INTERVIEW: RICHARD F. POST

A Fusion Pioneer Talks About Fusion and How to Get There

Dr. Post was interviewed by Managing Editor Marjorie Mazel Hecht on June 12, 2009.

Question: I'm honored to interview you Dr. Post. Reading over all your accomplishments, I think we might we need two interviews in order to ask you all the questions I have!

Our magazine, as you know, is the successor to *Fusion* magazine, and we have promoted fusion and advanced technologies for many years now, so what I would like to cover in the interview is the fusion question, the Inductrack maglev, the magnetic bearing, and your flywheel idea—and anything else you'd like to talk about.

Well, fire away.

Question: We also work with a Youth Movement, and I want to have the youth get acquainted with some of these technologies that have been your mission in your career. I'd like to start with fusion, and have you talk about your idea for the ATM, the Axisymmetric Tandem Mirror fusion reactor. You've been working on this for a long time. How do we bring this into being?

In the first place, I would not call it my idea. I did come up with a way of doing it, but there are many ways to skin a cat. The basic concept, that is not what I came up with. I'd been looking at a way of making an ATM, based on theory by [Dmitri] Ryutov but as we learned, there are also many other ways to stabilize the MHD [magnetohydrodynamic] instability mode of an Axisymmetric Tandem Mirror. All I was doing is taking one particular way of trying to see how one would implement that.

But I think that what we start out with, and take as a scientific given, is that an ATM can be MHD stabilized, and then go from there. The details of which particular technique, or combination of techniques, is left for the future. The real point is that what was once considered a bar to the use of axisymmetric fields in tandem mirrors is no longer relevant.

LLNL

Artist's drawing of the Mirror Fusion Test Facility (MFTF), built at Lawrence Livermore National Laboratory in the 1980s. The vaccuum vessel at center is shielded in a seven-story-high concrete vault. The MFTF was forced to shut down soon after it was fully completed because of budget cuts. The U.S. magnetic fusion program was then narrowed to concentrate on tokamaks.

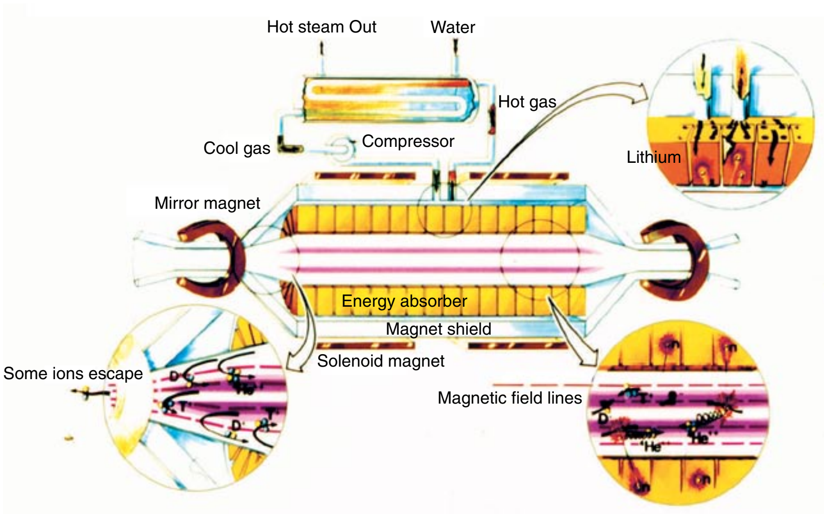
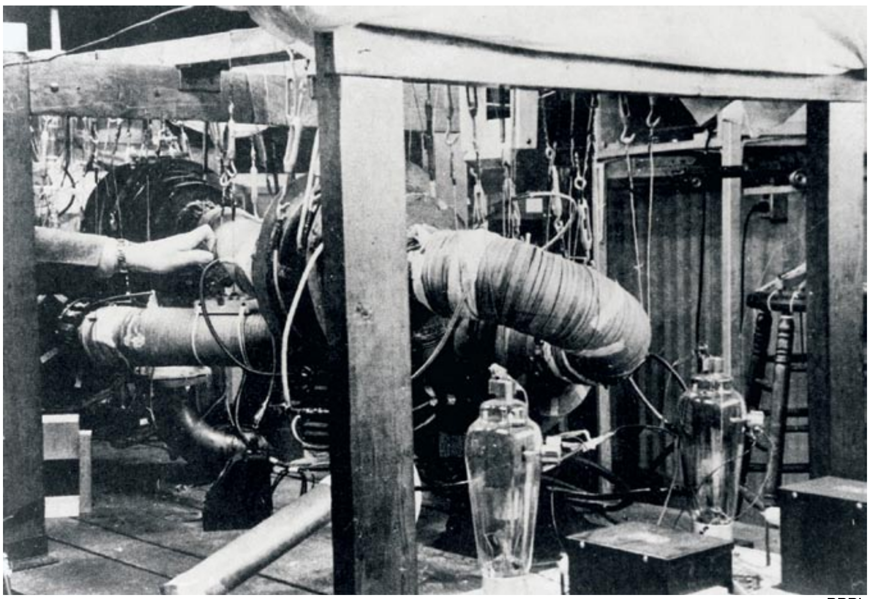


Figure 1
PRINCIPLES OF A TANDEM MIRROR FUSION REACTOR
The linear design of the tandem mirror makes it simpler to engineer and with fewer plasma instabilities than the tokamak configuration.
Source: LLNL

The early history of mirrors involved discovering this drift mode, MHD mode, and the quick fix for it, the genius fix for it, was the Ioffe work in Russia. And the abandonment of axisymmetry, which did solve that problem, introduced a whole host of new problems—

Question: What year was the Ioffe work?


PPPL

The Stellarator A, built at the Princeton Plasma Physics Laboratory in 1952, was Lyman Spitzer's first fusion machine. Its small size can be gauged by the hand at left. The early stellarators bent the torus into a figure eight. Later stellarators were larger, and had more instabilities than the early tandem mirrors.

That was reported in Salzburg around 1961 by Artsimovich, who was the head of the Soviet program. It came at a time when we were encountering that instability and reporting results, and so forth, and he came up with this discussion of the Ioffe experiment, which proved the theory of that. Ingenious, but a double-edged sword in the sense that it brought along a complexity and an introduction of new drift modes for the particles that were not present in axisymmetry.

Now, earliest on, in our ignorance, we had tried axisymmetric systems and found them to be stable, in those particular experiments. We didn't understand why, because we knew from the theory that they should be drifting sideways, but they did not; and so we reported in *Physical Review Letters* the fact that one of these experiments would produce a little spindle of very hot electrons.

We found that the transverse diffusion in this little spindle, which was a couple of centimeters in diameter and maybe 10-20 centimeters long—even though the electrons were very hot—was five orders of magnitude slower than the so-called Bohm rate that was simultaneously being encountered in the big model-C Stellarator at Princeton.

This is a very impressive difference. For the electron spin to drift across a field in that Stellarator experiment required the presence of fluctuations, characterized by the Bohm diffusion rate, and we simply were five orders of magnitude below it. Well, had we pursued this lead, and understood the stabilizing mechanism, which we think we understand years later now, I think we would have gone down a very different path, in terms of mirror research.

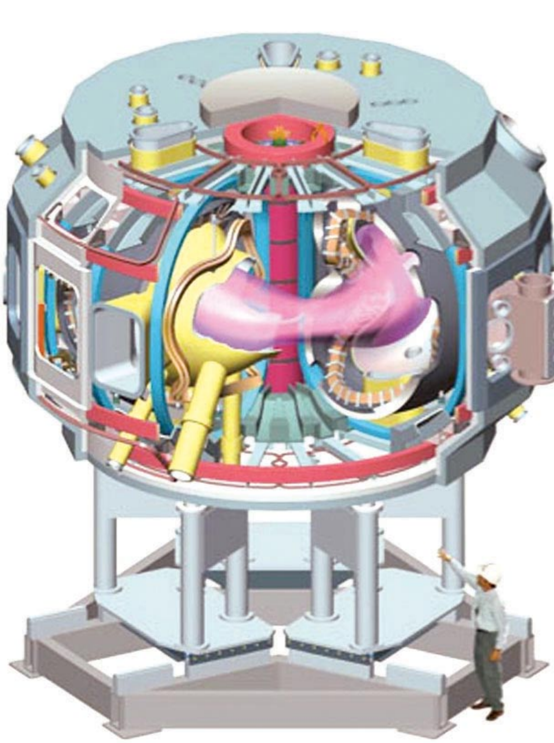
The Importance of Axisymmetry

There are many reasons why axisymmetry is important in this context. What I mean by axisymmetry is basically the shape of a cigar, or party-popper, or something—a cylinder, a cylindrical system with the flux lines running axially [see Figure 1].

Now, there are both physics reasons and engineering reasons why this open-ended axisymmetric system is very, very advantageous. In the first place, as was shown by Teller and Northrup way back when, in the 1950s practically, when you have an axisymmetric system, and particles are trapped in that axisymmetric system of the kind I just described, with a couple of mirrors at either end, the drift surfaces of the particles as they move back and forth, are reflected back and forth, and are drifting around, these drift surfaces are themselves cylinders, closing themselves.

The particle bounces back and forth and drifts sideways slowly. So its orbit generates a surface, and this surface is also axisymmetric.

If you take a Stellarator and put a particle in that, some classes of particles simply drift sideways out of the system. The only reason to confine them, it is maintained, is that those particles are knocked out of those special regions by collisions, so the diffusion



PPPL

The large stellarator project, the National Compact Stellarator Experiment, began construction in 2003 at the Princeton Plasma Physics Laboratory, but was cancelled in 2008 for budgetary reasons. The Lab's remaining project is the National Spherical Torus Experiment (NSTX), which is similar to a tokamak.

LLNL

Nicholas Christofilos, a Livermore physicist during the 1960s, designed the ASTRON Machine to produce controlled thermonuclear energy. He proposed a classic experiment using the Earth's axisymmetric magnetic field to test electron behavior.

rate is enhanced if they weren't doing that. So axisymmetry produced closed surfaces.

There was a classic experiment, that you may be aware of, proposed by Nicholas Christofilos of the Laboratory (LLNL)—an experiment that could never be performed today—which was to use the Earth's axisymmetric magnetic field as a test for confinement of hot electrons, by taking a rocket and blowing off a nuclear weapon in upper space, which released a cloud of hot electrons. And this cloud of hot electrons then was detected and remained being detected for a decade.

There are an enormous number of reflections implied by that number, and I'm just referring back to it, to give you some of the evidence why axisymmetric symmetry is important.

There's also a whole class of instability modes of other kinds that simply are not present in axisymmetric systems. That's because we have no parallel currents, no electrical currents flowing parallel to the field lines, as there must be in a tokamak, for example, for it to work. That's the way the tokamak works. You induce a very strong current around a donut, and that curls up the current into helices, and that's why the tokamak is able to contain a plasma. Otherwise, there's no equilibrium, and if you didn't have that current, the particles would simply drift promptly to the wall.

In any event, there's no parallel current in the axisymmetric systems, and so that source of instabilities is not present. I could list other physics reasons for the better stability for axisymmetric systems, but I think the one I mentioned makes the point.

The main engineering reasons in favor of the ATM are that a linear system with modular coils is far easier to execute than a toroidal system. In the tokamak, all the interior parts are ex-

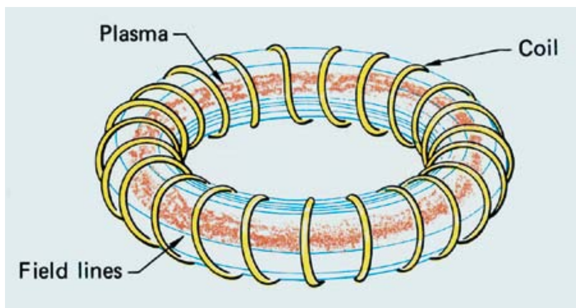


Figure 2
CLOSED TOROIDAL GEOMETRY

A closed toroidal configuration for magnetic confinement of a plasma. The plasma is contained by the fields produced by the magnetic coils and the electric current induced in the torus. This geometry has more instability modes than an axisymmetric system, which has no electrical currents flowing.

posed to neutron fluxes and separated from the exterior. In addition, there is all the complexity that goes with the shape of the magnet coils, and what have you. It's a far more complex device from an engineering standpoint than an axisymmetric linear system would be.

And, the sort of capper in my mind, in the long term, is that an open, axisymmetric system is ideally suited for a direct conversion of these charged particles to electricity.

Direct Conversion to Electricity

Question: Can you explain how the direct conversion works?

We did experiments here, way back when, and validated the theory of this concept. What it amounts to is: Suppose you have a fusion reaction going, and you have particles escaping, which are a mixture of t he slowly leaking fusion fuel and the charged reaction products, the alpha products, for example. They escape out the end, and they are directed by the shape of the flux lines.

You can—as we showed in our experiment, and as other people did in other types of experiments—selectively separate the electrons and ions from this stream of particles, and generate an electric current directly from this system, and at very high efficiency. In our experiments, we exceeded 90 percent efficiency of conversion of the thermal energy of those escaping particles into direct DC electric power.

So, in the long term, when I believe fusion power plants will be going to the primary fuel D-D [deuterium], and using the D-helium-3 end products of the D-D reaction. Most of the energy from that fuel cycle will be coming out in the form of charged particles. If you have a direct conversion system, then you're ideally suited to use these types of fusion fuels, some of which are neutron-free. So in the long term, really long term, fusion can aim toward being about the most ideal system you can think of, in terms of its ability to generate energy from an inexhaustible fuel source.

So if you really want to take a look down the century, so to speak, that potential exists there. It simply is not credible to do it with a tokamak. The field lines don't go out of the system in a way that would allow direct conversion. It's just not credible to me.

High Beta Value with the ATM

Another engineering aspect of the axisymmetric system is, as is shown in the gas dynamic trap experiments in Russia, the so-called beta value, or ratio of plasma pressure to the confining magnetic pressure, which can be very high. Beta values have gone as high as 60 percent in that experiment. Typically in a tokamak, it's about 10 percent. The power density increases with the fourth power of beta. So, being able to achieve that high a beta value makes a huge difference.

What I'm talking about concerning that fourth power variation of power density with beta, is that the plasma pressure

PPPL

Inside a large tokamak. The tokamak geometry is more complex than an axisymmetric linear system, because of the shape of the magnet coils. Also, the interior parts are exposed to neutron fluxes. This is the PDX tokamak at Princeton, constructed in 1978.

Stuart Lewis/EIRNS

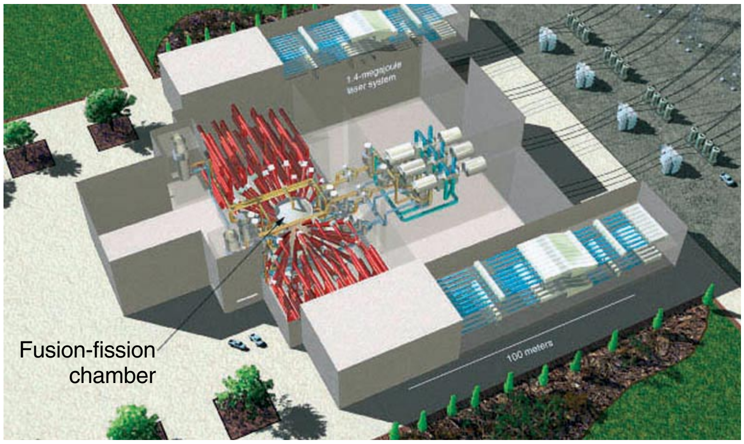
A major advantage of the axisymmetric system is that it can directly generate an electric current at high efficiency. With advanced fusion fuel cycles, which are neutron-free, this could be an ideal system for supplying electric power. The tokamak geometry does not allow for direct conversion.

is proportional to the square of the magnetic field and to the square of beta, the pressure of the plasma. And the pressure squared is what gives you the power density.

In other words, the particle density squared is the fourth power of the beta parameter. So as far as utilization of the magnetic fields for confinement, you have a fourth power of the difference between 10 percent and 50 percent, in your favor, from an engineering standpoint, with the ATM as compared to a tokamak. . . .

There are other uses of the ATM which are being considered, a whole spectrum of uses. One of them is related, in a certain sense, with the work being done in lasers here at the Laboratory. That is, it is proposed to utilize the fusion neutrons from the D-T [deuterium-tritium] reaction to impact the spent uranium fuel and in the process get energy from it. Energetic neutrons can do this. You don't have to utilize a chain reaction at all.

You can also create a situation where you're burning up the radioactive products from the reactions, which means less radioactive waste.



LLNL

A fusion-fission hybrid design would use 14-MeV fusion neutrons to burn spent uranium as fuel, or to transmute the radioactive fission products into non-radioactive or shorter-lived elements.

This is the LLNL design for a fusion-fission hybrid using a laser-fusion system. The fusion neutrons hit a subcritical fission "blanket," generating additional energy. The blanket could be composed of depleted uranium, unreprocessed spent fuel, natural uranium or thorium, or fission products (like plutonium-239) that are separated out of reprocessed spent nucleaer fuel.

Question: You're talking about a hybrid fission/fusion reactor.

Yes, a hybrid system. And then, of course, the direct use for it is simply incinerating radioactive fission products, which is another possibility. Use the 14-MeV neutrons to transmute the radioactive products from fission reactors into non-radioactive or fast-decaying radioactive materials. These are secondary uses; of course, my main interest is the long-term use of fusion power, but I just want to mention the hybrid concept.

Energy Is the Ultimate Raw Material

Question: I think the fusion torch idea is related to the incineration of used fuel. Just to be able to "mine" garbage or rock would be extremely useful.

Yes. And by the way, there is a quote from a very wise scientist, the man who was the director of Oak Ridge National Laboratory several years ago, Alvin Weinberg. In a speech, he said something which I've really thought about, something that was very perceptive, and I'll tell you why I think that is the case. His remark was, "Energy is the ultimate raw material." And the reason that he was so prescient on this is that in the long term, mankind is essentially going to have to recycle things completely. You simply cannot continue to use the garbage dump—you can't continue to throw away valuable materials, aluminum, copper, what have you; these are not limitless resources. And what it takes to recycle these materials, that is energy.

If you have energy available, you can do it. You can do it by chemical processes, what have you, but it always takes energy to do it. And so, what Weinberg meant was, that we should take a long-term view of a sustainable society. Mankind is going to have to use energy to reprocess essential materials, which have been used in the past, into a useful form. And that just takes plain energy. So that's why he made the remark.

That's why, if you really want to take a view down the centuries, I think that fusion is what's going to be our primary energy source—and what I meant in that talk [see accompanying article], is what I'm very serious about: If you have an inexhaustible fuel, and essentially, one of very low cost and one that is universally available, the political implications of that, in a positive sense, are great, really significant.

Question: I certainly agree. I think the question is, how do we get there? How do we take the society we have now, which is really an anti-scientific culture—

Yes, I know—

Question: And turn it into the kind of forward-looking scientific culture that is necessary, where you look at projects in terms of 50 and 100 years, not 2 minutes.

Well, I think we're moving in that direction with the present administration. . . . But you're exactly right. How do we get to create that mindset, particularly since we have this threat of global warming hanging over us. And that's not trivial.

Question: That's a whole other discussion! Our temperature has actually been cooling for the last eight years, and I don't really think we have this problem with global warming.

Well, we have at least some subsidiary problems, like ocean acidity, and what have you.

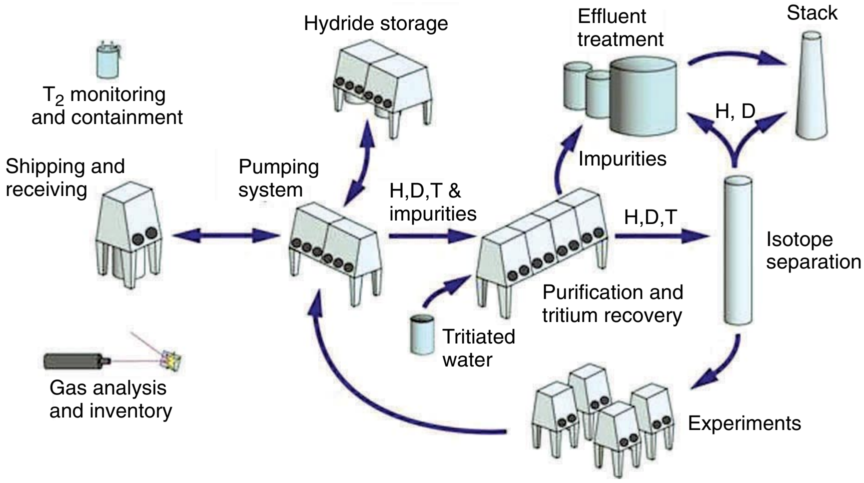
We Need a Broad Scientific Path

Question: Perhaps, but if you have the perspective that man's mind can solve any problem that comes its way, then you don't worry about it, and you don't cut back and say we need fewer people. You move ahead.

I agree. I think it's a solvable problem. In any event, I think the point is, you asked a specific question, and I can give you an answer to it. I tried to say it in my talk, that we had gotten off the path when the tokamak took over. The path we had before in fusion research was a broad scientific path, and my analogy to what happened is, what would happen to cancer research if there was a dictum that we should only work on chemotherapy and forget all the rest of this stuff in medicine. That's all you're allowed to work on.

Question: Ah, well, that's almost what we've got now with cancer research. That would be very bad, yes.

What I'm getting at is, that fusion is such an important topic, and involves questions of an important scientific nature that you'd better understand, that you must maintain a sufficient breadth of the program. You don't say, "I know what the answer is, and this is what you've got to do, by gosh." But that's what's happened. That's what I tried to say in the talk had happened. I wasn't poor-mouthing the tokamak per se, I was saying that the by-product of that policy, like the side-effects that can occur with some new medicines, is that concentration on the tokamak has had side effects that have been harmful to fusion research.



LANL

Fusion fuel—the heavy isotopes of hydrogen in seawater—is virtually inexhaustible. Here a schematic of the Tritium Systems Test Assembly facility (TSTA) at Los Alamos National Laboratory. The TSTA was dedicated to developing, demonstrating, and integrating technologies related to the deuterium-tritium fuel cycle for large-scale fusion reactor systems. The facility was was unique in that it contained all of the systems required to process fusion fuel, sized at full-scale, and fully integrated for a complete tritium-processing "loop."

The site operated from 1984 to 1999, when it was shut down, after the DOE determined that the TSTA mission had been completed.

And so, what we can do about it, and without even a huge expenditure of money, is to reinvigorate the breadth of the fusion program. Let many flowers bloom, so to speak. I mean really to take a serious look at other approaches, and that will bring in bright ideas from young people. They look at fusion now and say, okay, the tokamak, 10 years from now, we'll know if it's going to work or not. And they'll go back to school and study something else, instead of saying, "Gosh, I had this idea for fusion, and where can I work on it?"

Question: I think we've gotten away from that approach, not just in the fusion program, but it's a way of looking at a scientific problem that we don't really have any more, and certainly not to the extent that it's necessary.

Post: Well, there needs to be something like the John Kennedy statement about the Moon.

Question: Yes, I think that Apollo idea is very important. FDR had that idea, as I'm sure you remember the power of his ideas, and what he was able to do with the TVA, which wasn't an overnight "cost-effective" type program; it was looking 50 to 100 years in the future, which is what we have to do.

Sure, yes. I agree with you. That's basically optimistic. What we need to do is find ways of having the innovative side of humanity being favored.

Question: And to have the policy makers see how this is the only way to get the economy going, just as the Apollo Pro-

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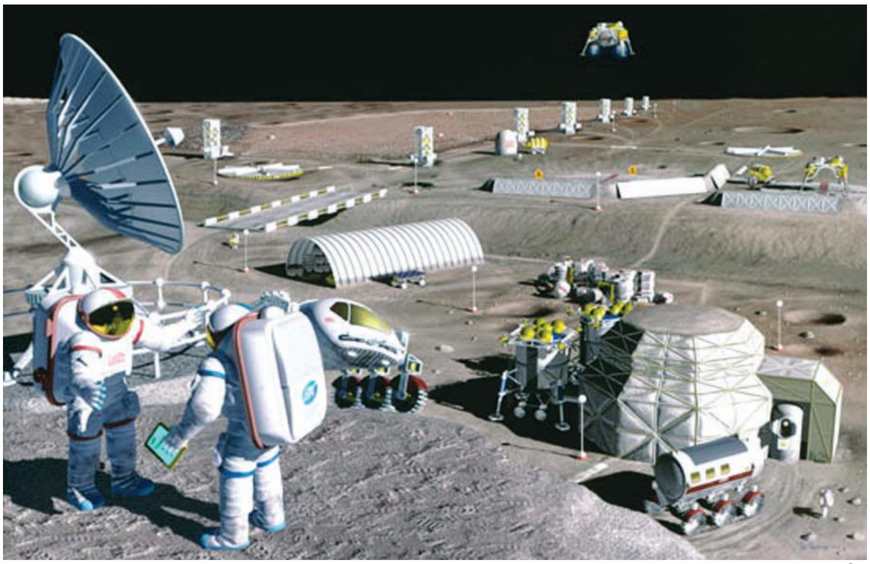
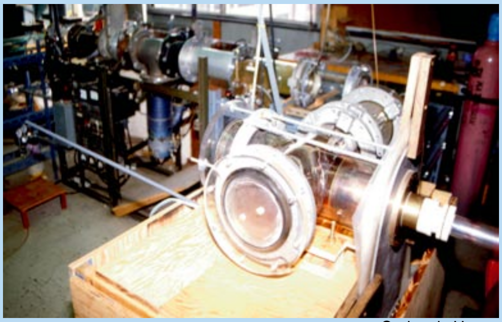


NASA

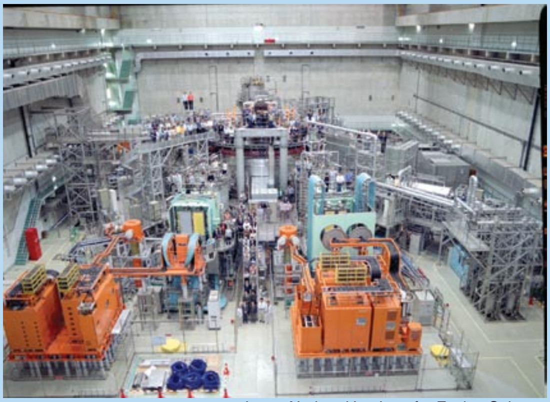
Helium-3 is another potential fusion fuel. He-3, a decay product of tritium, is rare on Earth, but can be found in greater quantity on the Moon. Here, an artist's conception of mining on the Moon.

Many Paths to Fusion Power



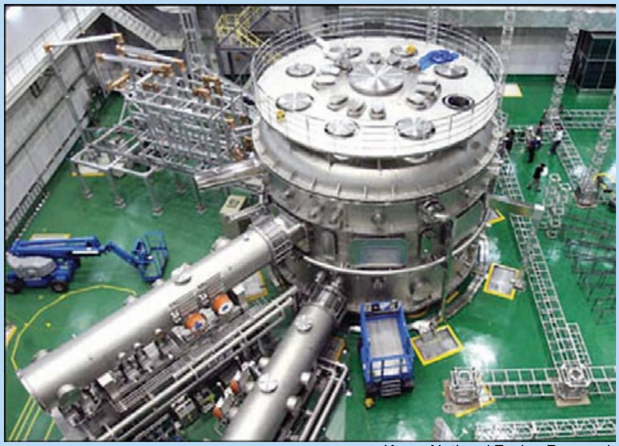
Carlos de Hoyos

The plasma focus fusion device, created by Winston Bostick and Victorio Nardi at the Stevens Institute of Technology, in Hoboken, N.J. Bostick developed the basic theory of the plasma focus, showing that energy is concentrated into tiny hot-spots or "plasmoids," coherent structures of magnetized plasma. These force-free structures carry current.



Japan National Institute for Fusion Science

Japan's Large Helical Device (LHD) project involved construction of the world's largest superconducting helical device, which uses a heliotron magnetic field, developed in Japan. To obtain fusion-plasma confinement in a steady-state machine, the LHD uses superconducting coils and plasma heating systems

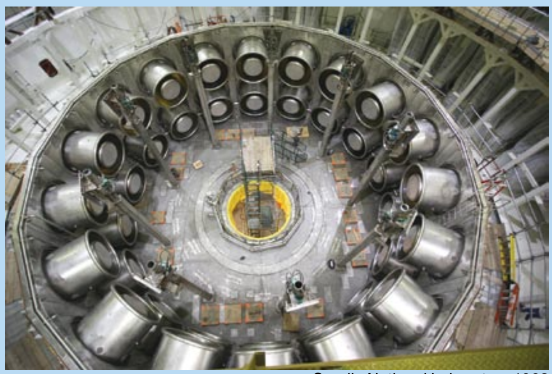


Korea National Fusion Research

Korea's KSTAR fusion reactor at the National Fusion Research Institute in Daejeon, which reached its first plasma on July 15, 2008. It features fully superconductive magnets.

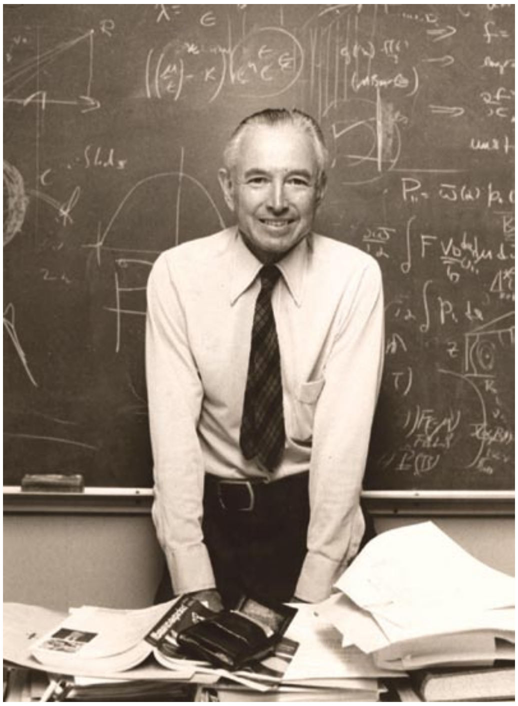
ORNL

An artist's drawing of an Elmo Bumpy Torus fusion power plant. The EBT uses steady-state electron cyclotron resonance heating to produce a steady-state plasma in a current-free geometry. The design features a hybrid magnetic trap formed by a series of toroidally connected simple mirrors. Operated at Oak Ridge National Laboratory in the early 1980s, the EBT's electron confinement agreed with theoretical predictions. The program was abandoned in 1985.



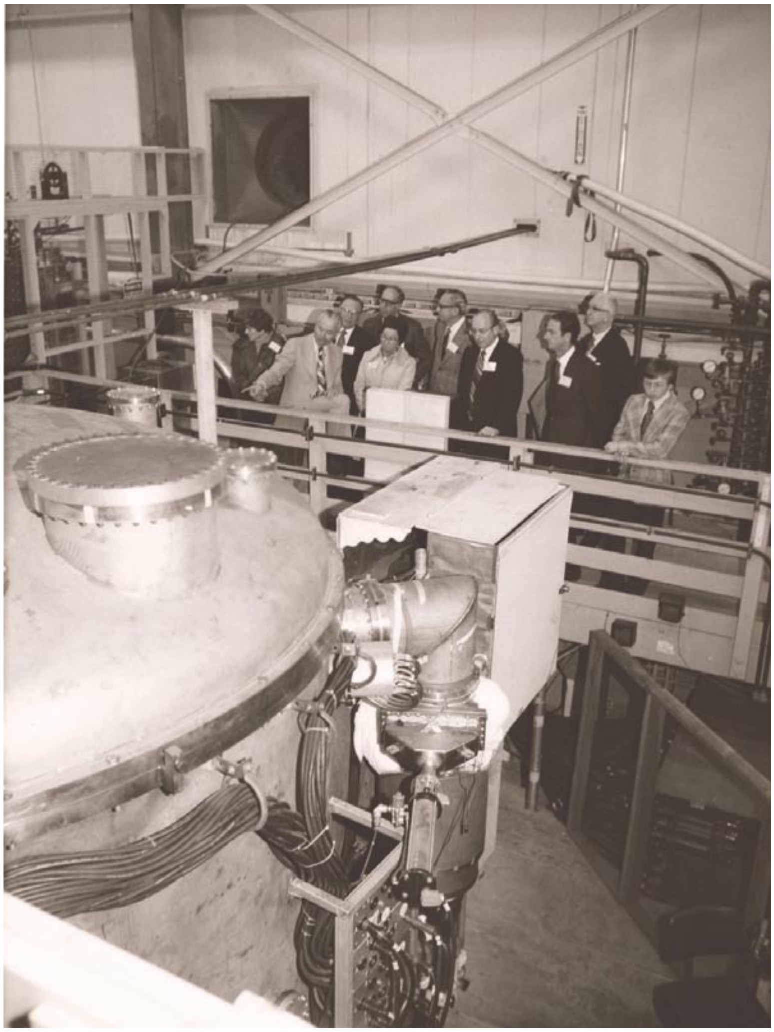
Sandia National Laboratory 1068

Sandia's Z-pinch machine during its renovation process. Its huge conduits focus a massive electrical current on a target the size of a spool of thread. The Z-pinch gets its name from the large current passing in the vertical direction—the Z direction in cylindrical geometry—which creates a magnetic field that pinches together the ions of thin wires that serve as electrical conductors until the current vaporizes them.



LLNL

Dick Post: "There needs to be something like the John Kennedy statement about the Moon." Here, Post teaching.



LLNL

Dick Post showing visitors at Livermore the Tandem Mirror Experiment (TMX), the reactor that preceded the larger MFTF.

gram put back, conservatively, $10 for every $1 that was invested in it, fusion would do much more than that. And advanced nuclear would. You get a transformative capability for the whole economy, for the whole society.

The U.S. is in a very good position to do this.

Something I didn't mention, which is relevant: Here at the Laboratory, we now have computational power, and when you combine that computational power with the relative simplicity of the ATM, you have something which could be simulated in exquisite detail, in my opinion, on a computer. Not that you wouldn't do experiments, but that you would have a much firmer correlation between experiment and theory, because you could say in advance, "this is what I'm going to see," so to speak.

The combination has been used in other technological areas, as a very powerful tool, one leap-frogging computation, leading one into an experiment and the experiment leading to new computation, and so forth, and thereby speeding up the whole process.

The Shut Down of Fusion Research

Question: After the Livermore Laboratory built the MFTF, the Mirror Fusion Test Facility—it was shut down. I don't remember the year it was shut down, but are any pieces of that still around?

No, it was literally cut up into pieces and salvaged. There's nothing left.

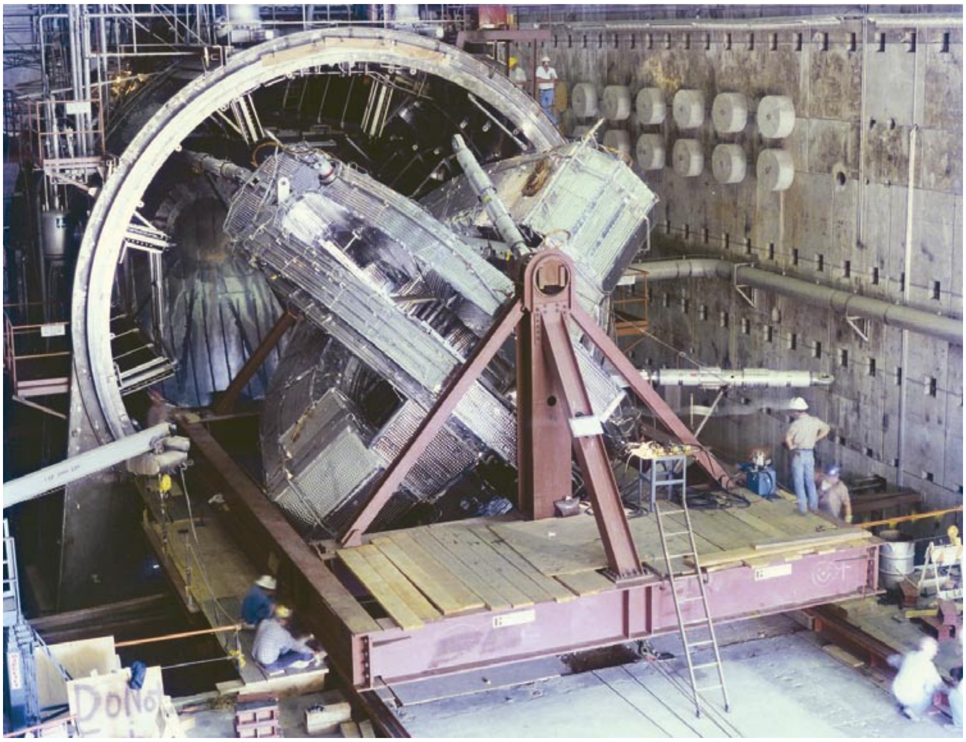
Question: I don't recall exactly the circumstances, but can you briefly say what happened?

Yes, the circumstances were that the U.S. fusion program was flying high as a result of the 1970s oil crisis. We got extra funding, and there was a call for new ideas. There was an ambitious call, an ambitious program here at the Laboratory when the tandem mirror was invented, to explore that concept as fast as possible. And there was authorization put through for this experiment, even though it would be very expensive.

MFTF was built, and then, all of a sudden, interest in fusion research collapsed politically in fusion and the fusion budget was cut. But the national fusion directorate, for whatever reason, decided that that was a signal to center down on one approach, rather than a signal to cut back but still maintain breadth. So they, by dictum said, there would be no support for anything other than the tokamak in this country.

That was not just a casualty, but it was a dictum. So that's what happened.

Question: What year was that?



LLNL

The MFTF in construction, 1981. The reactor was fully completed, but it was shut down before it could begin operating, and then dismantled, and sold for scrap.

The reactor vessel and structures weigh 8 million pounds, including 3 million pounds of superconducting magnets which are cooled by liquid helium to 4.5°C above absolute zero, to confine a fully ionized plasma of deuterium (heavy hydrogen) at more than 100 million degrees. As LLNL described it, "This experiment includes the coolest large body of material to contain the hottest gas on Earth in large amounts at about 8 times the temperature of the surface of the Sun."

Late 1980s, as I remember.

Question: A lot of other programs suffered the same fate at that same time.

That's right. It was a major policy decision which I think, in retrospect, was just plain wrong. But unfortunately, there was also kind of a bandwagon effect. The same thing happened worldwide. The U.S. did it, so others did it. It was a real bandwagon effect. There were only a couple of holdouts—the Japanese with their Gamma-10 Tandem Mirror experiment, and the Russians at Novosibirsk also hung on to the mirror idea. [Gersh Itskovich] Budker—the institute is named after him—was the Russian inventor of the mirror machine, for example. And they have done, on a very tiny scale financially, some beautiful experimental work there, and have continued in that work.

So, the mirror concept didn't completely disappear in the world, but if you look at the scientific papers presented at the international scientific meetings—and I did this for writing up a history of plasma physics for a review; you might like to look at that for fun. It was for a series of books on the history of physics in the 20th Century. I did a tabulation of the number of papers on tokamaks and related things on mirrors over the period, and there's a colossal collapse of papers on mirrors about the time that this happened. You don't even see the word "mirror machine" in a present-day IAEA (International Atomic Energy Agency) meeting, nothing but tokamaks or possibly stellarators.

Question: I know that we reported the MFTF closure, but our last extensive coverage of the mirror machine was at the height of the program.

I wrote a *Nuclear Fusion* survey article back in that time, that tried to collect all of the mirror stuff. If you haven't seen the article, you might just take a look at it. . . . It's the whole issue of *Nuclear Fusion*—it was such a long article, they made it the whole issue.

Question: So, where are we now with your ATM idea? You had mentioned that there's a group discussing it.

Well, after the workshop, which is actually funded by the DOE, Dmitri Ryutov suggested that we have what he calls a mirror forum, which has been "meeting" regularly—meeting in quotes, because it's by phone primarily. Participants make presentations, and send their viewgraphs beforehand, so other participants will know what they are, or some of them are on a TV link, so that they can see the viewgraphs.

There have been a series of papers on various aspects. I had to miss the last meeting, which was a report by Tom Simonen of his trip to China and to Novosibirsk. In his paper, he cited in depth what they are doing at Novosibirsk in mirrors, came back and reported on it. It's surprising the number of participants in the forum; Dmitri issues a list of who attended, and here must be 20 people across the country who were interested—Texas, MIT, someone at Princeton, University of Maryland. All get in on the meeting and toss in their two bits worth. So it's a very informal thing, but there's clear interest here in the country.

Question: Do you have a specific proposal for the U.S. Office of Fusion at DOE, for instance, to go ahead with?

Many specific proposals have been submitted, but none of them have been honored. There's no present one, but I think that will happen perhaps. I think the nearest thing to it is an upcoming meeting which is on neutron sources for material studies. That is a possible use of mirror systems as a neutron source, to do material studies for the tokamak.

Question: That's ironic. . . .

Yes, ironic. I'm not aware that it's gone to a full proposal yet, but there have been such proposals made in the past. You might like to have a conversation with Dmitri Ryutov. He's here at the Lab. And Tom Simonen would be a very fine source for you to talk to. He's living in Berkeley now. . . .

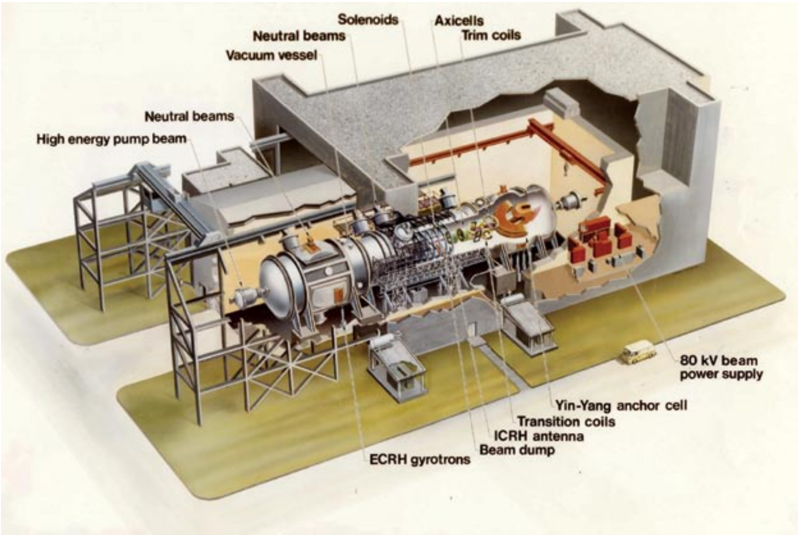


Figure 3
SCHEMATIC OF THE MFTF REACTOR
A cutaway view of the large tandem mirror magnetic fusion reactor. In this configuration, the MFTF has a high magnetic field axicell on either end of 12 solenoid coils. It includes ion heating in the central cell by radio frequency, 16 superconducting trim coils, and pumping with a high energy beam and magnetic field drift pumps. The main magnet coil system includes 26 large superconducting coils with a maximum magnetic field strength of 120,000 gauss at the center of the outer axicell coil.

Magnetic Levitation

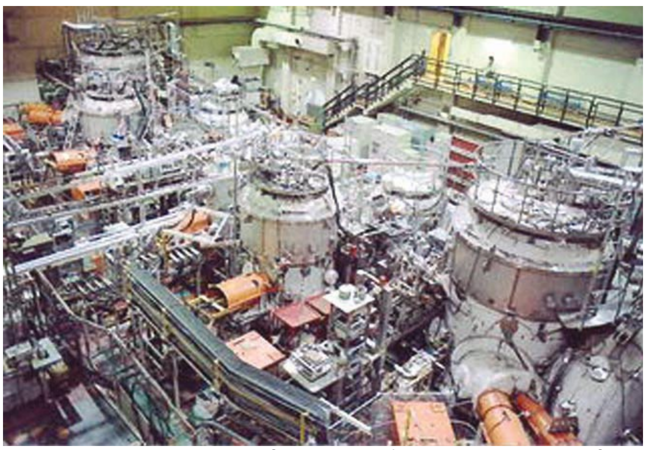
Question: I'd like to switch from the fusion subject to the maglev Inductrack. My husband and a young friend built a small model maglev Inductrack in our garage, and he reminded me of this when we talked about interviewing you. Can you tell us how you got involved with the Inductrack, and what you see as its future?

Well, way back in the 1990s, and much earlier in the 1970s, my son and I worked on flywheel energy storage, and we wrote a *Scientific American* article in 1973 on what we were thinking about. This was quite outside the Lab work. And then we toyed with licensing the patents that we got, and that was not a very successful enterprise. So, I didn't do anything on flywheels for maybe 10 years, but later on, there was an interest at the Lab in reviving such work, so we launched a program within the Lab to develop flywheels.

As part of that investigation, I was working on passive magnetic bearings, and so we came up with some ideas for a passive magnetic bearing. But if you sit down and look at a passive magnetic bearing—which in this case was a circular Halbach array—and look at the set of conductors with which it's interactive, and if in your mind you unroll this thing into a flat track, then you've got the Inductrack maglev system, identically. One is rolled up into a circle, and the other one is laid out flat.

And so I had this idea, and I went to John Holzrichter here, who was running a Laboratory Directed Research and Development Program (LDRD) at the Lab. This LDRD program was set up by Congress so that a director of the national laboratories could take a certain percentage of the budget and devote it to internal support for research into new ideas. It's either done by divisions or there's also an individual way to do it. You can sub-

(Text continues on p. 47.)



Teruji Cho, University of Tsukuba Plasma Research Center

The Gamma 10 Tandem Mirror at Tsukuba University. Japan has kept the mirror concept alive in this ongoing experiment. The Gamma 10 is 27 meters long, with large end tanks.

The Russians also are pursuing the mirror idea. See p. 34 for a photo.

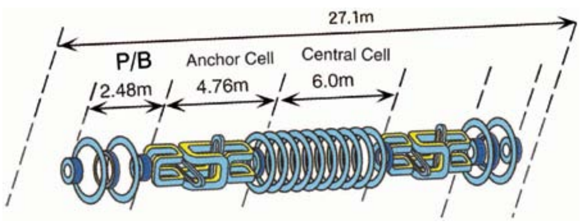


Figure 4
GAMMA 10 MAGNET GEOMETRY
The axisymmetric geometry in Japan's Gamma 10 Tandem Mirror. It is powered by ion cyclotron resonant frequency and Electron Cyclotron Heating.

Laser Fusion: 'Yes We Can'

John Nuckolls, director emeritus of Lawrence Livermore National Laboratory, has proposed a 10-year strategy for achieving laser fusion, which he said could be accomplished with 10 percent of President Obama's $150-billion projected energy program. The contents of Nuckolls's proposal addresses issues of science not well-known to today's general public, but which should be better known.

In laser fusion, a tiny target of deuterium, sometimes combined with tritium, is compressed by a shock wave which is produced by focussed laser beams. The shock causes the deuterium, a naturally occurring isotope of hydrogen present in seawater, and tritium to combine, forming a nucleus of helium and a neutron. The mass of the resulting helium nucleus is less than the component nuclei, and the mass difference is released as energy, according to the famous equation $E = mc^2$. The energy release per fusion is several times greater than that produced by the fission of a uranium nucleus, which is millions of times greater than the energy released by burning of a molecule of oil or natural gas. The heat of fusion energy can thus drive electrical turbines with far greater efficacy than any known power source, and can also be utilized in a device known as the fusion torch, to break down raw ore and even garbage into its constituent elements.

Dr. Nuckolls, who led research on laser fusion at the national laboratory 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.

Inertial Confinement Methods

Fusion energy by laser ignition, known more generally as inertial confinement, has already been repeatedly demonstrated, and was one of the leading paths being pursued when the national fusion energy program was effectively dismantled in the 1980s. Nuckolls was addressing the means needed to develop a laboratory proof-of-principle demonstration into a commercially workable energy generation project.

Inertial confinement production of fusion energy is related to the means by which a hydrogen bomb is detonated, and thus emerged from the national laboratories as one of the peaceful spin-offs of military research. In one method of laser fusion known as indirect drive, a closed chamber known as a hohlraum is used to focus thermal X-rays produced by the laser heating, which in turn can drive the nuclear fusion.

Indirect drive hohlraum targets are used to simulate thermonuclear weapons tests. A key to the technique involves understanding the singularity which occurs upon formation of a shock wave. Soviet research in the field was stimulated by study of the famous paper by the 19th Century mathematical physicist Bernhard Riemann, which had predicted the appearance of sonic shock waves decades before their experimental verification.

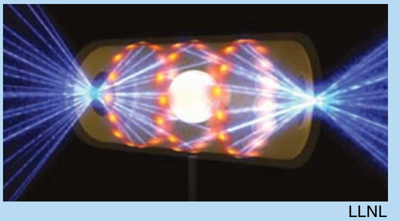
LLNL

Construction workers install equipment inside the 10-meter diameter target chamber at the National Ignition Facility. The spherical chamber, 10 meters in diameter, is constructed of aluminum panels covered in concrete that has been injected with boron to absorb neutrons from the fusion reaction. The holes in the target chamber permit the laser beams to enter the chamber and provide viewing ports for all of the diagnostics.

Other methods of inertial confinement fusion do not require lasers. These include the Z-pinch, in which the vaporization of fine wires by an intense electrical current causes a compression of the wire (Z-pinch) that produces X-rays which drive the fusion of the target. In another method, recently proposed by Dr. Friedwardt Winterberg, the high-voltage discharge of an early type accelerator known as a Marx Generator produces a very powerful instantaneous magnetic field pressure which compresses a cone-shaped deuterium-tritium target, using an ingenious geometry.

Nuckolls made his "Yes we can" proposal at the annual meeting of Fusion Power Associates held in Livermore, Dec. 3-4, 2008.

Lyndon LaRouche has been promoting efforts to develop thermonuclear fusion power since the 1970s. His energy policy calls for immediate deployment of nuclear power, including a rapid gear-up of the new fourth generation high-temperature reactors, expanded research and development of thermonuclear fusion energy, and broadened support for investigation into the anomalous nuclear effects implied by the phenomenon of cold fusion. —*Laurence Hecht*



LLNL

Artist's rendering of a NIF target pellet inside a hohlraum capsule, with laser beams entering through openings on either end. The beams compress and heat the target to the necessary conditions for nuclear fusion to occur.

mit a proposal as an individual, working with other individuals, to try out a new idea.

So, I took this Inductrack idea—Dmitri Ryutov helped me with the theory of it—and submitted it as an LDRD proposal, and we actually got a substantial amount of money—I forget how much—to build a larger scale model of it, and test it.

Our model actually worked very well. And we reported our work at scientific meetings. NASA people were at the meetings, and they had a project called Mag-Launch, which is the launching of rockets by maglev methods, in order to avoid double staging. So they gave us a very substantial contract to build a small model to demonstrate a technology that might be used in Mag-Launch. We built the model and we operated it, but then their budget was cut, so we had to take the model apart, and ship it back to Florida, for some university to put together and try it in the future.

But, while the model was working, General Atomics had received a substantial contract from the Federal Transportation Administration to develop a generic urban maglev system. GA had looked at the Japanese superconducting system, and the German system, Transrapid. And they decided that neither of them was really suitable economically or otherwise for an urban system.

So they came up and looked at our Inductrack, and adopted the idea. Following that we've had a series of contracts for several years now with GA. We helped them with the magnetics of it. We actually built a little model to test the laminated track idea here at the Lab, and we got a very close correlation with theory and experiment on that. So we've had an affiliation with GA since their maglev program started. We're a member of the team of engineering companies in Pennsylvania—General Atomics and the Laboratory. And GA has now, as you know, built a full-scale test track. And most recently they built a brand new chassis using a new magnetics design that we provided for them. It works very well, and they are hoping to be en route to building a demonstration maglev system at the University of California in Pennsylvania (!).

LLNL

The Livermore members of the Inductrack team: (standing, from left) J. Ray Smith, Louann Tung, Richard Post, Don Podesta, William Kent, and Edward Cook; (kneeling, from left) Joel Martinez-Frias and Dmitri Ryutov.

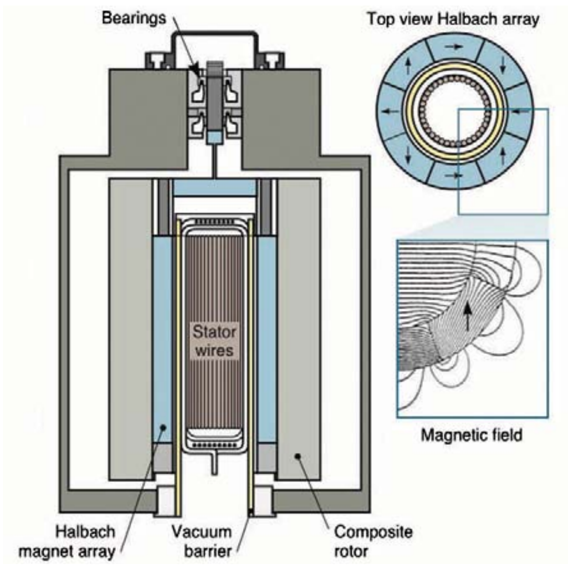


Figure 5
THE FLYWHEEL BATTERY

The LLNL flywheel battery, developed by Dick Post, is a high-tech version of an ancient concept: using a rotating wheel to store kinetic energy, as in a potter's wheel. Here, the energy is stored in a rotor made of a high tech fiber material that spins above a magnetic bearing at about 40,000 to 50,000 revolutions per minute. The flywheel is used for the bulk storage of electricity.

Post's complement to the flywheel, an electrostatic generator/motor, is useful for generating electricity.

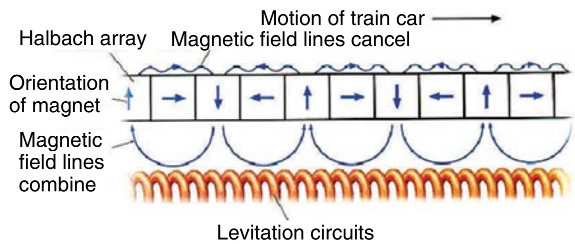


Figure 6
HALBACH ARRAY ON A MAGLEV TRACK

Post's idea was to unroll a Halbach array of magnets into a flat track, for use with a maglev train.

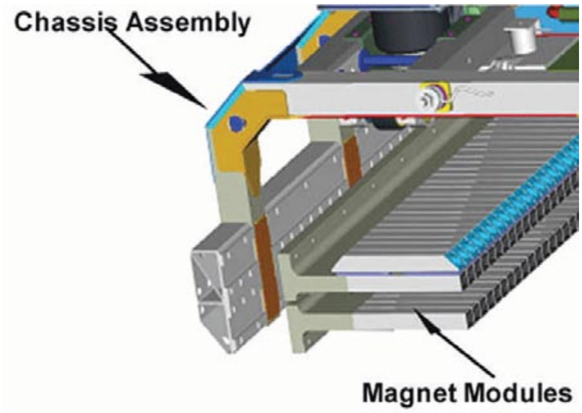


Figure 7
HALBACH ARRAY ON THE INDUCTRACK
Illustration of a Halbach array on the Inductrack maglev.
Source: General Atomics

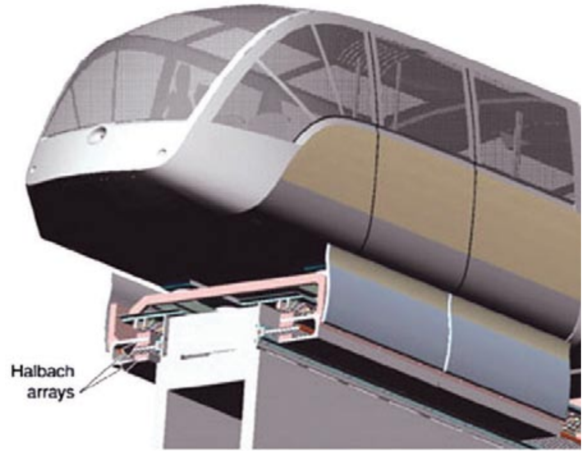


Figure 8
INDUCTRACK FRONT END OF VEHICLE
Illustration of the front end of an urban maglev vehicle, showing the vehicle's levitation/propulsion module. Dual Halbach arrays of permanent magnets are positioned under the train car to provide the levitating force.
Source: LLNL

Question: Yes, the name is incongruous.

It's ironic. They also did a study for adopting another form of our Inductrack, aimed at heavy loads for cargo transport, that is, container cargo transport in the Los Angeles port area, where they are now using diesel trucks to haul the containers inland, and they have a very serious pollution problem. It's also an expensive way to transport the containers. It could be replaced by a maglev system with no pollution and a lot less energy use. I don't know whether that project will be funded or not, but GA did a very good study in which we cooperated and were able to come up with a redesign of the magnetics for the Inductrack that made it suitable for very high loads.

Question: What is the difference between the high load and the passenger system?

It's a matter of the design of the Halbach arrays, how they are configured. They are configured in such a way that we were able to use a track which did not have to be cantilevered. It would lay flat on a piece of concrete, so that it would absorb the high loads. We were able to do this, at the same time, by keeping the losses very very low. So the magnets were redesigned, basically the magnetic configuration was redesigned to accomplish the result.

Question: It seems to me that the Inductrack and maglev in general have suffered the same fate as fusion. It's a wonderful idea, it's certainly the way to go for the future, and it hasn't been funded in this country.

That's right. I think that might be changing. There may be more reception now. By the way, I didn't mention this, but even though the Inductrack was developed for an urban system, it works perfectly well at high speed, and is thus a good candidate for high speed maglev systems.

Question: Our organization has proposed a Eurasian Land-Bridge, which would go from the east coast of China to Rotterdam in the west, with a northern and a southern route (large sections of this have already been built), and we have been urging the governments involved that maglev be chosen for the rail part of this.

Well, there are several different maglev systems, but the Inductrack is so simple, and also fail-safe.

Question: I know from reading what you've written on this, that it's also considerably cheaper, because you don't have to super cool the magnets.

It can be cheaper, that's correct.

LLNL
The 20-meter, scale-model test track used to test the Inductrack concept at LLNL. The test cart and electric drive circuit are in the foreground.

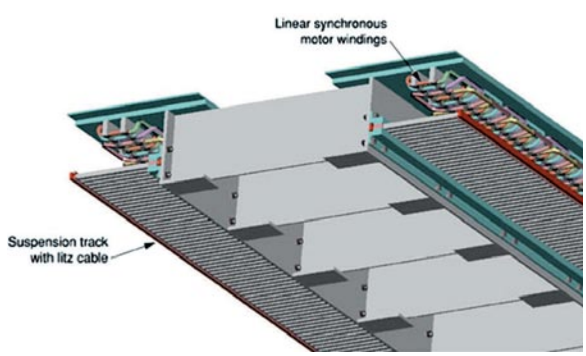


Figure 9
The GENERAL ATOMICS TEST TRACK
Illustration of the Inductrack maglev test track, showing motor windings embedded in the track. The windings are used with a linear synchronous motor to power and brake the train. Train cars ride on a suspension track of ladder-like construction, which consists of closely spaced rungs composed of tightly packed bundles of insulated wire. When the train starts to move, the magnets induce electrical currents in the track's circuits that produce a magnetic field. This magnetic field repels the array, thus levitating the train car 2.5 centimeters above the track.

LLNL

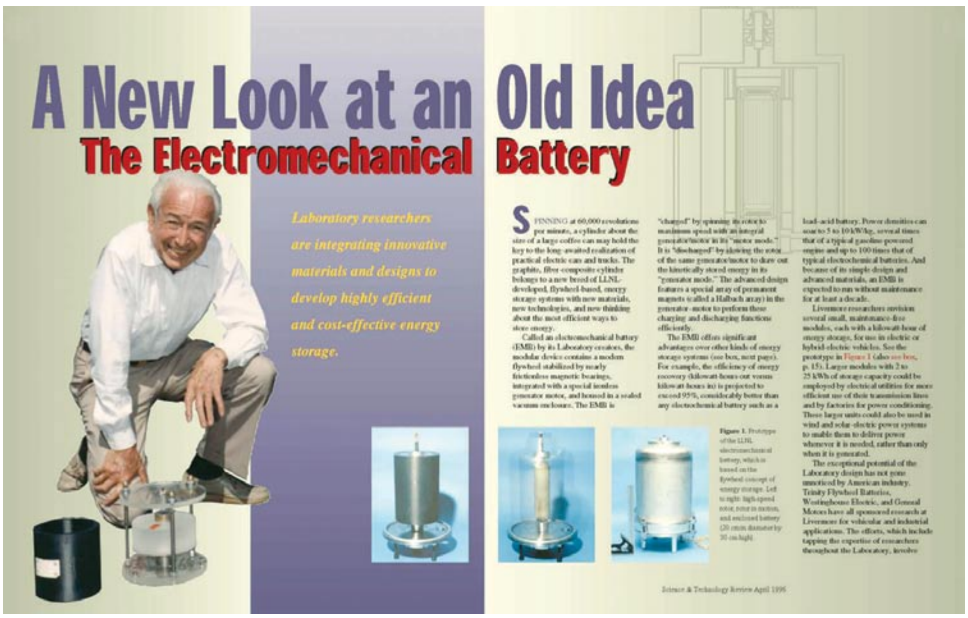
The General Atomics full-scale Inductrack test vehicle on the first section of its test track.

Now you also wanted to hear about energy storage? Well, we're right in the middle of trying to launch a new generation of flywheel-based energy storage systems aimed at bulk storage. The former work we did in the 1990s was aimed at a niche market which consists of essentially uninterruptible power supplies. In these systems you have them floating on the line when the power goes off, and it takes 15 seconds to start your diesel generators. So, the flywheel comes up with a burst of power for that period of time, until the diesel can come on. It's high power for a short time.

However, the solar and wind power industry in particular, needs a different kind of energy storage. It needs something where they can slowly charge it up during a few hours, and then, it can sit there charged until later it's used to deliver power. This creates the possibility of having what's called "dispatchable power" from wind and solar systems. It means that it could provide power at any time of the day, independent of whether the Sun is shining or not, so long as you have stored the energy.

So, there are several companies interested in what we call our new-generation flywheels. And the new-generation flywheels are different, in the sense that we've abandoned the electromagnetic generator and are going to a modified form of electrostatic generator, the pioneering work for which was done by Trump at MIT in the 1950s. However, we modified his ideas to make the electrostatic generator more suitable for our purpose. The point of the electrostatic generator is that it has extremely low parasitic losses. That is, if it's just sitting there, no losses.

On the other hand, if you have an electromagnetic generator with the permanent magnets, there are always eddy current losses and hysteresis losses going on, even though it's not drawing any power. So it's very difficult to reduce those losses. And also, electromagnetic generators are usually very heavy. Our



LLNL

Dick Post with his electromechanical battery, as featured in the LLNL Science & Technology Review*, April 1996.* *https://www.llnl.gov/str/pdfs/04_96.2.pdf* electrostatic generator is very light, and that helps.

Question: What does it look like, and how does it work?

Ours looks something like Trump's but is a different design. Trump used a system that resembled two sets of fan blades, one of them stationary, one rotating, facing each other. So as you rotate one fan blade, first it matches up with the other fan blade and the electrical capacity is high. When it rotates to a notch in between, where the plates don't match, the electrical capacity is low. And that's all it takes to make an electrostatic generator.

It works this way: If you charge any condenser with a fixed amount of charge and then you vary the value of that condenser, the voltage varies inversely with the capacity. In other words, charge divided by capacity is the formula. And so the capacity is a function of time. The voltage across the capacity is a function of time. So if it's periodically varying, then you're going to generate an AC-like wave form. From this simple process, having the capacity increase *and* decrease with time. We've done some additional modifications of Trump's designs, but that's the basic idea.

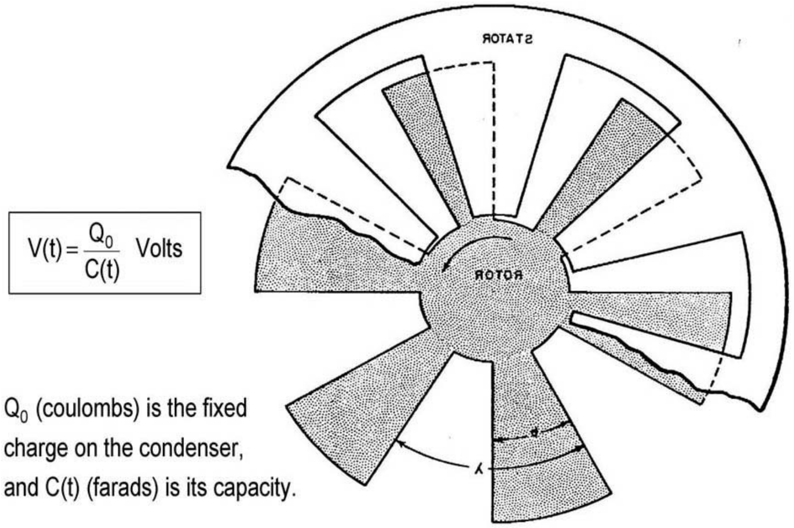


Figure 10
THE TRUMP DESIGN FOR AN ELECTROSTATIC GENERATOR

John Trump's design for an electrostatic generator. Post modified the pioneering design of Trump to develop a lightweight generator which has none of the eddy current and hysteresis losses of an electromagnetic generator that uses permanent magnets.

In Trump's concept, as one fan blade rotates and matches up with a stationary blade, the electrical capacity is high; when it rotates to a place where the blades don't match, the electrical capacity is low. The periodic variability generates a fluctuating voltage, which can be rectified to DC current.

And so you take this fluctuating voltage and couple it out through condensers to a rectifier system, and rectify it to DC current, and then transform the DC power to whatever you want. So the idea is to simplify matters, and reduce the parasitic losses. In an electrostatic generator, the internal losses are essentially zero.

LLNL

In this device, LLNL-designed Halbach-array generators are incorporated in AFS-Trinity Flywheel modules, producing 350-kilowatts output from 25-centimeter diameter rotors.

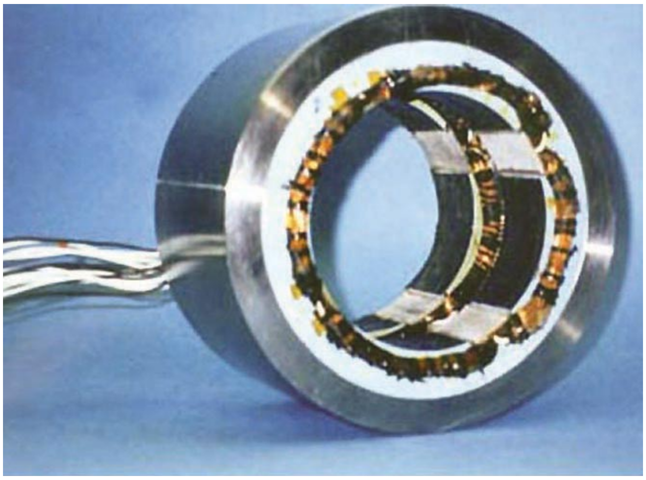
In a flywheel system, it's important to minimize internal heat losses, because it's very hard to carry away heat in a vacuum. The electrostatic generator has essentially zero heat losses internally, and the only inefficiency that's associated with it is whatever inefficiency there is in the rectification and power electronics, not in the generator. Whereas, electromagnetic generators always have hysteresis losses and eddy current losses, internally. And there's heat to be dissipated, for one thing, internally. . . .

Question: You are still carrying out what seems to me to be a mission in life. You're coming to work four days a week, at age 90.

As my wife says, "Friday's your retirement day."

Question: But that's good! We need to get more people like you in the younger generations, to get that kind of spark.

Well, I really do want to see something come of my knowledge of physics in my lifetime, with some of these things. I have no hope that fusion will be in my lifetime, but I think that the work that all the fusion people have done is money in the bank, and fusion power will come to pass. But it would be really nice if the Inductrack or the energy storage systems actually happen before I kick the bucket.



NASA

A magnetic bearing uses magnetic levitation to support a load in moving machinery without any physical contact. Magnetic bearings are an essential part of Post's flywheel system.

Question: Well, I think that human beings have immortality in the sense that their ideas live on, and that the effect is felt long after the person is gone.

There certainly are some occasions where that is true. Also, what the heck, I like to work on the things that I think are going to help problems.

Question: That's a good thing. Youth today don't know how things work. They are in the digital age. They press buttons. . . .

That's a very interesting comment. When I was a kid, 12 years old, I was a radio ham, and I had to build all my own stuff—transmitter, receiver, the whole shmear. And where I got my parts was going out to the back, behind radio stores, where they'd thrown out old radio sets. And I picked them up, took the parts out of them.

Question: But that's the way you learn; that gets you going on a project, and I don't think that many youth have that experience today.

No, they don't. My son has a very interesting observation. My son Steve is a very fine engineer. He runs a little company near Livermore that builds electronic controllers for electric vehicles. And his kids are in the Athenian school, a very fine private school here in the area. The school entered the robotics contest. . . .

This is the contest for schools where they go and compete against other robots, doing various called-out tasks and games. They had to build the stuff from a kit that's supplied to them, plus manufacture their own parts. So Steve had the school kids come to his own home shop to do the building. And he said that the girls were much better than the boys. The girls really learn to do these things. The boys are so tied up in video games and so forth, that they just didn't know what to do. I'm making an overall generalization, which is probably not completely true, but he certainly noticed the difference.

Question: That's very interesting. I do know the problem of the video games. It's like an addiction that keeps these children out of reality and out of the real world, the nuts and bolts of how things work.

You know tinkering is somewhat of a lost art, except when it's particularly pushed, as Steve did with these kids and robotics. They did a beautiful job. (They won, actually.)

Question: What the Youth Movement is working on, in small groups, is going through the basic experiments and work of Kepler, Gauss, Riemann, and other scientists, and redoing them, just to know what the thinking process was; that's the way they've been approaching it.

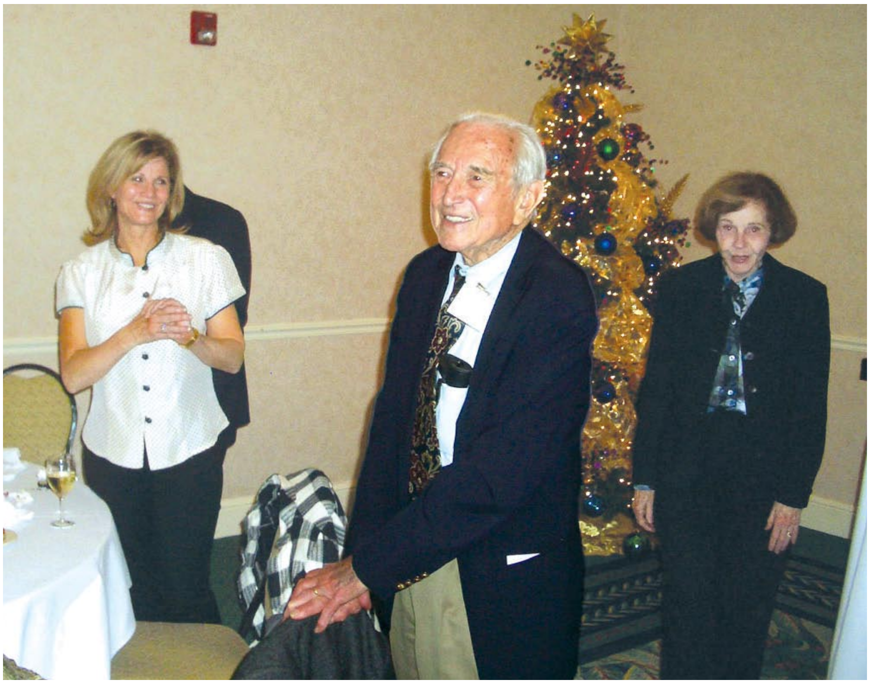
That's wonderful.

Question: We're trying to spread that idea and so I think this interview, which we'll publish with your talk, will give people some ideas about how you go about solving some of these problems. What impressed me was the magnetic bearing, and how important that can be in so many applications.

Yes, there are many applications. They are an essential part of the new flywheel

LLNL

Livermore's UNIVAC computer, on its last run in 1959. Today the Lab's high-performance computing capability enhances experimental work, such as that for the ATM, by previewing design results and potential problems.



FPA

Richard Post with his daughter, Markie Post Ross (left), and his wife, Marylee, at the 90th birthday celebration hosted by Fusion Power Associates.

Question: That sounds like an important factor in the trajectory of your whole career.

I had some wonderful teachers, and Hansen was one of them. He died about halfway through my thesis, which was experimental, and so I had to shift to a theory—inadvertent pun—Leonard Schiff was the theorist, and so half my thesis is experimental, and half is theoretical. That was a tragedy, Hansen's death, but there was a fortunate consequence of it. . . .

I know I have very little brain when it comes to some areas. Dmitri Ryutov can run rings around me in theory. I'm sort of a funny half-mixture, but anyway, it works!

Question: It's not funny—it's very useful.

system that we have.

And the other thing, just a general comment is—and I think you've already said it, but I'm going to say it again because it's so important: It's such an important thing to have a combination of computing and hardware, because the devil is in the details. You get sobered by the fact that when you are actually trying to do something, you've got to work out all the things that you hadn't thought of. And there's a very powerful way of coordinating theory, and computation, and experiment—but the experiment has got to be there; it's an essential part of it.

And so what you said a minute ago is exactly right: Repeating some of these experiments, because the actual doing of them, and the actual finding out what's what, is very important.

Question: The whole thinking process that goes on. . . .

I had a wonderful physics professor in graduate school, Professor Hansen, who is one of the co-inventors of the linear accelerator at Stanford and also one of the coinventors of the klystron [a linear beam vacuum tube]. Anyway, Professor Hansen had what he called a modern physics lab, and one of the experiments I particularly remember, was measuring the gravitational constant, and the very clever way he did it with a torsion pendulum with big balls of lead.

You had a torsion pendulum, with the ball of lead hanging on an arm so that it could torque. And then you would bring up a big mass at a particular time, and you would leave it there for a particular time. And those two masses would attract each other ever so tiny a bit, and move that torsion pendulum. And so you took the data from that and then calculated the universal gravitational constant, and you darn well better be within 10 percent. That was among the very clever experiments that were done in that lab.

For Further Reading

R.F. Post, 2007. "The Kinetic Stabilizer Axisymmetric Tandem Mirror: A Review of Approaches to Its Implementation," *Fusion Science and Technology*, Vol. 51, No. 2T, pp. 112-117 (Feb.)

R.F. Post et al., 2005. *Fusion Science and Technology*, Vol. 47, p. 49.

R.F. Post, 2000. "Maglev: A New Approach," *Scientific American* (Jan.)

R.F. Post, 1999. "Fusion Research: The Past Is Prologue," in *Current Trends in International Fusion Research: Proceedings of the Second Symposium*, E. Panerella, Ed. (Ottawa, Canada: National Research Council Press).

R.F. Post, 1999. "Mirror-Based Fusion: Some Possible New Directions," *Transactions of Fusion Technology*, Vol. 35, p. 40 (Jan.)

R.F. Post, 1997. "Open Systems in the Quest for Fusion," *Plasma Physics Reports*, Vol. 23, p. 756 (Sept.)

R.F. Post and S.F. Post, 1973. "Flywheels," *Scientific American* (Dec.)