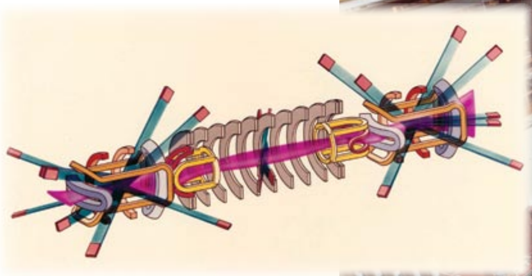
Thoughts on Fusion Energy Development After a Six-Decades-Long Love Affair

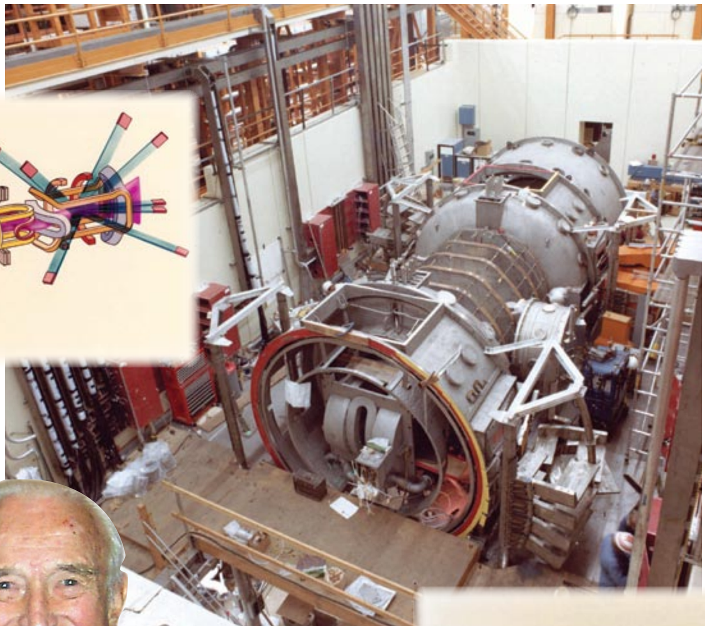
by Richard F. Post

A fusion pioneer reviews 60 years of fusion history, and proposes the axisymmetric tandem mirror as a fast track to achieving ignition with magnetic confinement fusion, bypassing some of the problems with large tokamaks.

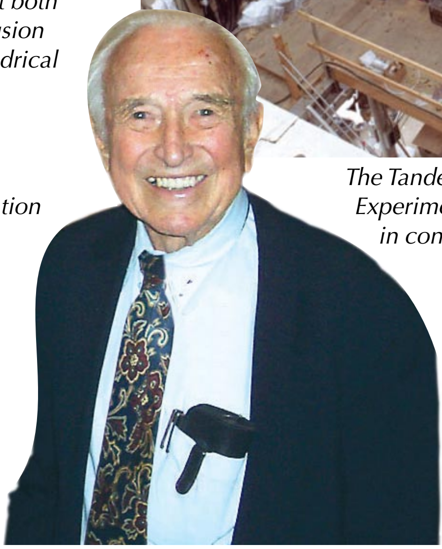


LLNL

A schematic of the Tandem Mirror Experiment. The magnetic mirrors at both ends confine the fusion plasma in the cylindrical reactor chamber.

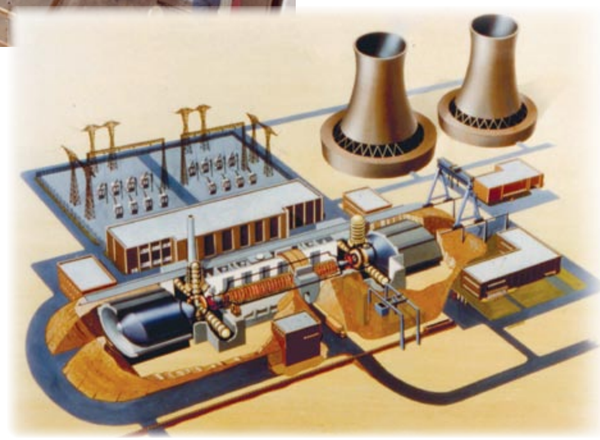


The Tandem Mirror Experiment (TMX) in construction.



Courtesy of Fusion Power Associates

Richard F. Post at Fusion Power Associates' celebration honoring his 90th birthday.



LLNL

Artist's conception in the 1980s of what the larger MFTF tandem mirror power plant would look like in 1990. As Dr. Post explains, the fully built MFTF was mothballed just after it was completed, and tandem mirror work was terminated.

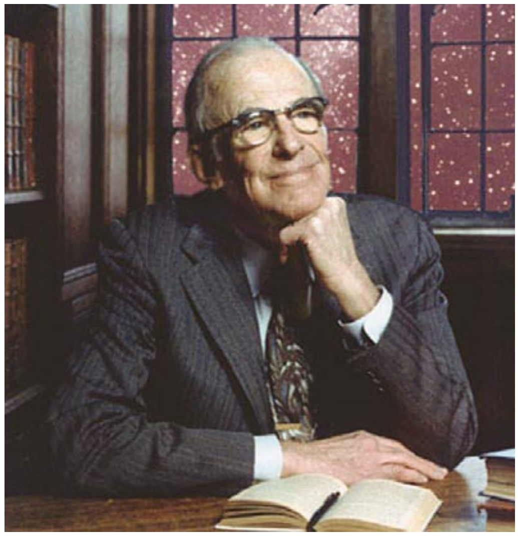
Dr. Richard F. Post, a pioneer in fusion research., made these remarks at the the Fusion Power Associates Annual Meeting and Symposium, Dec. 3-4, 2008, "Fusion Energy: Countdown to Ignition and Gain."

The two-day meeting in Livermore, Calif., included awards to fusion pioneers Post and John H. Nuckolls, Director Emeritus of Lawrence Livermore National Laboratory (LLNL). There were also a celebration of Dr. Post's 90th birthday and presentations by researchers in magnetic and inertial confinement fusion. (See http://fire.pppl. gov/fpa_annual_meet. html#2008 for more details.)

First, I wish to thank Steve Dean and his Fusion Power Associates for honoring John Nuckolls and me, and for giving us this opportunity to comment on a field of research that has been our passion for decades. In my case, I would also like to thank [former associate director for magnetic fusion energy at LLNL] Ken Fowler for proposing the theme of the symposium to Steve Dean [president of Fusion Power Associ-

LLNL

The men most responsible for organizing the new laboratory at Livermore in the early 1950s: Herbert York (right) with Ernest Lawrence (left), and Edward Teller, in 1957.



NASA

Lyman Spitzer, Jr. (1914-1997). Spitzer began work on controlled thermonuclear reactions in 1950, with a Stellarator configuration, in a classified program code-named Project Matterhorn.

ates] many months ago and then diligently following through on its details..

In what I have to say, I will be talking about paths to fusion and about fusion's history as I recall it. Not about the negative aspects of history, as in those who forget history are doomed to repeat it, but the positive view that: If we remember that in the past we had a clearer vision of the path to fusion, and if we have gotten off that path, we know that the path exists and that we can find it again if we try.

Where to begin? And what to highlight about the six-decades-long love affair that I have had with fusion research? My fascination with fusion really began early in 1952, as a result of three classified lectures given by Herb York. I was then a year out of graduate school and working at the Radiation Laboratory (now Lawrence Berkeley National Laboratory). Herb's series of lectures covered the physics issues of controlled thermonuclear reactions (CTR) and described the U.S. fusion programs at Princeton University, headed by Lyman Spitzer, and at Los Alamos, headed by Jim Tuck. Both groups were working on

Richard F. Post: A Brief Biography

Richard Freeman Post was born in Pomona, California, and received his B.A. from Pomona College in 1940 and a Ph.D. in Physics from Stanford in 1950, with intervening years at the Naval Research Laboratory. He also received an honorary Sc.D. from Pomona. At the Lawrence Livermore National Laboratory, he was appointed group leader in Controlled Thermonuclear Research in 1951, as the lab was being founded; then Deputy Associate Director for Magnetic Fusion Energy in 1974, and Senior Scientist in 1987.

Post has (thus far) authored over 25 patents in fusion, accelerators, electronics, and mechanical energy storage. He is a Fellow of the American Physical Society, the American Nuclear Society, and the American Association for the Advancement of Science. His many fusion honors include the American Nuclear Society Outstanding Achievement Award in 1977, the American Physical Society James Clerk Maxwell Prize in 1978, and the Fusion Power Associates Distinguished Career Award in 1987. His magnetics work has been recognized by a Popular Science Design and Engineering Award for passively stabilized magnetic bearings in 2000 and an R&D 100 Award for Induc-Track (Maglev) in 2004.

Excerpted from a tribute to Dr. Post on his 90th birthday, written by Ken Fowler.

LLNL

John Nuckolls (center), the seventh director of LLNL, with Roger Batzel his predecessor at left and Carl Haussmann at right. Nuckolls pioneered work on inertial confinement fusion with lasers.

versions of the only game in town at that time: trying to use specially shaped magnetic fields to stably contain a 100-million-degree hot, ionized gas—plasma—composed of electrons and fusion fuel nuclei, heavy hydrogen isotopes.

For the benefit of the non-scientists, getting power from a magnetically confined fusion plasma is the nuclear equivalent of burning natural gas in a furnace, except that here the furnace liner is to be made up of non-material magnetic field lines. The other main present approach to fusion—using lasers to heat a tiny pellet of fusion fuel to ignition—did not exist. The laser had not yet been invented and John Nuckolls' pioneering work in the area of laser-based fusion research was yet to come.

Herb York's lectures on magnetic fusion had a specific goal in mind, to stimulate the interest of us physicists to join him in forming a new laboratory on a site near Livermore. This new lab was to have fusion research as one of its main goals.

IAEA

The 1958 Atoms for Peace conference in Geneva, where the United States, Soviet Union, and United Kingdom declassified their fusion research and made it available to all nations. Here, the top officials of the conference (from left): Sir John Cockcroft (U.K.), Dr. Homi Bhabha (India), Dr. V.S. Emelyanov (USSR), Professor S. Eklund (Sweden), Professor F. Perrin (France), Dr. Homi M. Sethma (India), Contreadmiral Otacilio Cunha (Brazil), Dr. W.B. Lewis (Canada), and Dr. I.I. Rabi (U.S.)

A New Laboratory Formed

To make a long story short, after Herb's lectures there was ferment among many of us—trying to think of ways to solve the controlled fusion problem. Several of us then joined the new lab, some to work on controlled fusion, and others to work on classified military applications.

At this point, I think it is important to make clear the underlying source of our fascination with fusion research—then and now. Even before 1952, it was beginning to be evident that within perhaps less than a century, the world could no longer count on fossil fuels for its ever-increasing energy demands. In the long term, it would have to rely on energy released in nuclear reactions, that is, either fission or fusion.

To those of us who went to Livermore with Herb, it seemed obvious that the fusion of heavy hydrogen was the way to go, and we pointed to the world's huge fusion fuel reserve—the fact that 1 in every 6,500 atoms of hydrogen in water was a deuterium atom. Here was a fuel reserve that was not only virtually inexhaustible, but one that would be cheap and universally available; no fusion OPECs, and no future conflicts born of competition for limited fuel resources.

To emphasize the significance of fusion's fuel reserves, here is a thought experiment: Think about the amount of ordinary water—H_2O—that would flow through a city water main about a foot and half in diameter at normal pressures. Then think about putting that flow of water into a deuterium separation plant, using well-known energy-efficient separation techniques. From that input of ordinary water, there would come out of the separation plant a small stream of heavy hydrogen—deuterium. This deuterium, if distributed to fusion power plants and fused to completion, would represent a fuel energy input rate equal to the entire world's energy input rate today: all the oil and natural gas wells, all the coal mines, all the hydroelectric plants—everything!

And as to inexhaustibility, how long do you think it would take to pump all the water in the oceans through an 18-inch water main?

Magnetic Fusion Research Begins

A bit more fusion history: Serious effort on magnetic fusion research began in about 1950, in classified research programs in the U.K., the U.S., and the Soviet Union. By 1955, it was apparent that magnetic confinement of a hot plasma was a much more complex process than first thought, so that at the 1958 Geneva Atoms for Peace Conference, these three countries declassified and described all of their fusion research results in order that the fusion quest could be pursued by all the nations.

To achieve net fusion power it is necessary to heat and then to confine a fusion plasma long enough for the fusion energy released to exceed the energy required to heat the fuel to fusion temperatures. However, as of Geneva 1958, it was clear that the plasmas in every magnetic configuration that had been tried, exhibited plasma instability and turbulence, leading to unacceptably rapid loss of the plasma. This universal observation of the negative effects of turbulence on magnetic confinement defined the central problem for magnetic fusion research from that day forward, up to and including today.

First, some basics of the magnetic confinement for the non-

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T. Kenneth Fowler (left), Associate Director of LLNL from 1970 to 1987, was a co-inventor of the tandem mirror concept in 1976. Here he discusses the MFTF plasma guns with Project Manager Victor Karpenko (center) and Program Leader Fred Coensgen.

scientists: Strong magnetic fields change the straight-line orbits of the ions and electrons of a plasma into tight spirals moving along the field lines. This inhibits escape of the particles across the field lines, but unless something is done about it, does not restrict their motion along the field lines.

In magnetic fusion research, the choice of what that something should be has from its beginning separated magnetic fusion researchers into two distinct groups: those solving the problem of the ends by using closed-field systems—field lines chasing their tails inside a doughnut-shaped chamber—or those studying open-field systems, that is, using a tube-shaped bundle of field lines and then plugging the end leaks by strengthening the field at the ends to form magnetic mirrors.

But the plasma physics issues introduced by making one or the other of these choices are profoundly different, and (here comes the personal bias) the choice that was actually made, in the late 1980s, by most of the world's fusion programs—to restrict their research to closed-field systems—has severely slowed our progress toward the fusion goal.

From Broad-Based Program to Tokamak Only

Up to the mid-1980s, the world's magnetic fusion energy program was on the right path. The program was a broadly based one, with sizable experiments investigating a variety of both closed and open systems, backed up by an extensive theoretical and computational effort. But, not surprisingly, the criterion that was adopted by the policy-makers at that time for judging the merit of one approach over another was how close the magic fusion numbers—plasma confinement time, plasma density, and plasma temperature—that had been achieved experimentally, came to the numbers required for net fusion power.

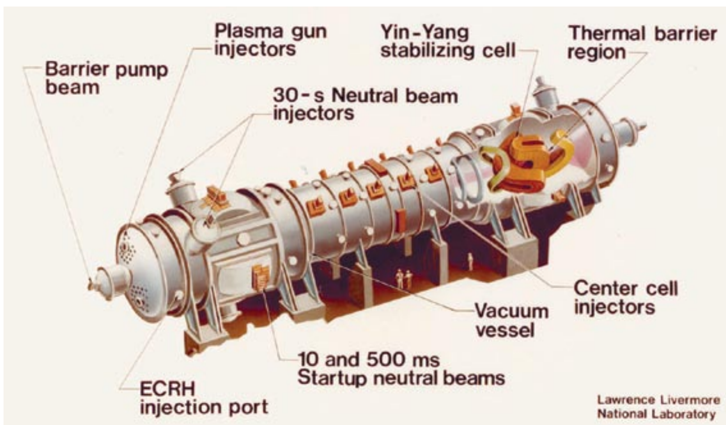
By the middle 1980s, one closed-field system, the tokamak, was the clear winner by this criterion. Why? Because early on, starting with experiments by its Russian inventors, it was found that all you needed to do to get better numbers out of a tokamak was to build a bigger one. Though the tokamak was very difficult to analyze theoretically, and was clearly plagued by a variety of plasma instabilities, nevertheless when one plotted the confinement times of succeeding generations of ever-larger tokamaks against the square of their plasma radius, the data lay on an upward-sloping straight line, aiming directly at plasma fusion ignition in some future, necessarily very large, tokamak.

As I see fusion's history, this simple curve sounded the death knell for all approaches that did not resemble or support the tokamak in some way. Specifically, it virtually terminated the study of open-ended systems, apart from some pockets of resistance at Tsukuba in Japan and at Novosibirsk in Russia.

This shift in program breadth happened even though great progress had been made in open-ended mirror systems, following the invention of the tandem mirror in 1976 by Ken Fowler and Grant Logan, here at the Laboratory, simultaneously with its invention in Novosibirsk, Russia, by Gennady Dimov.

In that heyday for mirror research, a large tandem mirror experiment here at Livermore, TMX, was proposed and construction was completed in 18 months. Tandem mirror systems were also built with similar speed at MIT and the University of Wisconsin in the United States, and at Tsukuba in Japan. At Livermore, TMX was followed by an upgrade, TMXU, and then by the construction of a really large tandem mirror, MFTF.

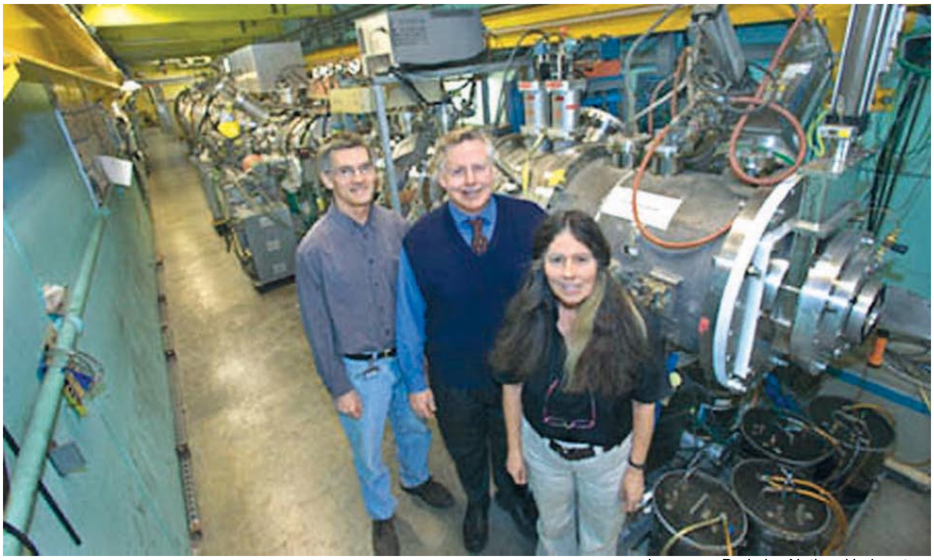
Days after its completion and first shakedown tests, MFTF



THE MFTF TANDEM MIRROR CONFIGURATION

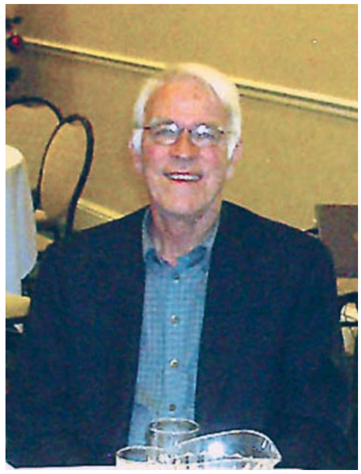
The tandem mirror is a linear system with modular magnetic coils, which is simpler from an engineering standpoint than the tokamak. The plasma flux lines run axially, contained at each end of the reactor by magnetic mirrors.

Source: LLNL



Lawrence Berkeley National Laboratory

Grant Logan (center) the other co-inventor of the tandem mirror, shown here at the High Current Experiment with Peter Seidl (left), and Christine Celata.



Fusion Power Associates

Tom Simonen, former mirror group leader at LLNL, chairs a committee that is investigating the Axisymmetric Tandem Mirror.

was mothballed and all mirror-based work in the United States was terminated.

Where Are We Today?

Where are we in magnetic fusion research today? We are partway down a long trail that dates back to 1985, when a proposal for a really large, internationally sponsored, tokamak, ITER, was made. It then took 20 years—until 2006—before funding agreements ($10 billion) and a site was chosen by the international partners. Another 10 years will be required for construction, and 20 years of operation are planned, after which a demonstration tokamak, one actually generating electricity, would be considered (since the ITER experiment will generate only heat).

To wrap up (here comes the personal bias): Can we afford to wait that long for fusion? Are there faster, better, ways to get there? Here I'll be discussing magnetic fusion only. I'll not talk about the impressive progress in laser-based fusion towards fusion ignition. [National Ignition Facility director] Ed Moses and his co-workers will certainly be covering that in their talks.

First, about ITER: I give ITER high marks for keeping magnetic fusion from dying on the vine, for the international cooperation it has fostered, and for the fusion-related science and technology that was developed and is being developed to implement it. But ITER is like the TV ads for a new wonder drug: If you are patient, this drug will do wonders, but look out for those side effects!

The side-effects of ITER, in my opinion, have been catastrophic for magnetic fusion research. They include: (1) narrowing a program that cries out for breadth to insure success, (2) turning away bright young researchers from magnetic fusion research because its course is already a done deal, and (3) drying

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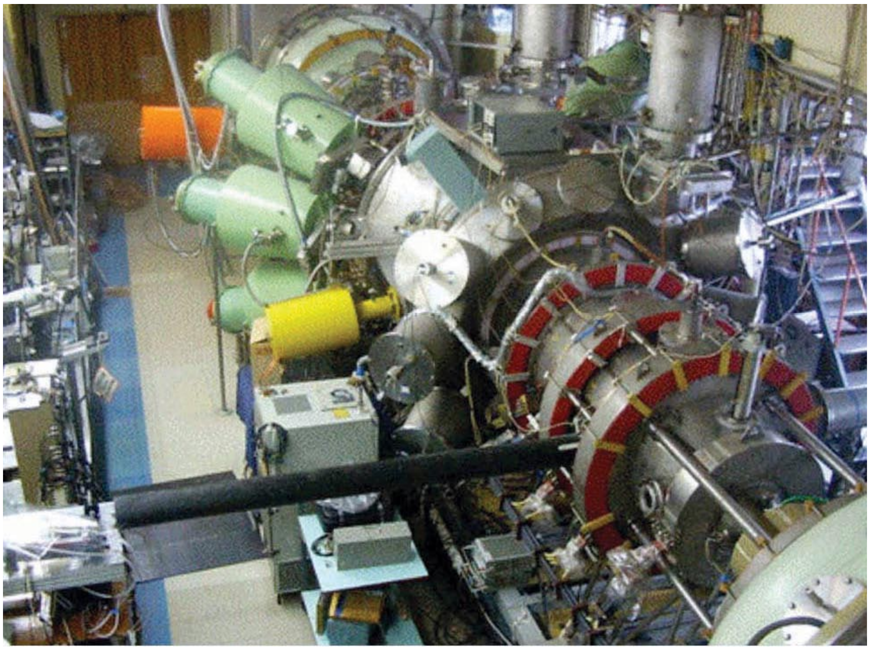
The huge Yin-Yang superconducting magnet for the MFTF, en route from its fabrication site to the construction site.



PPPL

The Gas Dynamic Trap axisymmetric mirror machine at Novosibirsk, Russia, which has demonstrated plasma confinement with no turbulence.

up funding for anything that does not support, or at least resemble, a tokamak.

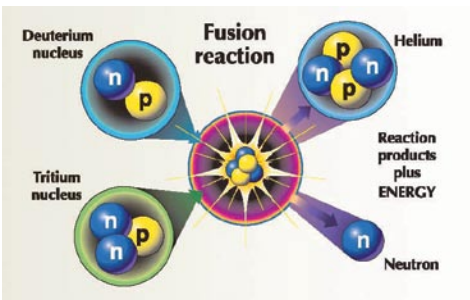
Enough of negativity! I would like very much to finish this talk on a positive note.

First, our critical need for clean and sustainable sources of energy represents a real opportunity for fusion research, if we take advantage of it. One way to put the situation today is to talk of it in terms of present reality and future reality. Present reality says: In the present economic climate and with our prior commitments there is no way we can support a new effort.

The prime example of future reality was when John F. Kennedy said we are going to put a man on the Moon in 10 years. He knew that the science and rocket technology needed for a Moon landing was there, along with the money to pay for it.

I believe that we are in a similar situation today with respect to the magnetic approach to fusion power. We have the basic scientific understanding, the computational horsepower, and the technology to take a new, broader, look at the problem.

And we certainly have the financial wherewithal. For example, we are spending $700 billion a year to import oil. One week of that rate of expenditure—$11 billion—is equal to the entire U S. magnetic fusion funding over its 56-plus years of existence. A 4/10th percent tax on that oil could



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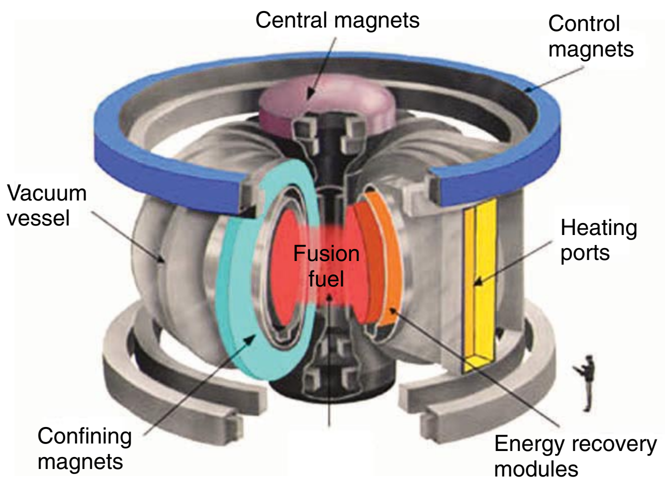
THE FUSION PROCESS

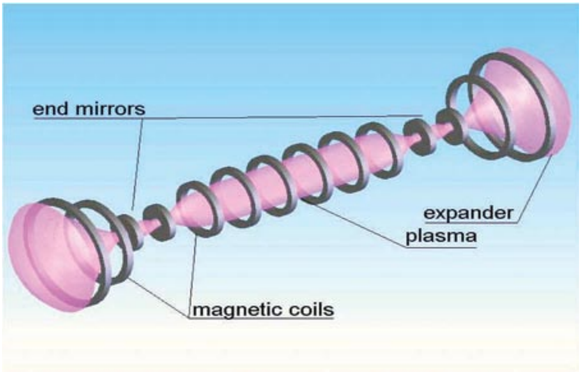
A fusion reaction takes place when two isotopes of hydrogen, deuterium and tritium, are combined to form a larger atom, releasing energy in the process. The products are energetic helium-4 (He-4), the common isotope of helium (which is also called an alpha particle), and a more highly energetic free neutron (n). The helium nucleus carries one-fifth of the total energy released, and the neutron carries the remaining four fifths.

Fusion fuels the Sun and stars, but in the laboratory, atoms must be heated to at least 100 million degrees under sufficient pressure, to produce fusion. Other light elements can also be fused.



MAGNETIC CONFINEMENT FUSION IN A TOKAMAK

In the tokamak, the fusion plasma is contained using a strong magnetic field created by the combination of toroidal and poloidal magnetic fields (the first refers to the long way round the torus, and the other, the short way). The resulting magnetic field forces the fusion particles to take spiral paths around the field lines. This prevents them from hitting the walls of the reactor vessel, which would cool the plasma and inhibit the reaction.



THE AXISYMMETRIC TANDEM MIRROR

In the ATM configuration, end mirrors and magnetic coils confine the fusion plasma. The system is more stable, and no new technologies are required.

T.C. Simonen

pay for a fusion budget that is a factor of 10 larger than the present budget.

A Better Bet: The Fusion ATM

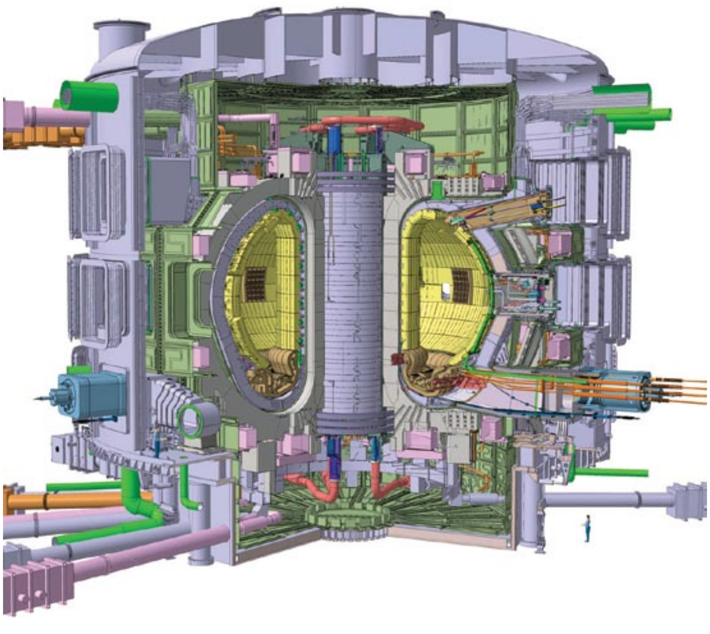
Are there better, faster-to-develop, approaches to magnetic fusion than the tokamak? Yes, there are! As an example, I would cite the recent findings of a Department of Energy-sponsored committee that is taking a new look at open-ended systems, in particular at new forms of the tandem mirror that we call ATMs (for Axisymmetric Tandem Mirror, not for machines for getting money—yet). The committee is chaired by a former Lab employee and mirror group leader Tom Simonen (who is doing a great job). Its members include several Lab employees and retirees, plus researchers from other labs, including MIT, Princeton, the University of Texas, and Los Alamos.

We are now writing the final report. It concludes that the open-ended ATM represents a simpler, and easier-to-engineer, approach to magnetic fusion than ITER, since it is modular in nature and, being axisymmetric, it employs only simple circular coils to create its confining magnetic fields.

What is even more important is that we believe that the ATM could be free of the plasma turbulence that haunts the tokamak and that dictates its huge size. In support of this possibility is a plasma stabilization concept analyzed theoretically by Lab physicist Dmitri Ryutov (when he was at Novosibirsk in the 1980s).

His theory has been confirmed in detail by a series of experiments in the Gas Dynamic Trap axisymmetric mirror machine at Novosibirsk. In the GDT a hot, dense, plasma is confined stably for times in agreement with theoretical predictions, and the plasma shows no evidence of turbulence.

Do I think that the ATM could be a future reality? Yes I do! Do I think that it is the only worthwhile new approach to magnetic fusion? Definitely not! Do I think this country should rapidly re-invigorate its magnetic fusion program? You bet I do!



THE ITER DESIGN

The internationally supported ITER tokamak, now under construction in Cadarache, France, will take 10 years to build, and has a planned 20-year operation. After that, a demonstration tokamak to generate electricity will be considered. Dr. Post makes the case that the tandem mirror is faster and easier to develop.

Source: ITER

A 'Yes We Can' 10-Year Plan for Fusion

John Nuckolls, director emeritus of LLNL, proposed a 10-year strategy for achieving laser fusion, which he said could be accomplished with only 10 percent of President Obama's $150-billion projected energy program. Nuckolls made his presentation at the December 2008 Fusion Power Associates meeting, where he and Dick Post received awards.

Nuckolls, who led research on laser fusion at LLNL for many years, proposed "four steps to fusion power": (1) build an efficient high-average power laser module, a factory for producing laser targets, and a fusion chamber; (2) build a surged, heat capacity inertial fusion energy system; (3) build a fusion engine; (4) build a fusion power plant.

His presentation is available on the FPA website.