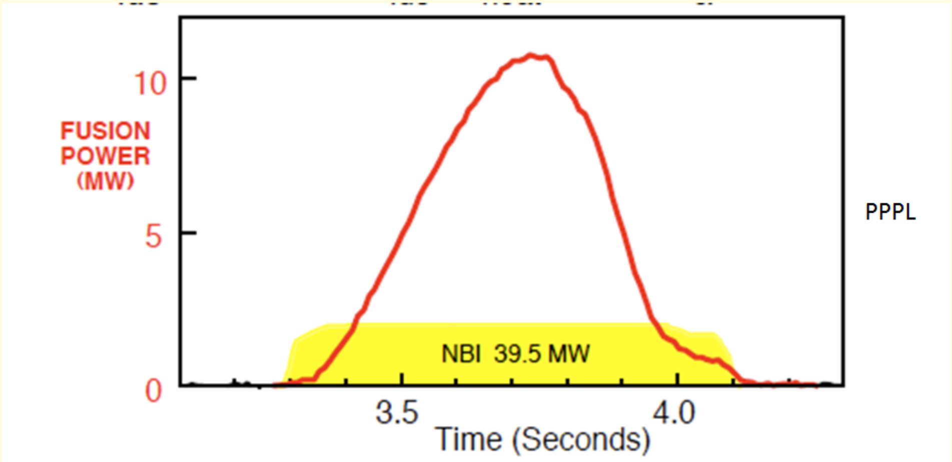
But Prager didn't say anything in his slides about the electrical input power those reactors consumed:

TFTR: 950 megawatts
JET: 700 megawatts

Fusion Energy Progress — According to Stewart Prager

We have produced fusion energy

10 MW in 1994

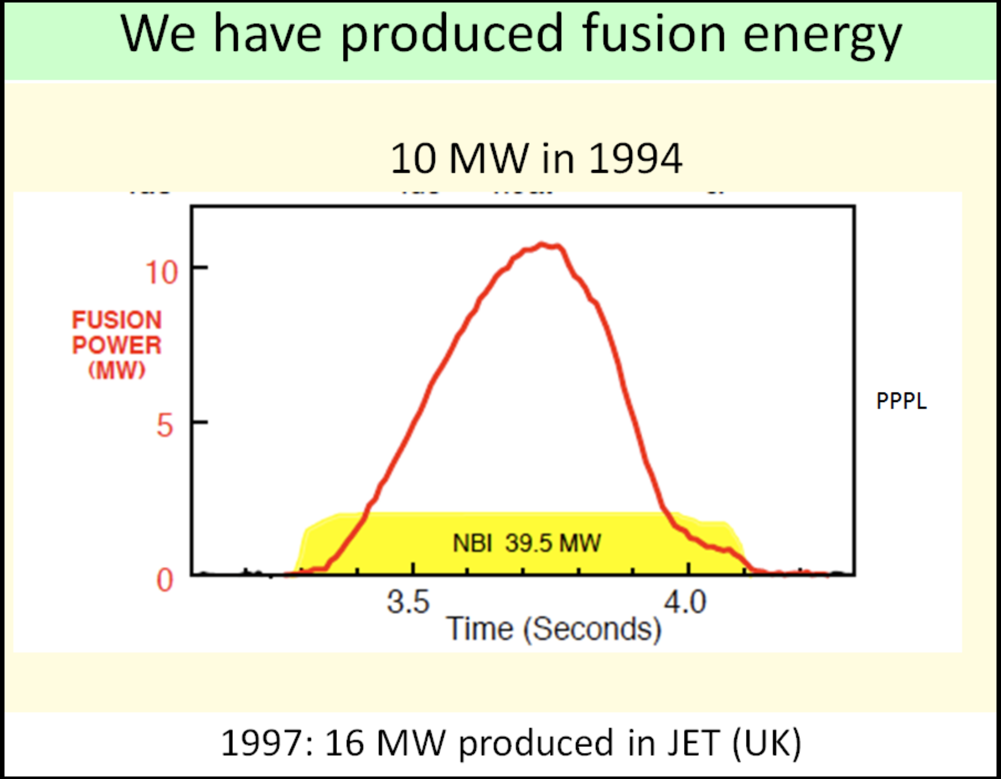


1997: 16 MW produced in JET (UK)

Prager told the meeting attendees that the Princeton TFTR reactor produced 10 megawatts in 1994.

The graph shows that TFTR sustained the 10 MW level for a tenth of a second. If we round it up to 1 second, that gives us the data point in Goldston's graph at 10,000,000 Watt-seconds.

Three Unscientific Aspects of Stewart Prager's Graph



1. He did not define in his slides, intended for an audience of non-experts, the special meaning of "fusion power."

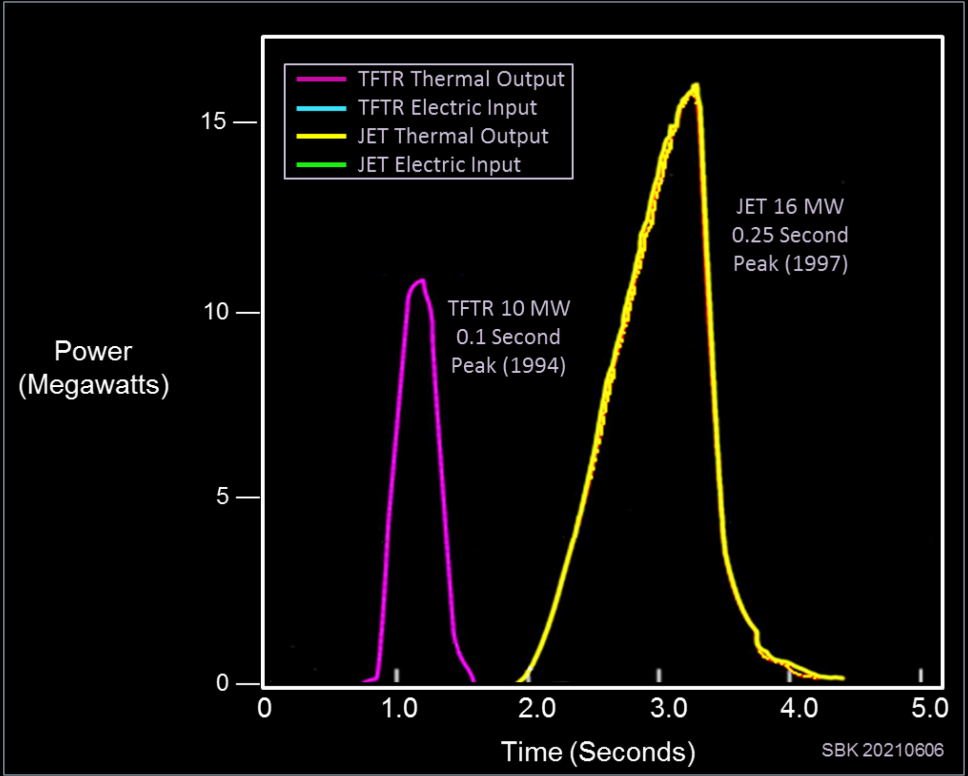
2. He graphically misrepresented the 39.5 MW of heating power from the neutral bean injectors. The curve/area shown in yellow should be 20 times higher.

3. He failed to disclose the total input values needed to "produce" this "fusion energy."

Refresher on Science Ethics

1. Show your data.
2. Show *all important data.*
3. Define your terms as needed for the target audience.
4. Provide a glossary for any unusual terms or unusual meanings of terms.
5. Communicate transparently for the target audience.

The Scientific Way to Display the TFTR and JET Results: *Step 1*

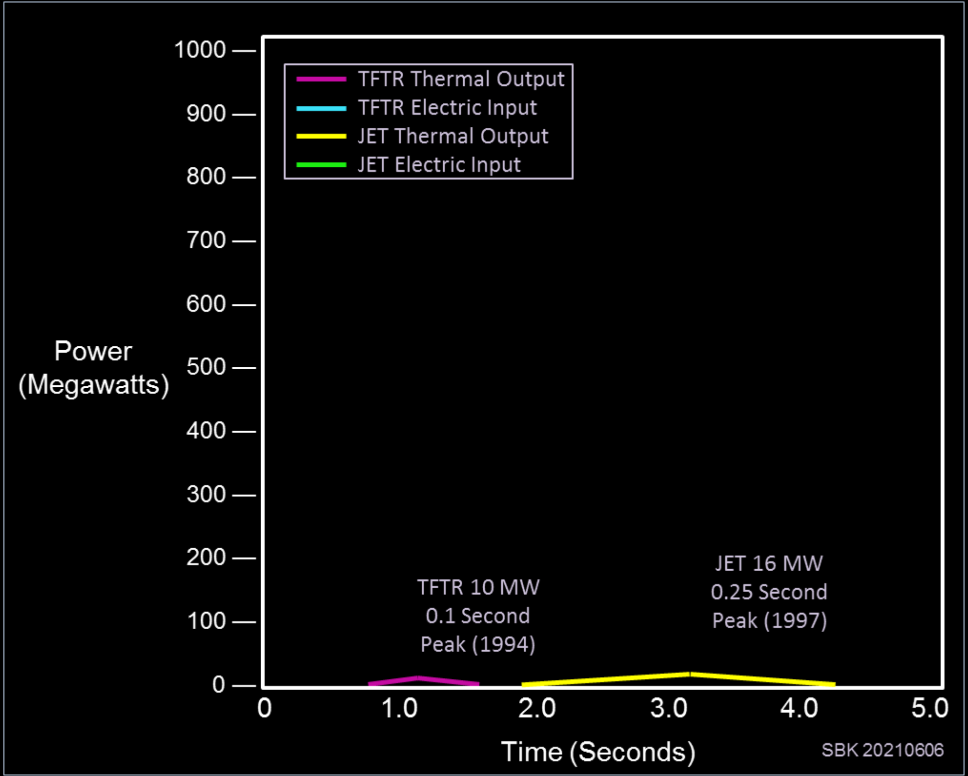


These are the plots for the best results from Princeton's TFTR reactor and the Joint European Torus (JET) reactor.

I labeled the vertical axis label "power." Not a specific form of power; just power. No hidden meaning of "fusion power."

The two curves shown here represent the thermal output from the fusion reactions.

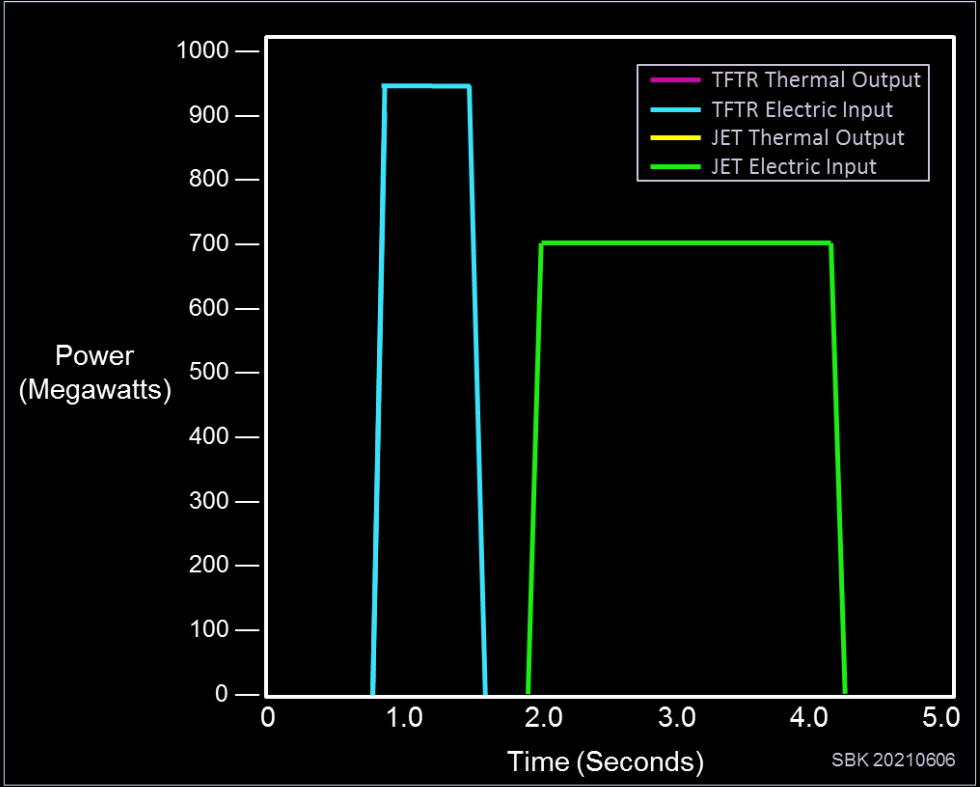
The Scientific Way to Display the TFTR and JET Results: *Step 2*



Only one change here: Adjust the scale of the vertical axis.

It's the same data. Just on a less-exciting scale.

The Scientific Way to Display the TFTR and JET Results: *Step 3*



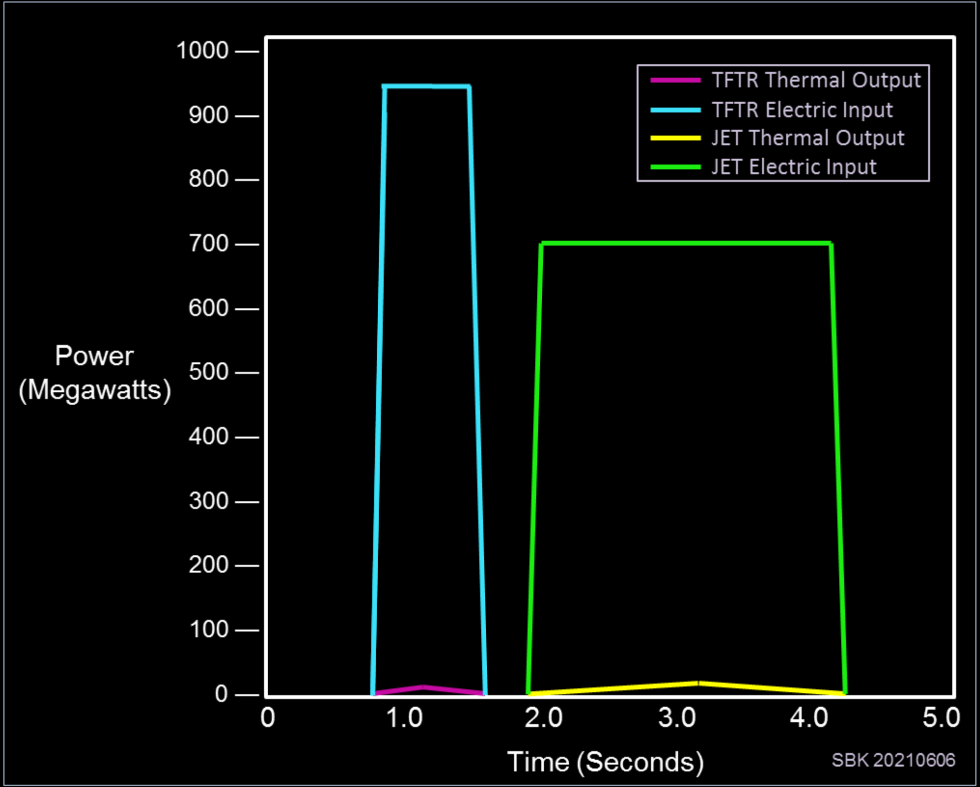
These two plots represent the electric input power values:
TFTR: 950 MW; JET: 700 MW

For a 1-second duration, they represent these energy values:
TFTR: 950,000,000 Watt-seconds
JET: 700,000,000 Watt-seconds

Andrew Zwicker, the head of public relations for PPPL, and Dale Meade, a well-known retired PPPL physicist who knows the history of PPPL, told me that they "don't know" and "can't find" the TFTR electric input power value. I searched the 'net and found it. (link)

In 2014, the electrical input power value for JET did not exist anywhere on the 'net. I asked Nick Holloway, the head of public relations, for the value, and he gave it to me. (link)

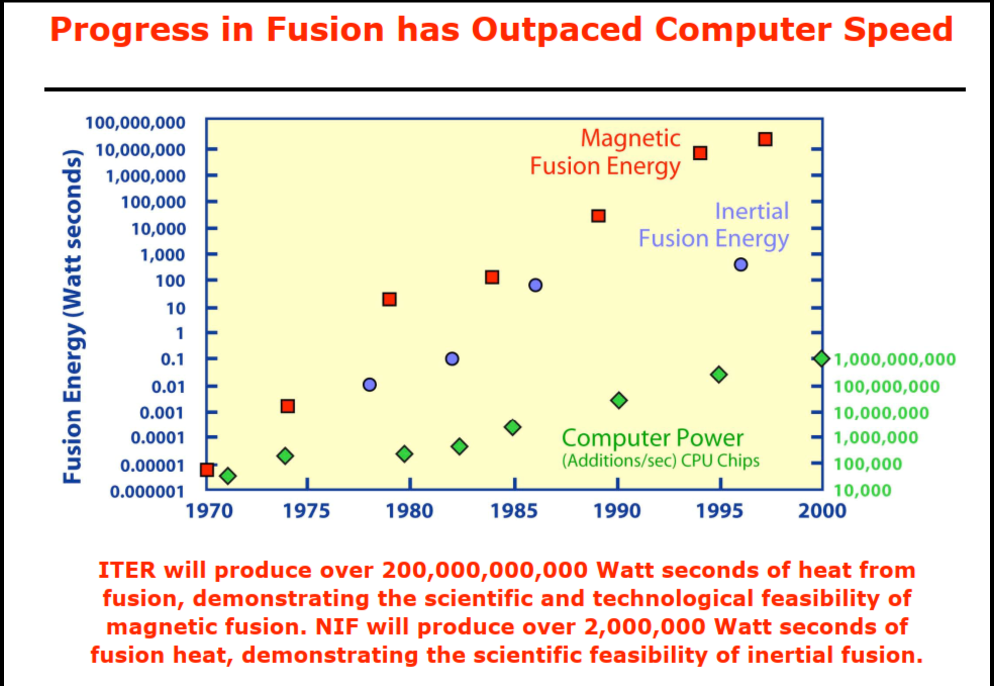
The Scientific Way to Display the TFTR and JET Results: *Step 4*



Any legitimate scientist who displays a graph of output power (or energy) from a device that he or she claims produces power (or energy) must display both input and output power (or energy) values, together, on the same timescale, as shown here.

Doing anything less is hardly different from making a claim of perpetual motion.

Fusion Energy Progress Reported by Princeton Lab Representatives



ITER is not displayed on this PPPL graph. The top two MFE points are for TFTR (1994) and JET (1997).

Now we know the following:

1. The values of "fusion energy" produced do not include the input energy.
2. The slide presentation does not disclose this fact to viewers.
3. The best result, as shown here, lasted for a quarter of a second.
4. The "fusion energy" produced was 99 percent less than the electrical energy consumed.

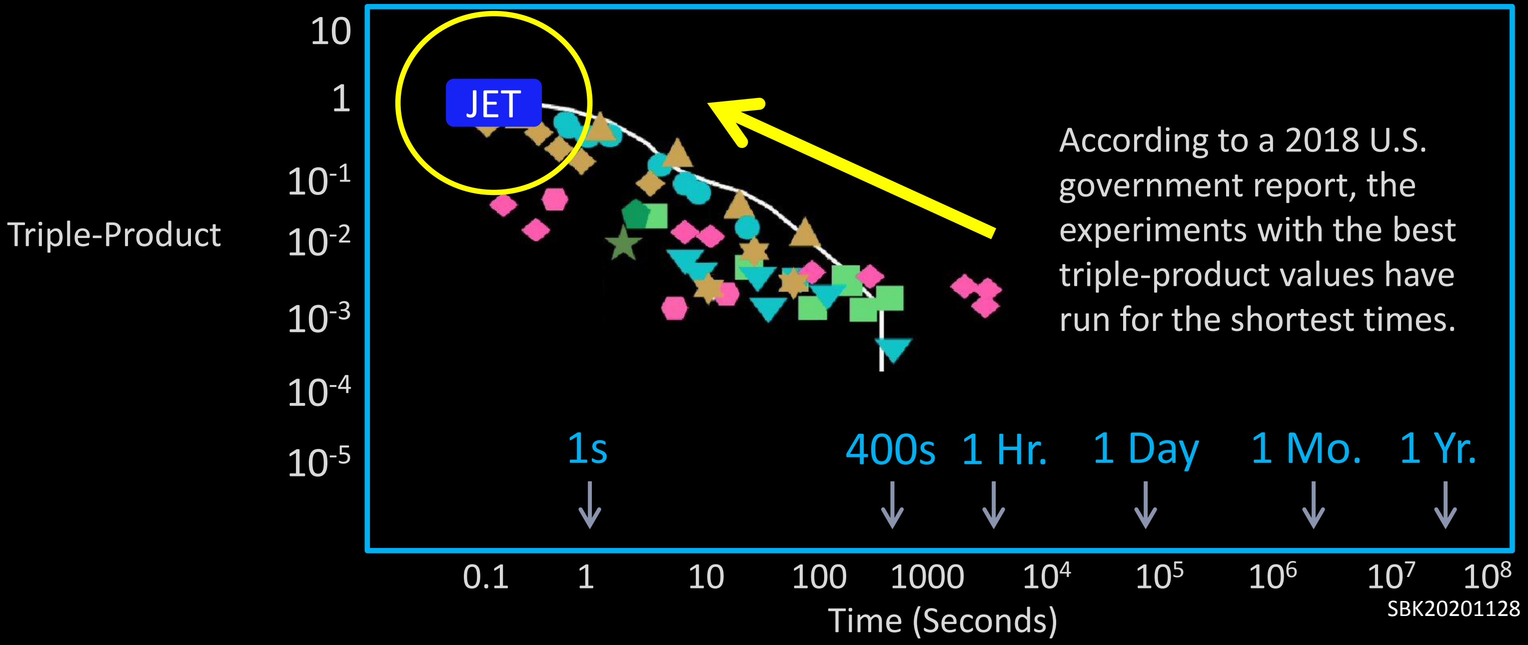
These are the only words that can politely and accurately describe this graph:

Complete Nonsense

But there's another problem.

Progress in Fusion (Plasma Duration)

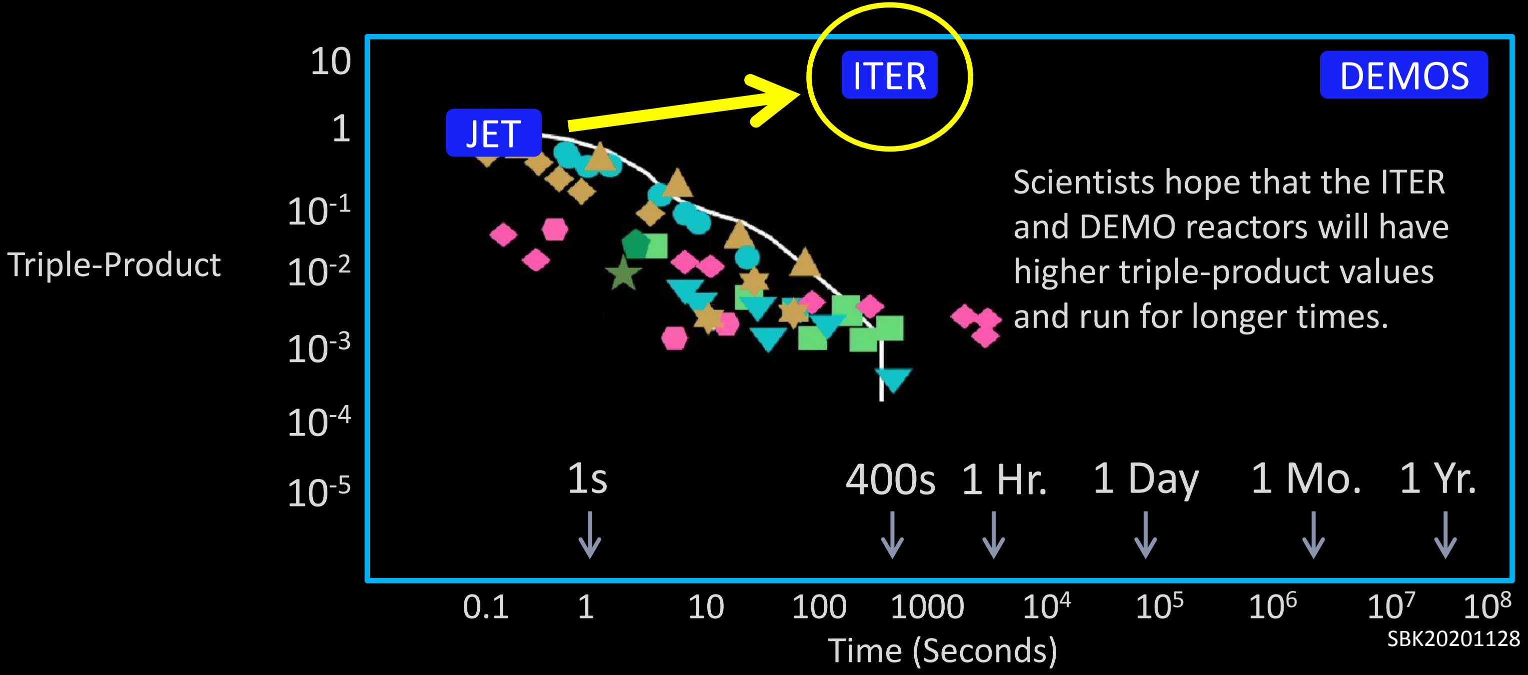
Results From Large Fusion Experiments Around the World



Source: 2018 Pre-print of Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research, page 102

Progress in Fusion (Plasma Duration)

Results From Large Fusion Experiments Around the World

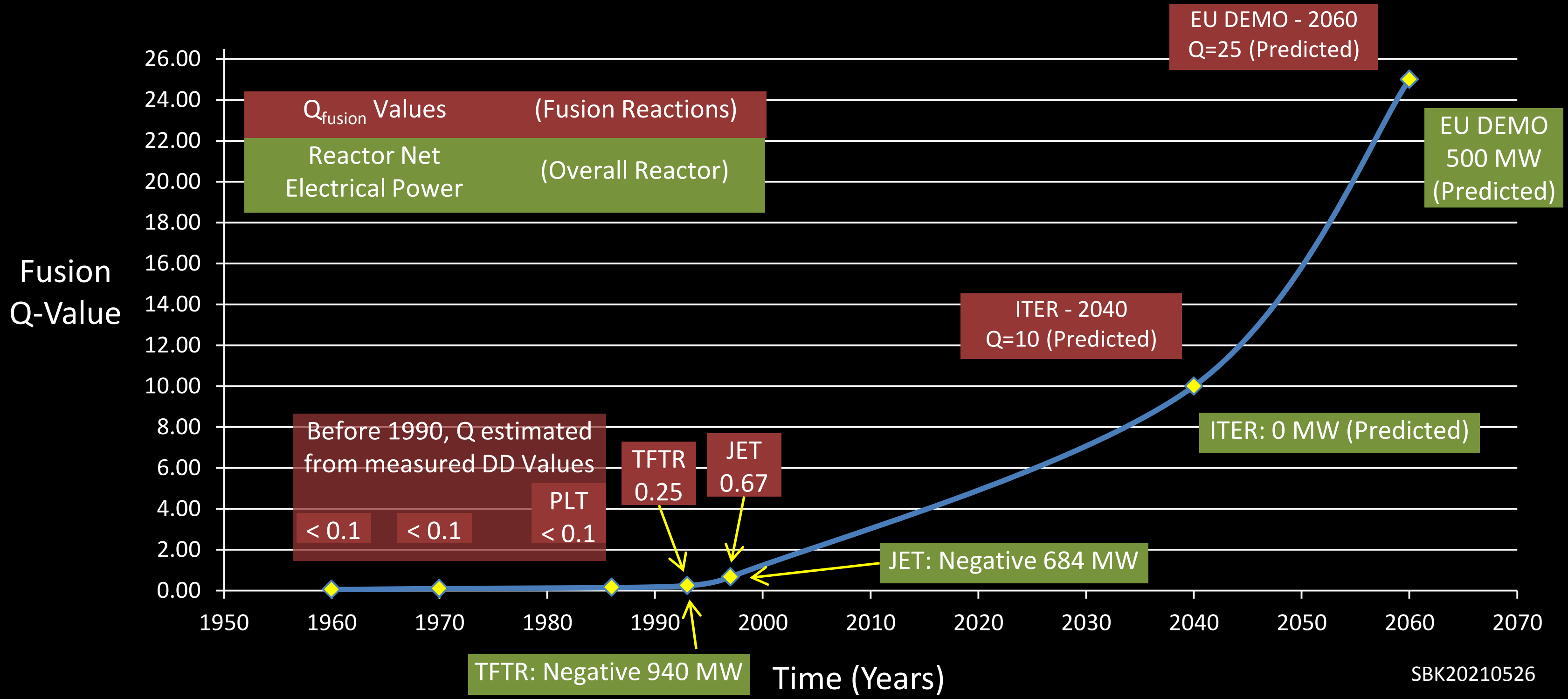


Source: 2018 Pre-print of Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research, page 102

The Physical Measurements

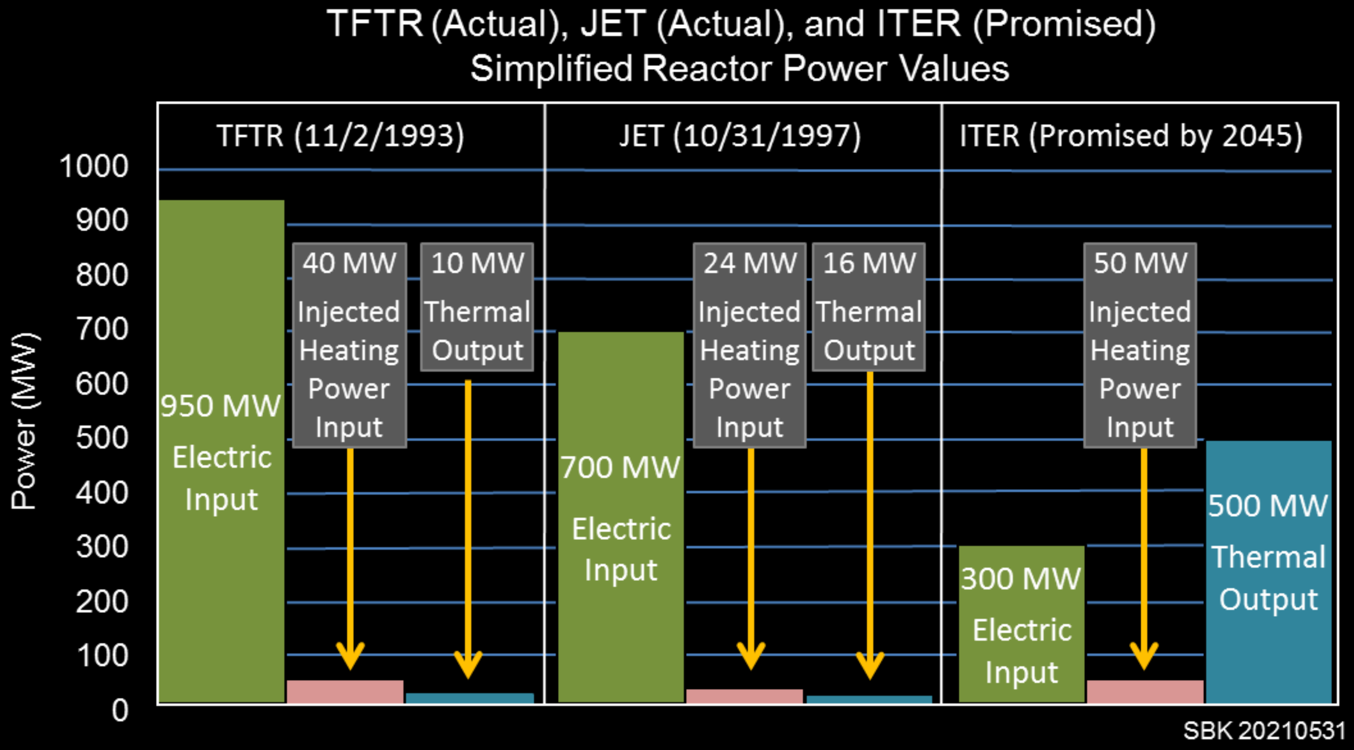
Theories guide, and experiments decide.

The Real Progress in Fusion: Overall Reactor Power Output



Sources for ITER and EU DEMO data: 2018 EUROfusion Roadmap

Yes, There Has Been Progress in Fusion: Less Input Power Required



But Net Reactor Power Does Not Equal Commercial Fusion Power

There are a few more very serious issues, like tritium.

The *Whole* Truth About Fusion Fuel

Fusion reactors will **require a 50/50 mixture** of deuterium and tritium.
Deuterium can come from ocean water. Yes, it is abundant.

Tritium does not exist on Earth as a natural resource.

Tritium is a man-made radioactive isotope.
It is produced by a few heavy-water fission reactors.

99% of the tritium for ITER will come from these older, aging, reactors.
After ITER, there will be *almost no remaining tritium*.

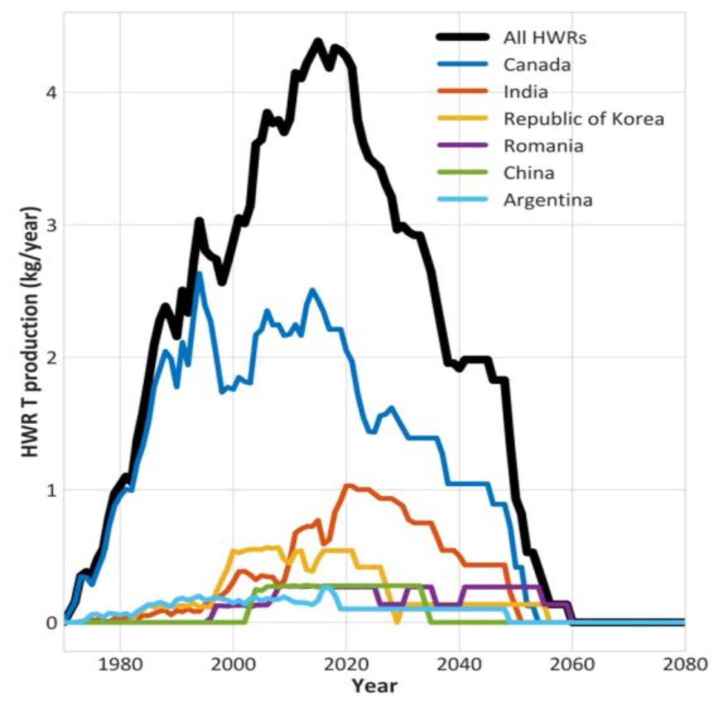
You Can't Build a Long-Term Inventory of Tritium and Stockpile It

Why not?

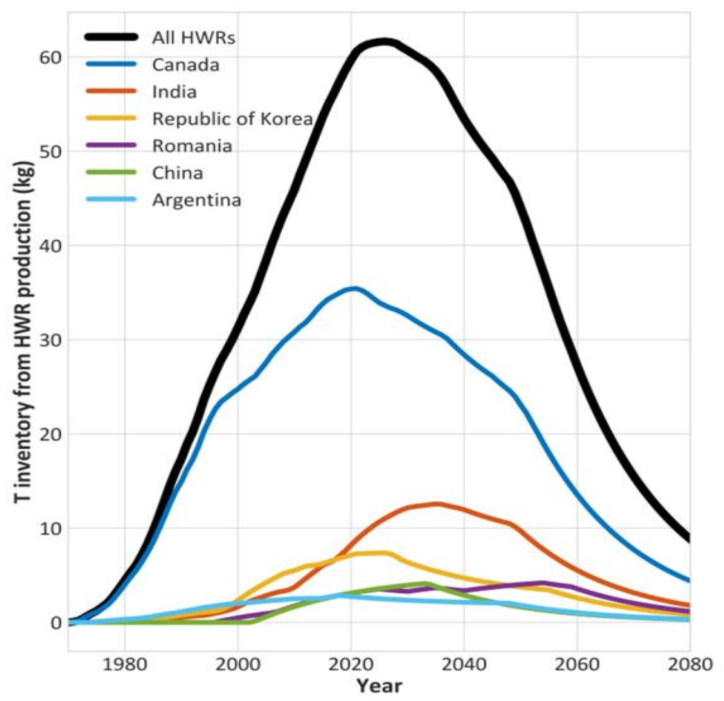
Because as soon as tritium is produced, it starts undergoing radioactive decay and changes into helium. After 12.3 years, half of the tritium is gone.

Global Production of Commercial Tritium Expected to Hit Zero By 2060

Production Rate



Inventory Decay Rate



IOP Publishing | International Atomic Energy Agency Nuclear Fusion

Nucl. Fusion 58 (2018) 026010 (10pp) https://doi.org/10.1088/1741-4326/aa9d25

If ITER Works, It Will Exhaust Most of the Worldwide Supply of Tritium

Tritium Consumption in Fusion is HUGE!

Unprecedented!

55.8 kg per 1000 MW fusion power per year

Production & Cost:

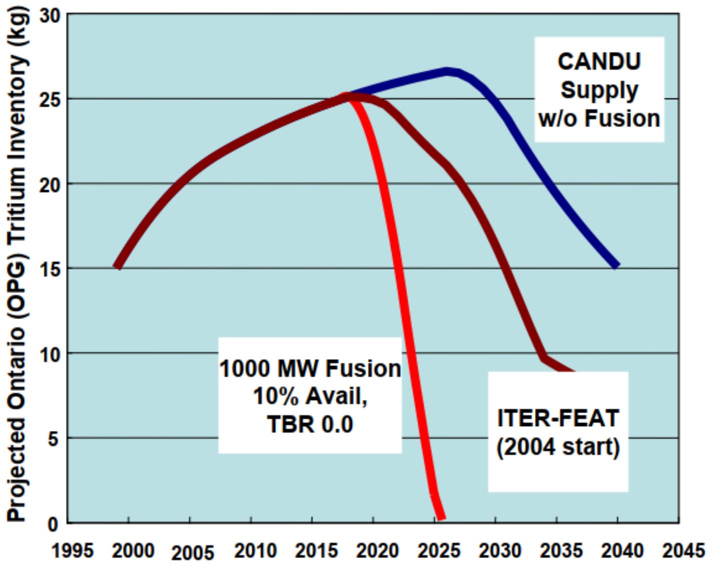
CANDU Reactors: 27 kg from over 40 years, $30M/kg (current)

Fission reactors: 2–3 kg/year/reactor,

$84M-$130M/kg (per DOE Inspector General*)

*www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

- A Successful ITER will exhaust most of the world supply of tritium



Mohamed Abdou
for the US ITER TBM Team
Fusion Energy Sciences Advisory Committee Meeting
Gaithersburg, Maryland
March 1-2, 2007

ITER will not have a tritium breeding blanket. It will have four tritium breeding mockup modules. "They cannot produce more than 1% of ITER's tritium consumption at the best conditions." — M. Abdou

Fusion Scientists Claim That DEMO Reactors Will Make Their Own Fuel

Most heavy-water fission reactors will be decommissioned by 2060.

Fusion scientists imagine that the DEMO-class reactors, after start-up,
WILL MAKE AND CONSUME THEIR OWN TRITIUM.

But the all the DEMO reactors will need a source of tritium to start up.

There May Not Be Enough Tritium to Start Even one DEMO Reactor

"The tritium available commercially from the Canadian reactor production programme after the retirement of ITER may not be sufficient to start [the EU] DEMO."

"Two factors make the tritium supply for [the EU] DEMO even smaller than previously considered. First, ITER will be severely delayed, and if [the EU] DEMO is similarly delayed, then all the Canadian CANDU reactors will have been shut down, while the civilian tritium stockpile will have undergone decay."

IOP Publishing | International Atomic Energy Agency Nuclear Fusion

Nucl. Fusion **58** (2018) 026010 (10pp) https://doi.org/10.1088/1741-4326/aa9d25

After Start-Up, DEMO-Class Reactors Will Need a Tritium Miracle

No existing technology will enable DEMO reactors
to make tritium at a faster rate than they consume tritium.

Abstract

The tritium aspects of the DT fuel cycle embody some of the most challenging feasibility and attractiveness issues in the development of fusion systems. The review and analyses in this paper provide important information to understand and quantify these challenges and to define the phase space of plasma physics and fusion technology parameters and features that must guide a serious R & D in the world fusion program. We focus in particular on components, issues and R & D necessary to satisfy three 'principal requirements': (1) achieving tritium self-sufficiency within the fusion system, (2) providing a tritium inventory for the initial start-up of a fusion facility, and (3) managing the safety and biological hazards of tritium. A primary conclusion is that the physics and technology state-of-the-art will not enable DEMO and future power plants to satisfy these principal requirements. We quantify goals and define

IOP Publishing | International Atomic Energy Agency — Nuclear Fusion

Nucl. Fusion **61** (2021) 013001 (51pp) https://doi.org/10.1088/1741-4326/abbf35

Don't Forget the Lithium!

To make its own tritium, a fusion reactor will need lithium —
a non-renewable natural resource.

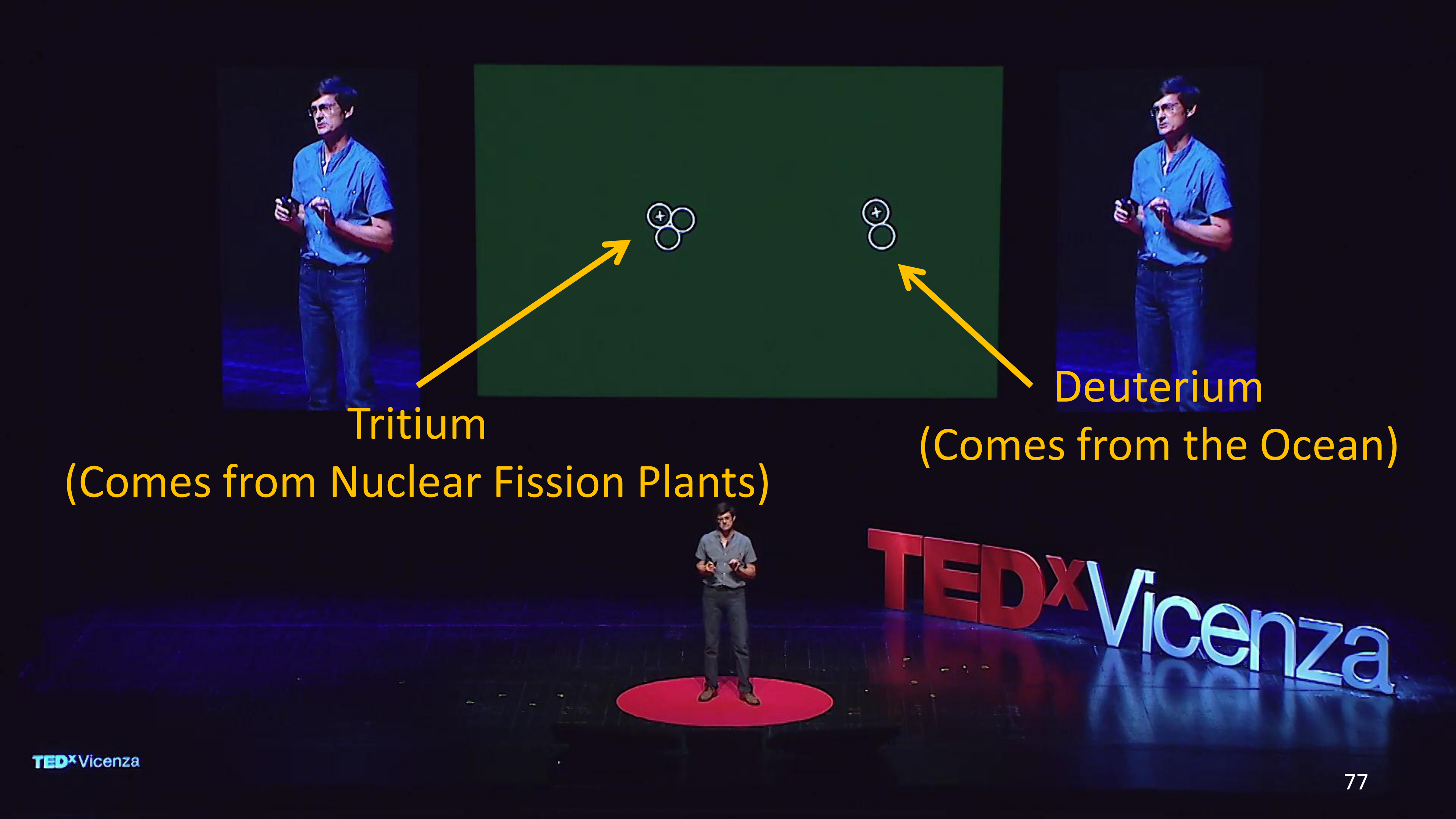
The European Commission's Half-Truth about Fusion Fuel

Presented to the European Parliament Committee on Budgetary Control

Mark Henderson's Half-Truth about Fusion Fuel

"If I go out to the ocean and take a liter of water, and I take a little bit of a special hydrogen isotope out of that water, put the rest of the liter back into the ocean so I don't damage the ocean, and I take those two isotopes and I want to put them together, I want to fuse them together. ... Each liter would be equivalent to about 200 to 350 liters of gasoline and with that we'd be able to power all of Italy."

— Mark Henderson, Plasma Physicist
Formerly Employed by the ITER Organization


Tritium
(Comes from Nuclear Fission Plants)
Deuterium
(Comes from the Ocean)
TEDxVicenza
TEDxVicenza

"We were able to create a reaction where the amount of energy we put in equaled the amount of energy out."

The Facts:

Joint European Torus (JET) Fusion Reactor: Oct. 31, 1997, Shot #42976

Heating power that was injected into the fuel: 24 MW

Peak thermal power produced from fusion: 16 MW

Electrical power consumed by the reactor: 700 MW

Equivalent thermal input power consumed by the reactor: 1750 MW

"Our goal is to build a machine that performs 10 times better. So we have one Watt going in equals 10 Watts out."

The Facts:

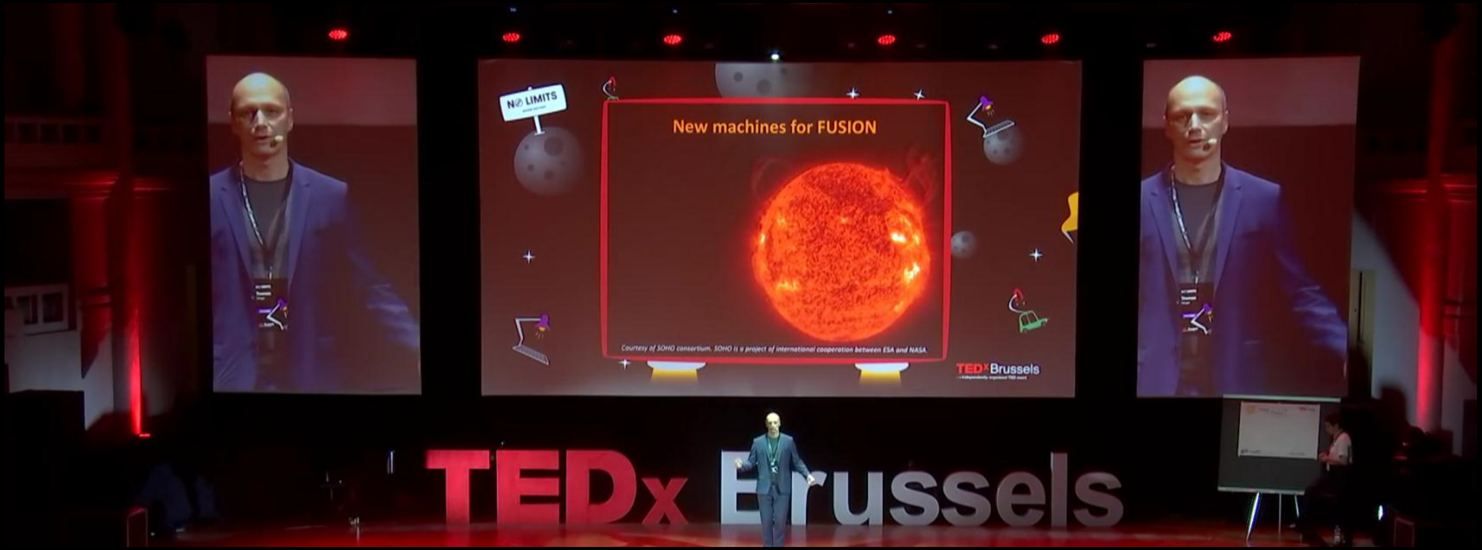
Heating power that will be injected into the fuel: 50 MW

Peak thermal power expected from fusion: 500 MW

Minimum electrical power expected to be consumed by the reactor: 300 MW

Minimum equivalent thermal input power expected to be consumed by the reactor: 750 MW

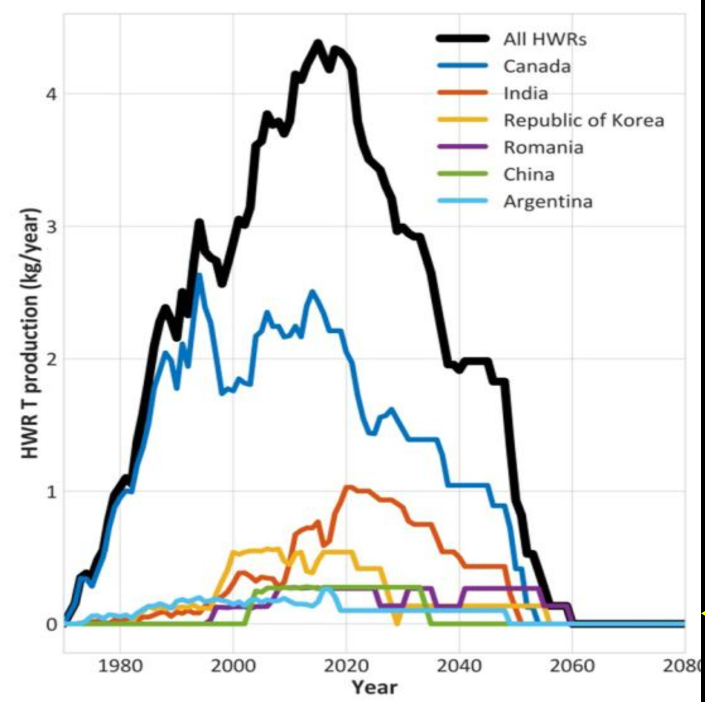
Thomas Klinger's Half-Truth about Fusion Fuel



"It is abundant, enough fusion fuel for millions of years – and is accessible to everybody. So nobody owns the fusion fuel. The machines are expensive but the fuel cost is essentially zero."

— Thomas Klinger, Scientific Director of Wendelstein 7-X Project
Max Planck Institute for Plasma Physics

Fact-Check: Six Countries "Own" Tritium Fuel and Production



Commercial tritium is produced by a few heavy-water fission reactors in Canada, India, Republic of Korea, Romania, China, and Argentina.

By 2060, most of these reactors will have reached the end of their lifespan. Replacement reactors are generally not being built.

GLOBAL DEPLETION: 2060

IOP Publishing | International Atomic Energy Agency — Nuclear Fusion

Nucl. Fusion **58** (2018) 026010 (10pp) https://doi.org/10.1088/1741-4326/aa9d25

Fact-Check: Tritium Costs $30 Million Per Kilogram

All Major Fusion Reactor Designs Will Require a 50% Tritium Fuel Mixture

Tritium Consumption in Fusion is HUGE!
Unprecedented!

55.8 kg per 1000 MW fusion power per year

Production & Cost:

CANDU Reactors: 27 kg from over 40 years, $30M/kg (current)

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**www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf*

- ❑ A Successful ITER will exhaust most of the world supply of tritium

$30 Million / kg

Mohamed Abdou
for the US ITER TBM Team
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Michel Laberge's Half-Truth about Fusion Fuel

"The fuel that you need for fusion, you can extract it from the ocean. You can extract the fuel from the ocean for one-thousandth of a cent per kilowatt hour. If the whole planet was run on fusion there would be enough fuel in the ocean for two billion years. So there's enough fuel, and it's nice, and it's clean, and it's fantastic."

— Michel Laberge, Founder of General Fusion Inc.

Derek Stork Was Honest About the Remaining Challenges

Any scientist who says that nuclear fusion IS, or even WILL be, a source of energy is ignorant, dishonest, or delusional.

	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma physics/ Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady-state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Heating, current drive and fuelling	1	2		r	R	R
	Remote handling	1	2		R	R	R
Materials & Component Nuclear performance & lifetime	Materials characterisation			3	R	R	R
	Plasma-facing surface	1	2		3	4	R
	Vessel/First Wall /blanket/divertor materials		1	1	3	4	R
	Vessel/ First Wall /blanket/divertor components		1	1	2	4	R
	T self sufficiency		1		3	R	R
Final System	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

Outputs:		
	1	Will help to resolve the issue
	2	May resolve the issue
	3	Should resolve the issue
	4	Must resolve the issue

Inputs:		
	r	Pre-existing Solution is desirable
	R	Pre-existing Solution is a requirement

UKAEA October 2007 (revised/improved version of original table in UKAEA FUS 521, 2005)

DEMO and the Route to Fusion Power

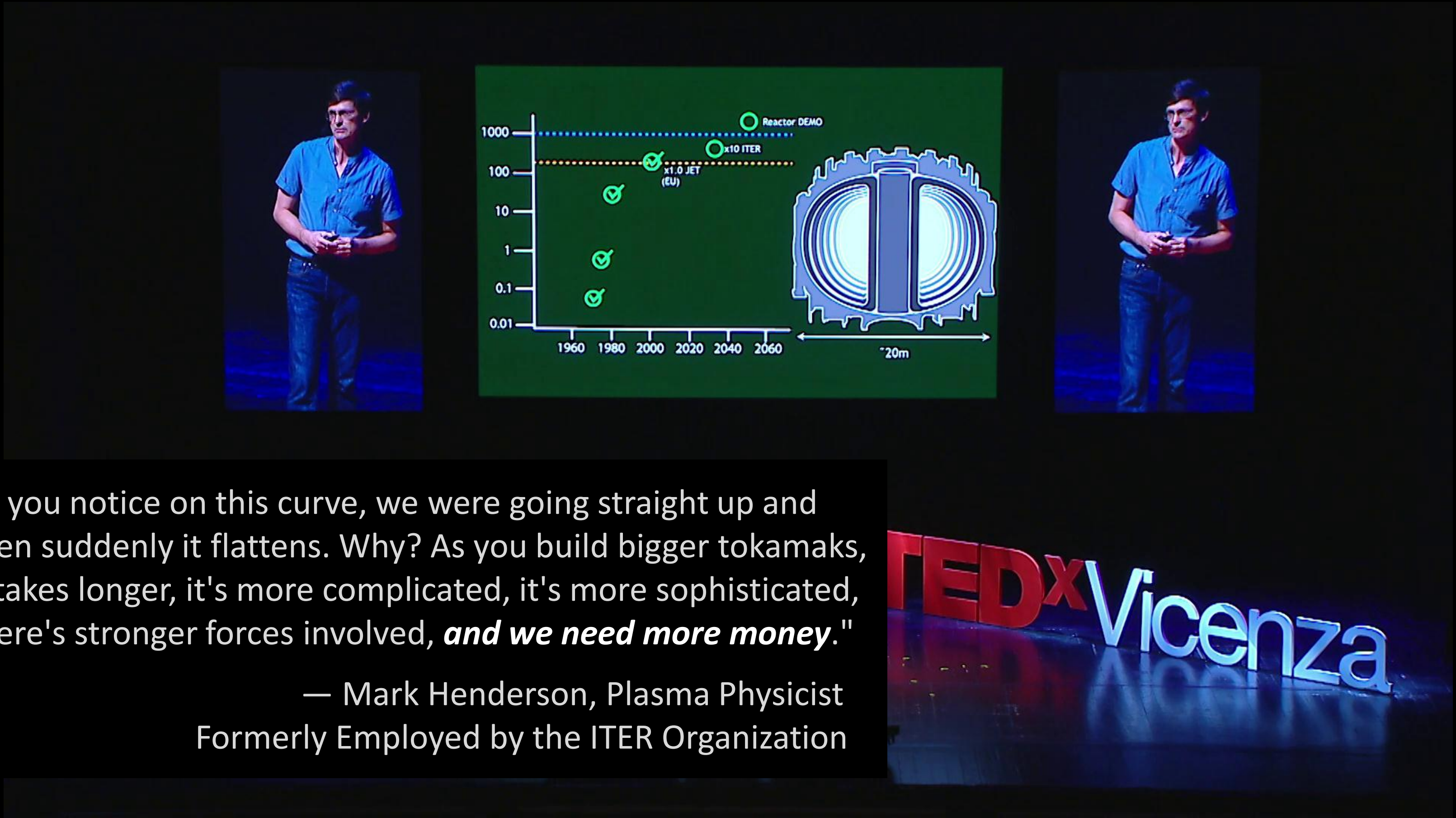
Derek Stork

Euratom-UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, England

(this work was supported by UK EPSRC and Euratom)

D Stork : 3rd Karlsruhe Intl School on Fusion Technology – Sept 2009

Mark Henderson Defends Fusion Progress Stagnation



"If you notice on this curve, we were going straight up and then suddenly it flattens. Why? As you build bigger tokamaks, it takes longer, it's more complicated, it's more sophisticated, there's stronger forces involved, ***and we need more money***."

— Mark Henderson, Plasma Physicist
Formerly Employed by the ITER Organization

And fusion energy has been a lot harder than scientists imagined: "Plasmas don't behave like we expected."

No, *confined plasmas on Earth* don't behave like you wanted and hoped they would behave.

You had no evidence that confined plasmas on Earth would behave like *plasmas confined by gravitation* in the stars.

Conclusion

The triple-product value does indicate *scientific progress* in fusion.

Because the triple-product value does not measure reactor power input, power output, or produced net power, it has no direct relevance to the practical feasibility of fusion, aside from being one of several minimum thresholds.

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- L. J. Reinders, author of *The Fairy Tale of Nuclear Fusion* and *Sun in a Bottle?... Pie in the Sky! The Wishful Thinking of Nuclear Fusion Energy.*

Any remaining errors are mine alone.

Appendix — DD and DT Fusion

DD Fusion: Deuterium-Deuterium Fusion
DT Fusion: Deuterium-Tritium Fusion

Atomic nuclei are normally repulsed by one another. It's not that they have personality conflicts, but they each have positive electric charges. The electrostatic force, an iteration of the electromagnetic force, one of the four fundamental forces of nature, normally keeps them apart. It's just like a pair of magnets with their positive poles facing each other.

But if you can coax the nuclei close enough to each other, a different fundamental force of nature, called the strong force, overpowers the electrostatic force and slams the two nuclei together. This forms a single nucleus that has slightly less mass than the sum of the two starting nuclei. That lost mass, thanks to Einstein's famous $E=mc^2$ equation, is converted to a lot of energy. This is the concept of nuclear fusion.

Two types of hydrogen isotopes — deuterium and tritium — are the easiest elements to fuse. Deuterium can be extracted from water by a complex and costly chemical process. It is stable. Tritium does not exist as an available resource in nature and must be made by nuclear fission reactors. Tritium is unstable — that is, radioactive — and is used in nuclear weapons. (S.B. Krivit 20210614)

Appendix —Scientific Feasibility

BASIC: The hypothetical condition when fusion reactions produce power at a greater rate than required to produce those reactions.

ADVANCED: A triple-product value within the operating regime of a fusion reactor that indicates combined concomitant values of temperature, plasma density, and plasma confinement time, wherein deuterium-tritium fusion reactions are expected to produce power at a greater rate than required to produce those reactions. Such triple-product values are concerned with only plasma parameters, not reactor parameters. Triple-product values do not measure or indicate the electric power input, power output, or net power produced by fusion reactors. (SBK/Th.P. 20201130)

Note: In MCF research, values are almost always given and measured in terms of power: Watts. In ICF research, values are almost always given and measured in terms of energy: Joules.

Appendix — Q-Values in Nuclear Fusion

Q_{fus} Versus Q_{eng}

- **Q_{fusion} (Q_{fus})** (Sometimes called Q-physics)
  The ratio of thermal power produced by a fusion reaction compared with the injected heating power used to heat the plasma. This value does not apply to the overall reactor power balance.
- **$Q_{engineering}$ (Q_{eng})**
  The ratio of electric power produced by a fusion reactor compared with the electrical power used to operate the reactor. For a reactor that is not designed for electric output, the thermal output value is normalized to an electric value for an equivalent apples-to-apples comparison.
- If a fusion scientist does not specify which "Q" he or she means, assume he or she means **Q_{fusion}.**

Examples:

- **Q_{fusion} = 1**: Fusion reactions produce the same thermal power rate as the injected heating power rate. The overall reactor power rate will be negative. JET is an example.
- **Q_{fusion} = 10**: Fusion reactions produce 10 times the thermal power rate than the injected heating power rate. The overall reactor power rate will be about zero. The ITER design is an example.
- **Q_{fusion} = 20**: Fusion reactions produce 20 times the thermal power rate than the injected heating power rate. The overall reactor power rate may be positive. DEMO-class reactor designs are an example.

Disclosure Statement

The author has no financial interest in any energy research or technology, including fusion, fission, or low-energy nuclear reaction (LENR) research.

The author has no career investment in fusion or fission research.
The author has some career investment in LENR research. He's written three books about LENRs.

The author has no career investment in fission technology but has this opinion:
Fission works, right now. Generation IV nuclear fission reactor technology will work even better.
The scare tactics, most recently by fusion scientists, are uncalled-for and counterproductive.
There is hope, right now. See the next slide.

Nuclear Fission Is the Safest Source of Baseload Energy

Death Rates

Brown Coal

Coal

Oil

Biomass

Gas

Nuclear Fission

Wind

Hydropower

Solar