Supplement to The Selling of ITER
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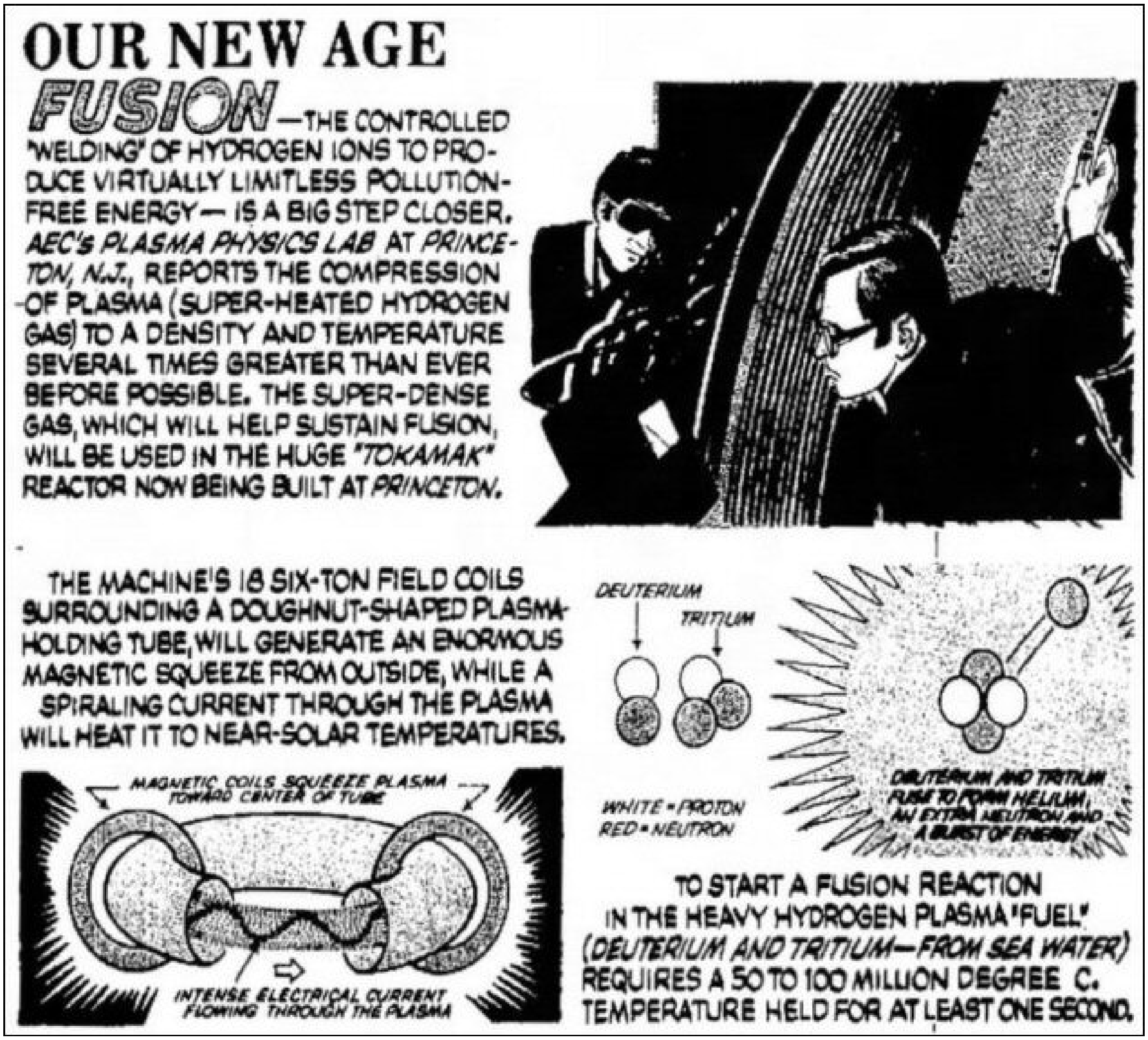

"Our New Age" comic strip, from April 22, 1973. Written by Athelstan Spilhaus and illustrated by Gene Fawcette

Early History

In the U.S., controlled fusion research began in 1951, and, according to a June 1966 Atomic Energy Commission (AEC) report, fusion research was conducted as a classified program at AEC laboratories until 1958. Then, in Geneva, at the Second International Conference on the Peaceful Uses of Atomic Energy, the U.S., the U.K. and the Soviet Union jointly declassified their respective fusion programs. In 1977, after an intermediate reorganization of the AEC, U.S. President Jimmy Carter created the Department of Energy, which included the former AEC. The AEC undertook a major review of its fusion research programs in 1965 and summarized the review in a June 1966 report:

> The requirements for achieving useful power from sustained thermonuclear fusion reactions stagger the imagination. The temperature of the fuel, hydrogen isotopes, must be in the hundreds of million degrees, hotter than any material can withstand. Heat from the reaction must be captured in a high-tech blanket without the destruction of the blanket itself.
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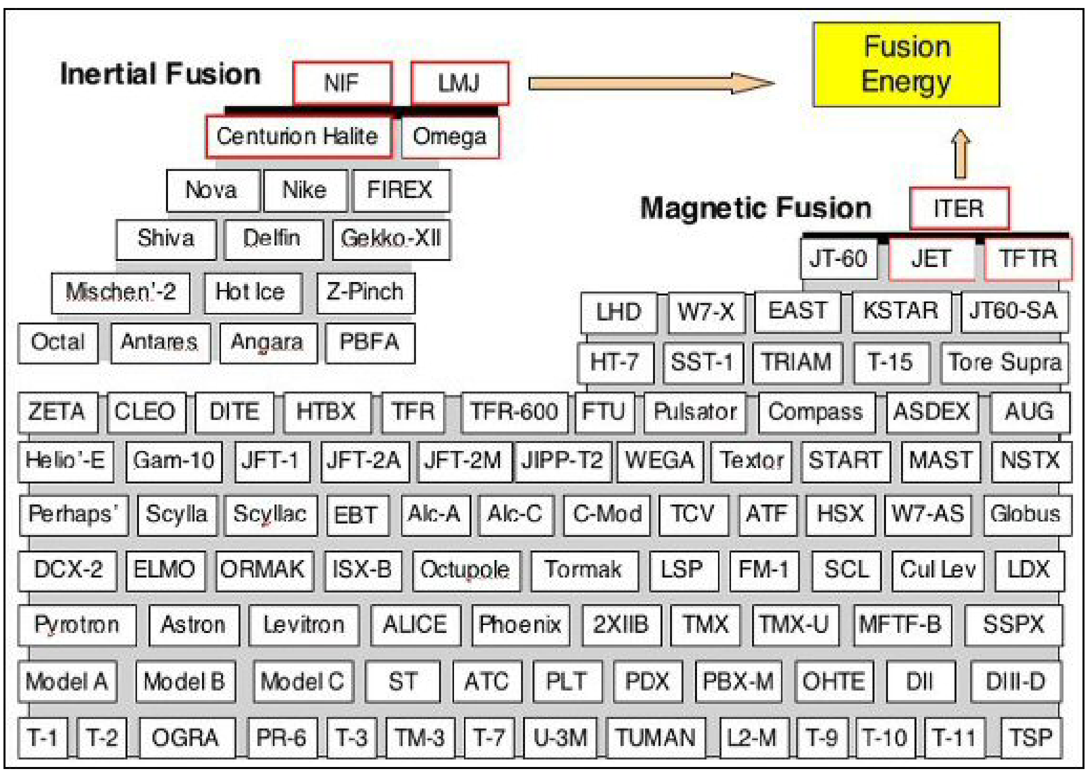
> Not only must this scientific legerdemain be performed with finesse, but to be useful, it must obviously be accomplished with an expenditure of energy substantially smaller than that released by the fusion reactions themselves.

The goal of fusion power was unambiguous: a practical source of energy for an energy-hungry world. The phrase *fusion power* appeared throughout the 1966 AEC report: "a viable approach to fusion power," "full-scale fusion power plants," "fusion power development program." In the 241-page report, which included a glossary of terms, the authors did not see the need to define the phrase "fusion power." Nothing in the report indicates that the phrase meant anything different from what it appeared to mean: power generated by an experimental nuclear fusion reactor.

At some point, fusion researchers developed a special meaning for the phrase "fusion power," which is explained in the article "The Selling of ITER."



List of fusion reactors compiled by Dale Meade, a prominent fusion physicist and key member of the Princeton Plasma Physics Laboratory, at Princeton University

Twenty-Seven Years Later
By May 1992, fusion reactors had not produced any useful fusion power. They had not produced more power, even for a moment, than they had consumed. Energy, which is equal to power multiplied by time, would not and does not become relevant as a measure of success, at least not until an experiment produces excess power.

On May 5, 1993, the Committee on Science, Space, and Technology of the U.S. House of Representatives convened a hearing on fusion energy research. The objective was threefold: to review the current state of fusion research, to obtain a better understanding of the Department of Energy's proposed program for the years ahead, and to hear testimony on alternative fusion processes.

A major impetus for the hearing was a bill introduced by Sen. J. Bennett Johnston that, according to the hearing summary, "shocked the fusion community" because it proposed to limit fusion research in the U.S. to only that directly associated with ITER, which was still on the drawing board. "This bill," the hearing summary said, "served to put the fusion community on notice that time was running out in the era of tight money supply."

Davies Testifies
At 1:35 p.m., in Room 2318 in the Rayburn House Office Building, Rep. Marilyn Lloyd, of Tennessee, the chairman of the committee, brought the meeting to order:

> The United States has participated in the development of systems to derive energy from the fusion processes for 40 years. We've learned much. We still do not have an operating power-producing fusion facility, however, and many challenging obstacles lie ahead. Well, someone might ask, why then continue to bother with such a difficult technology? Well, the answer is that we seek to provide a reliable source of electric power for future generations. Our oil, our natural gas, and coal are all limited to a relatively short period of time.
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> Columbus reached our shores about 500 years ago. In much less time than that, fossil fuels, which provide for today's energy, for much of today's energy, for all practical purposes will be exhausted. Fusion promises us a virtually unlimited supply of potentially clean energy.
>
> But our fusion program may be entering a state of reassessment. This, in part, may be the result of not having produced a fusion energy plant, or maybe it's because we have all become much more aware of the pressure on federal research funds. Last year, we produced an energy policy bill which became public law. Now, less than one year later, Senator Johnston has prepared a new bill, S. 646, called the International Fusion Energy Act of 1993. That bill would essentially focus the fusion program exclusively on the International Thermonuclear Experimental Reactor.

The first speaker to testify was Anne Davies, the associate director for Fusion Energy Sciences in the Department of Energy. Davies emphasized the safety and environmental aspects of fusion and focused on the reduced amounts of radioactive waste material compared with the amounts from nuclear fission reactors. She agreed with critical remarks made by some of the representatives that developing fusion energy seemed to be a difficult challenge.

"A year ago," Davies said, "when we were here, we reported on results from the experiments in JET. In that experiment, 2 megawatts of fusion power were produced in a short pulse length of about 2 seconds. Dr. Rebut, who's going to appear before you later today, was the director of JET at that time, and he is now the director of ITER. At Princeton, we expect to begin the deuterium-tritium experiments in September, with the production of 10 megawatts or more of fusion power by next year."

Two megawatts of fusion power was good; ten megawatts was even better. But 2 seconds was far from self-sustaining, let alone practical. In her written testimony, Davies gave some impressive numbers.

"The improvement in [magnetic confinement fusion] performance has increased by a factor of more than a million over the past 20 years," she wrote.

Davies wrote that a practical fusion reactor was on the horizon and that ITER could deliver on the promise. "The objective of ITER," she wrote, "is to demonstrate the scientific and technological feasibility of using magnetic fusion energy for the production of electricity."

Davies' budget request for fusion energy for fiscal year 1994 was a third of a billion dollars. In addition to providing funding for ITER, the budget request included funding for the Princeton reactor, which, according to Davies, was "designed to produce over 10 megawatts of fusion power."

In her oral and written testimony, Davies provided no indication that her use of the phrase "fusion power" meant anything different from what it appeared to mean, power generated by an experimental nuclear fusion reactor.
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Rebut Testifies

Next to testify was Paul-Henri Rebut, the director of the U.S. ITER effort. He, too, presented numbers that appeared exciting and promising:

> Since the mid-‘70s, a thousand-fold increase has been achieved in the overall performance of experimental fusion devices. We are now within a factor of five of the fusion performance required for a fusion reactor. This factor will be gained by an increase in the size of the plasma.
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> On November 9, 1991, a deuterium/tritium fuel mixture, including only 10 percent of tritium, introduced in JET, Joint European Torus, produced over a megawatt of fusion power for more than 2 seconds. I believed for us when we started — and I have started in 1958 in this field — this will have been the demonstration that physics of fusions is controlled. So having effectively demonstrated the scientific feasibility, the subsequent development stages leading to fusion power stations

> can now be defined. And we can now focus our effort on the fusion reactor. In fact, the International Thermonuclear Experimental Reactor, ITER, is the core of a power reactor.
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> U.S., Europe, Japan, and Russia have signed the ITER Engineering Design Activity Agreement on the 21st of July 1992. The ITER device is foreseen to be the first experimental reactor and will be able to produce high-grade heat from controlled fusion reactions well over 1 billion watts.

One billion watts were even better than 10 megawatts. In his oral and written testimony, Rebut provided no indication that his use of the phrase "fusion power" meant anything different from what it appeared to mean, power generated by an experimental nuclear fusion reactor.

Baker Testifies

Next to testify was Charles C. Baker, the U.S. ITER team leader and the associate director of the Fusion Energy Division at the Oak Ridge National Laboratory. At the time, Oak Ridge was operated by Martin Marietta Energy Systems for the Department of Energy. After reminding Chairman Lloyd that the dogwoods in her home state were blooming and absolutely gorgeous, he began his testimony:

> We are about to undertake a serious effort to design an actual fusion reactor for the first time. If ITER is built, which we all hope, it will essentially be a complete model of the core of an operating fusion reactor. ... For those of us who have committed our professional careers to this, it's a culmination we have looked forward to for a long time, and we are quite excited about it and very pleased to be part of this process. ...
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> The mission that ITER meets in our program is that of what's generally called an engineering test reactor. It represents the time in which we will actually construct the components of a real fusion reactor and find out how to assemble them and make them work. This central mission is common to the strategy of all the countries involved in fusion.

Baker explained that the U.S. effort included personnel from eight national laboratories, 10 universities, and nine industrial companies, including General Atomics, General Dynamics, Grumman, McDonnell Douglas, Rockwell International and TRW.

Baker's testimony reinforced earlier statements by Davies. The science was now understood; ITER's success was only a matter of engineering. Reinforcing Rebut's message, Baker's written testimony said that "ITER will produce 1,500 to 3,000 megawatts of fusion thermal energy."

In his oral and written testimony, Baker provided no indication that his use of the phrase "fusion thermal energy" meant anything different from what it appeared to mean, power generated by nuclear fusion in the ITER machine.

"Our New Age" comic strip, from April 22, 1973. Written by Athelstan Spilhaus and illustrated by Gene Fawcette

Davidson Testifies

Ronald C. Davidson, the director of the Princeton Plasma Physics Laboratory, testified next. He limited his remarks to the Princeton reactor:

> This fall, [the Princeton reactor] is expected to produce about 5 million watts of fusion power in experiments using tritium mixed with deuterium, a high-octane fusion fuel which will be the fuel mixture used in a commercial fusion reactor. In 1994, [we] expect to increase this power level to about 10 million watts, an historic milestone in fusion energy development and about five times the power level produced in the European JET experiment in 1991.

In his oral and written testimony, Davidson provided no indication that his use of the phrase "fusion power" meant anything different from what it appeared to mean, power generated by an experimental nuclear fusion reactor.

After the panel representing magnetic confinement fusion finished testifying, members of the committee asked the panel many questions. But none of them asked any questions about the claimed megawatts of fusion power, let alone whether the panel's use of the phrase "fusion power" meant anything other than what it appeared to mean: potentially useful nuclear fusion power.

After the hearing, several of the committee members sent follow-up questions to some of the witnesses. The questions were about the feasibility of success, safety, and economics. Again, there were no questions about the claims of megawatts of fusion power, let alone questions about the meaning of the phrase "fusion power."

In fact, the hearing record included a statement from the Energy Policy Committee of the Institute of Electrical and Electronics Engineers (IEEE). The IEEE statement confirmed the organization's understanding that the JET reactor had produced "an average of 1 megawatt (peak 1.7 megawatt) of fusion power for a duration of 2 seconds." IEEE wrote that it expected the Princeton reactor to produce 10-20 megawatts of fusion power by the end of 1994.

Sixteen Years Later

In 2006, the U.S. and Japanese teams had lost their bids to host the ITER reactor on their own soil, and by international agreement, the site in France was chosen for ITER.

On Oct. 29, 2009, the Subcommittee on Energy and Environment of the Committee on Science and Technology of the U.S. House of Representatives convened another hearing on fusion energy research.

The meeting was called "The Next Generation of Fusion Energy Research," and its purpose was to examine the fusion energy research activities conducted by the Department of Energy's (DOE) Office of Science. The *Congressional Record* provided background information on basic explanations of nuclear fusion, plasmas, and the concepts of magnetically confined fusion and inertially confined fusion. The background gave no indication that the phrase "fusion power" was a specific technical term that had a singular, narrow, technical meaning.

The *Congressional Record* said that "ITER is a major international research project with the goal of demonstrating the scientific and technological feasibility of nuclear fusion energy." It was essentially the same goal that Davies stated in 1993 except that the phrase "for the production of electricity" had been dropped.

Chairman Brian Baird brought the meeting to order:

> Fusion energy has successfully powered the sun and the stars for billions of years, so it is no surprise that humankind has tried to re-create and harness this energy here on Earth. However, we all know that a working fusion reactor has been much more difficult to achieve than our Atomic Age scientists initially expected. Over the years, there were also some overly optimistic or even, in some cases, fraudulent proclamations by folks who skipped the peer review process and went straight to

> the media, which has further complicated the popular and political assessment of the extent to which the federal government should continue to support this research.
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> That said, however, according to recent reviews by the National Academies and the Department of Energy, there have been significant developments in the fields of advanced computing, engineering and plasma science over the last 20 years that have led to a far better understanding of how to create and control a fusion system. Within about three years' time, the National Ignition Facility in California is expected to become the first fusion device in the world to produce more energy than it consumes, though only for at most a handful of brief experiments per day. In Cadarache, France, the large international fusion project called ITER is about to begin construction. This experiment is designed to produce five times more energy than it consumes for several consecutive hours.
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> If these new facilities are successful, they will represent a dramatic turning point in developing a viable commercial fusion reactor.

Synakowski Testifies
Edmund Synakowski, with the U.S. Department of Energy, spoke first. In his oral testimony, he used the phrase "fusion power" only twice:

> - "In the lab, we use hydrogen isotopes as the fuel, and I have had the privilege of being part of experiments that have generated millions of watts of fusion power."
> - "A plasma at a high enough temperature and density to undergo nuclear fusion in a reactor, while generating close to a billion watts of fusion power, will present a uniquely hostile environment to the materials comprising the reactor."

In his oral testimony, Synakowski provided no indication that his use of the phrase "fusion power" meant anything different from what it appeared to mean, power generated by an experimental nuclear fusion reactor.

In his written testimony, Synakowski spoke grandly of the promise of fusion power and provided some more-technical details. Plasmas, he explained, were a fourth state of matter, hot gases in which "electrons have been knocked free of atomic nuclei, forming an ensemble of ions and electrons that can conduct electrical currents and can respond to electric and magnetic fields. ... At the heart of fusion energy in the stars and on earth, is the world's most famous equation $E=mc^2$, which summarizes our understanding of how mass can be converted into energy."

He used clear, simple language to explain the basic concept of how fusion energy would lead to electricity. "The energy of the fusion reaction byproducts — energetic ions and neutrons — escaping the plasma will be captured and converted into heat. This heat will drive conventional power plant equipment to boil water, generate steam, and turn turbines to put electric power on the grid," Synakowski wrote.

His written testimony also provided a brief history of fusion energy science research.

Among the details of the history and progress Synakowski provided were the record results at the JET reactor in the U.K.:

> [JET] soon announced to the world the generation of a few million watts of fusion power, enough to power thousands of homes. The race was on: [The reactor] at Princeton began its experimental campaign with the deuterium-tritium fuel mix and completed it with experiments in 1994 that generated over 10 million watts of fusion power. The JET experiment ultimately created a record 16 million watts of fusion power in 1997, a result enabled by the larger size of the device as compared to TFTR.

Synakowski added an obscure (for non-specialists) qualifying statement:

> Notably, however, more power was used to heat and control the plasma in each of these cases than was used to create the fusion reactions themselves. The figure of merit used in magnetic fusion, Q, relates the fusion power created to the power used to heat the plasma. The JET experiment yielded a Q of about 0.6.

For nonexperts, such as members of Congress, if they read his written testimony, the terms "figure of merit," "Q," and the value of 0.6 might have seemed incidental, particularly following his enticing comments about enough fusion power to light thousands of homes. Synakowski's qualifying statement did nothing to inform Congress that the term "fusion power" might have had a special, technical meaning.

Prager Testifies

Stewart C. Prager, the director of the Princeton Plasma Physics Laboratory, testified next:

> By any metric, we are far along the road to commercial fusion power. In the past 30 years, we have progressed from producing 1 watt of fusion power for one-thousandth of a second to 15 million watts for seconds, and ITER will produce 500 million watts for 10 minutes and longer. ... The most recent National Academy study notes remarkable progress in recent years. But my focus today is the future, the remainder of the journey to fusion power.

Prager gave no indication that his first and third uses of the phrase *fusion power* meant anything different from his second use of the phrase *fusion power*. Prager, and everyone else who testified, failed to explain that, when they used the phrase "fusion power" *in the context* of "millions of Watts of fusion power," they were using the special, technical meaning. Not only did they fail to define their use of the special meaning of "fusion power," but they also gave no indication that a special meaning existed.

The last scientist on the panel to testify in support of magnetic confinement fusion and ITER was Thomas E. Mason, the director of the Oak Ridge National Laboratory, but, as he stated, he was not an expert in fusion.

Concluding Questions

After a few more people testified before Congress, primarily on inertially confined fusion, Baird asked Synakowski a question that revealed his limited understanding of the testimony he had just heard.

"When we speak of ignition," Baird said, "which I understand is when more energy is put out than put in, in layman's terms, what is the longest period of ignition achieved so far in any of our modalities in terms of time? How much time?"

"Today, actually no plasma has ignited," Synakowski said. "We have had plasmas with controlled fusion reactions. An analog I like to use is that it has been like burning wet wood. We have created a fire, we have controlled the fire; when we take away the external flame, the fire goes out."

Uncovering the Omission
All the claims of megawatts of fusion power by the congressional witnesses were extraordinarily misleading. Not one fusion experiment ever produced real megawatts of net excess thermal power when accounting for full power input; the truth had been hidden for decades through the use of the meaning of "fusion power." In fact, not one fusion experiment produced even 1 watt of real thermal power.

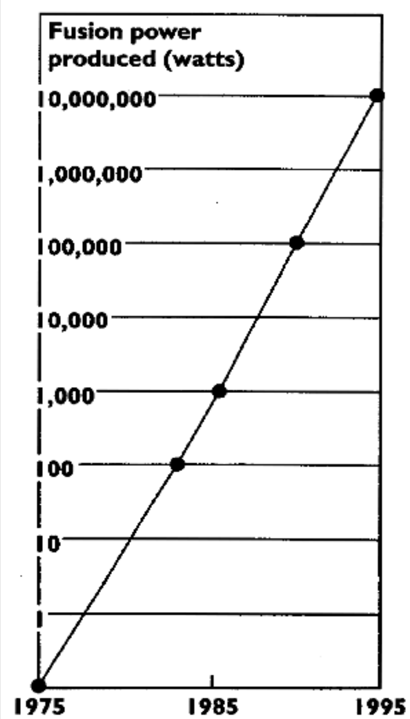

Fig. 1. Fusion power produced in the laboratory has increased 100 million-fold over 20 years to more than 10 million watts.

Left: Fusion Power Associates' chart implying that fusion reactors have produced net power and steadily increasing rates of produced net power.

On Nov. 29, 2014, while I was writing my book *Fusion Fiasco*, I sent my editing team a graph, published by Stephen O. Dean, the director of Fusion Power Associates, a nonprofit research and educational foundation. His graph was published in the American Nuclear Society's *Nuclear News* in July 2002. The numbers in Dean's graph echoed those given by the fusion experts in their congressional testimony.

One of my editors responded critically: "I find the graph interesting, but who cares about power? 10 MW for a very, very short period of one second is not much energy. You want energy. It would be interesting to see this graph as 'fusion energy produced,' and then instead of Joules, use kWh for easy of understanding."

I sent an e-mail to Dean asking whether he had such information. He didn't, and he explained why.

"The applied fusion power," Dean wrote, "is not a relevant measure of progress since these have all been experiments not designed for net [power]. The input referred to is just the input to the plasma and does not include the power to operate the equipment."

I was confused. I thought that the numbers — for example, the 65% cited for JET — reflected total net power, the total output power divided by the total input power. I asked him whether he knew the best total net power for those devices. He didn't. I asked him whether this meant that JET's and TFTR's multi-megawatt peaks were based just on the input heating power rather than the total input electrical power. Yes, it did, he wrote.

As I soon learned, in addition to the power required to heat the plasma, power is consumed in tokamaks by a variety of processes. The greatest among these is the power required to create and maintain the magnetic field that suspends the plasma within the toroidal chamber.

At first, I didn't believe that fusion researchers customarily ignored a major portion of the total input power when they stated net power values. I called Michael Schaffer, whom I knew as an expert in the area. Schaffer is a retired senior staff scientist formerly with the energy group at General Atomics, in San Diego. I asked him to explain what Dean had told me. He corroborated Dean's statement.

Yes, it was true. People in the magnetic fusion field, since the 1970s, have always used only a fraction of the total input power when reporting their progress. I asked Schaffer whether he knew how much greater the actual total system input power was than the plasma heating input power. He guessed that, typically, total input power was about 10 times as much.

I sent an inquiry to Nick Holloway, at the Culham Centre for Fusion Energy. I told him that I understood JET had generated 16 MW fusion power with 24 MW applied heating power input. I asked him whether he could tell me about how much total input electrical power was required to make that much fusion power output. He immediately understood my question and promptly responded with an unambiguous, factual response.

"We don't have the electrical power input figure for this pulse to hand, unfortunately," Holloway wrote. "Below is some information from my colleague Chris D. Warrick on JET's typical electrical power levels, so it will be of this order. But if you do need the exact input figure, we can find out." Here is Warrick's e-mail:

> The general answer is that a JET pulse typically requires ~700 MW of electrical power to run. The vast majority of this goes into feeding the copper magnetic coils and the rest into subsystems and energizing the heating systems. In future machines, the copper coils will be replaced with superconducting coils, which will ensure the total input power is dramatically reduced. I don't have on hand the specific numbers for this particular pulse.

On Dec. 1, 2014, Holloway and Warrick had confirmed it: The total reactor input power was 30 times larger than the applied plasma heating power. This meant that JET had never produced a single watt of power in excess of what it consumed, let alone producing megawatts, which had been used to sell ITER to Congress. (PDF Archive)

According to the Web site Internet Archive, sometime in 2015 the EUROfusion Web site created a page that mirrored my communication with JET. It also gave a rough estimate of the required input power for the magnetic coils for ITER:

> JET consumes large amounts of power — for fusion to occur, we need to create and maintain plasma at extremely high temperatures. Additionally, we need to contain the plasma by energizing large magnetic coils. In total, when JET runs, it consumes 700-800 MW of electrical power (the equivalent of 1-2% of the UK's total electricity usage!). Future reactors will use superconducting magnetic coils, which are much more efficient, so they will not expect to use so much power — maybe 200-300 MW of electrical power. (PDF Archive)

Thus, when fusion representatives told Congress that the Princeton reactor would produce 10 megawatts of power, that the JET reactor had produced 16 megawatts of power, and that the ITER reactor will produce 500 megawatts of power, they were saying something completely different from what the members of Congress believed they were saying.

The JET reactor did not produce 16 megawatts of excess power. With a full accounting of input power, the reactor consumed 700 megawatts of power from the electrical grid. The power balance at JET did not reach 65 percent of the total power that went into the reactor. It reached only 2 percent of the total power that went into the reactor.

At no point did any of the congressional witnesses explain to the members of Congress that — sometimes — when they spoke about "fusion power" they were using their own special, technical definition, one that excluded the vast majority of input power that was consumed in those "megawatt-producing" fusion experiments. Despite their statements that results of fusion experiments were large enough to provide power to thousands of homes, they did not explain that zero usable power had been produced in fusion experiments.

Fusion Philosophy

Over the decades, a deeper philosophical transformation took place in the fusion science community. In advance of this article, I reached out to three dozen professors who taught plasma physics, randomly selected based on a Google search. I wanted to discuss the ITER power input and output with them and to understand their perspective about the present-day power-gain goals of fusion research, specifically for ITER. Thirteen of them responded.

The professors were from the following well-known institutions: Dartmouth, Imperial College (U.K.), the Max Planck Society (Germany), Princeton Plasma Physics Laboratory, Purdue University, University of California at San Diego, University of Maryland, University of Michigan, and William and Mary University. One professor wrote that the power claims on the ITER Web site were "bullshit," and another professor wrote that they were "misleading." However, all of the professors shared this philosophy: Production of megawatts of power from fusion is not (now) important and is not (now) the goal of ITER.