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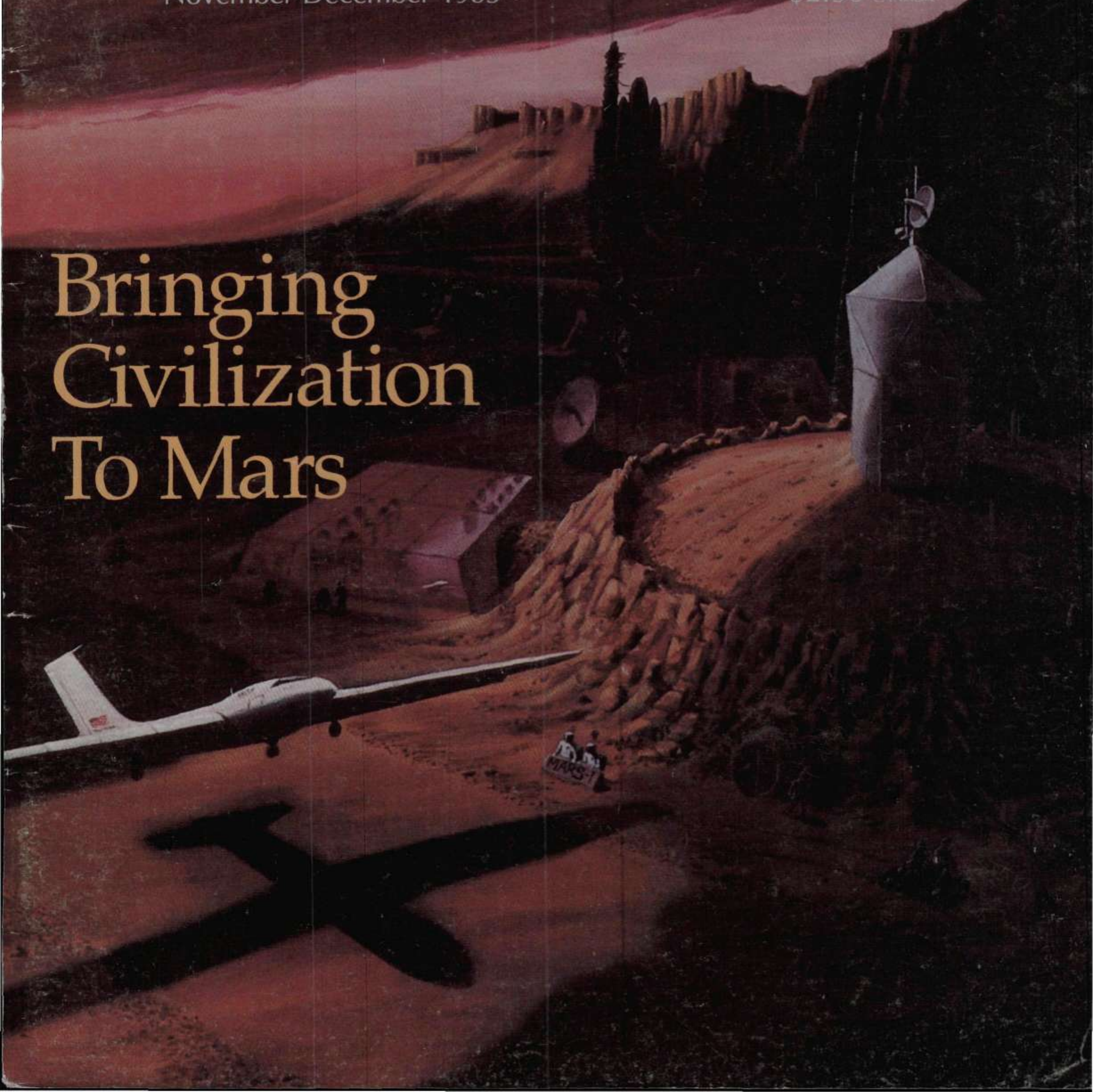

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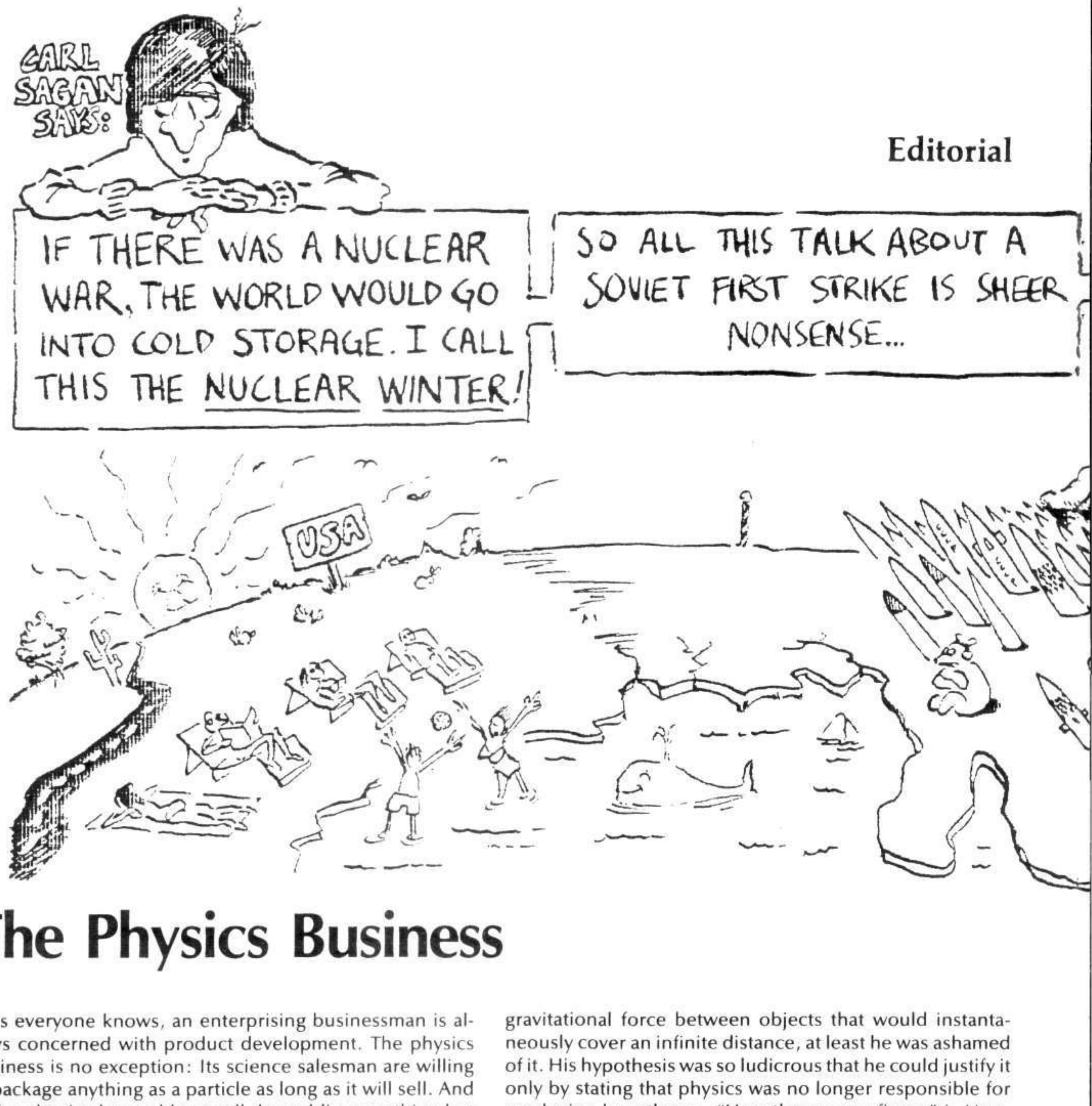
Editorial



The Physics Business

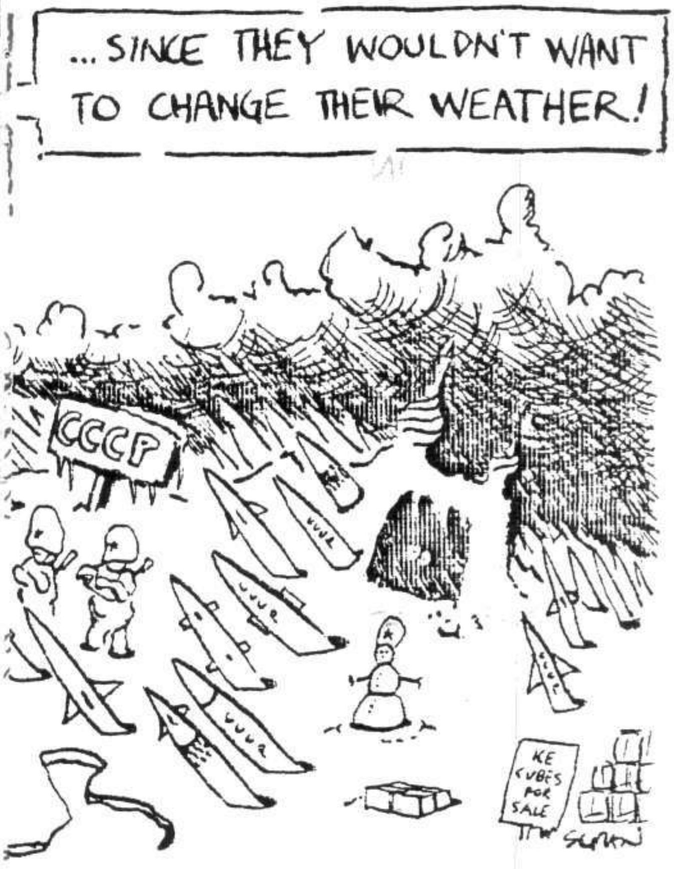
As everyone knows, an enterprising businessman is always concerned with product development. The physics business is no exception: Its science salesman are willing to package anything as a particle as long as it will sell. And so far, they've been able to sell the public everything but the Brooklyn Bridge.

Today, every action in physical space-time is reified by physicists as a particle. And there are new ones on the market all the time. We even have the gluon, which purports to bind quarks together. While such packaging is by no means unique in marketing, physicists have come up with a new wrinkle: Each particle comes with its own antidote or antiproduct.

The notion of objects exerting forces upon each other was an evil distortion of the clear-cut concept of the least-action principle elaborated by Kepler and Leibniz. However, even when Isaac Newton attempted to distort the work of Kepler and Leibniz by introducing the fiction of a gravitational force between objects that would instantaneously cover an infinite distance, at least he was ashamed of it. His hypothesis was so ludicrous that he could justify it only by stating that physics was no longer responsible for producing hypotheses. "Hypotheses non fingo," is Newton's famous remark.

James Clerk Maxwell continued this tradition of obliterating hypothesis from science, a tradition finally codified by Niels Bohr in his famous complementarity theory. According to Bohr, it will forever be impossible to develop a coherent picture of the physical universe because matter can be viewed as either particle-like or wave-like in its action.

Bohr thus sought to obliterate the work of Bernhard Riemann and his followers who had directly addressed the particle-like behavior of waves, as this occurred in the development and interaction of shock waves. In reality, Bohr's complementarity theory was a simple piece of thuggery



meant to silence Erwin Schrödinger, who had developed a shock wave model of the electron. Present-day mainliners have dropped the polite fiction. Going one step further than even Newton, they have picked up the cudgels for Bohr and turned every so-called force into a particle; hence the gluon.

The Netherworld of Cost Accounting

In 1930, Paul Dirac predicted the occurrence of a positron—a positively charged electron. With this he introduced an underside to physics—the antimatter world. Confirmation of the existence of the positron occurred soon thereafter, in 1932. Now it is canon law in the physics business that every particle found in nature must have its opposite number, the antiparticle. Thus the books are made to balance, and the record is kept straight.

Applying the method of cost-accounting to physics has led to the creation of new credits, in much the same way as debt hypothecation occurs in business. For example, on the heels of the discovery of the positron, the neutrino was mandated into existence as matter of papering over the "debt." This debt occurred when the energy total showed an apparent deficit in the conversion of a neutron to a proton and electron, as in the creation of a positron-electron pair.

Those who question the abysmal state of affairs in theoretical physics are, in general, treated as pariahs. Patronage and money for experiments, as well as access to publishing, is controlled in such a way as to eliminate any fundamental challenge. On the level of experimental verification, of course, the proliferating particles can never be directly observed. The inferences about their existence and behavior, from observations, depend upon the theoretical preconceptions of the experimenter.

The reliance on preconceptions may be carried to the point where, as described by physicist Erich Bagge in this issue, the experimental design—in this case the thickness of the lead foil target—masked the creation of low energy positrons. As Bagge explains, this failure in experimental technique led to an underestimation of the number of electron-positron pairs that were created, and therefore a misestimation of the energy profile of the electrons that were produced. High-energy electrons were assumed to be independent individuals created by the Compton effect rather than by pair formation. The apparent energy imbalance, according to Bagge, is accounted for by the work done to free the electron from the nether world.

The Symmetry Error

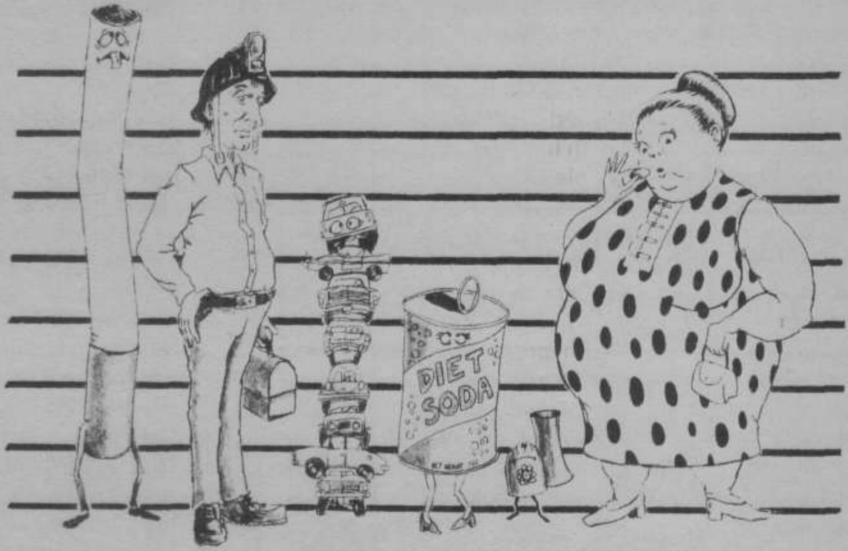
This error was compounded by the assumption that the positron and the electron had to be symmetrical. Once this false symmetry assumption is rectified, the existence of the neutrino is called into question. Far more significant, all of particle physics is called into question, in particular that supreme accomplishment of cost-accounting methods, quantum chromodynamics.

Is the universe symmetrical? To answer that question, it is first necessary to do away, once and for all, with the abominable notion that the universe is somehow made up of a collection of randomly moving particles that interact with each other.

There is a purposiveness in the universe, which is best expressed by man's own existence. By our own capacity to transform the universe, we can gauge the continuous process of self-transformation and self-development that characterizes all of nature and physical process as well. The universe is characterized by evolution—an evolutionary development that would be rendered impossible by the imposition of symmetry conditions.

Erich Bagge's work is of critical epistemological significance in overthrowing the nonsense of the necessity for symmetry. He has called into question every fundamental assumption of particle physics today. We eagerly await the response of those who will accept the challenge.

Letters



Risk and Statistics

To the Editor:

A few comments are necessary regarding the article, "Putting 'risk' in perspective," by Dr. Bernard L. Cohen [*Fusion* March-April 1985, pp. 37-44]. These concern primarily human epidemiology and uses and misuses of statistics regarding health effects of low-level radiation and use of cigarettes.

In his Table 10, Cohen states that 1 million (mrem) of ionizing radiation may be equated with a "loss of life expectancy" of 1.2 minutes. Such an allegation is in accord, qualitatively at least, with claims of several individuals[1-3] that all levels of radiation, no matter how low, are hazardous to human health in direct proportion to exposure. Such claims, widely reported by the "media," are incompatible with observed data involving millions of persons.[4-9]

For example, based on data for 43 U.S. metropolitan areas, epidemiological analyses showed that mortality rates for cancer of the respiratory organs vs. backround radiation levels for these regions led to a correlation coefficient of $r = -0.514$ ($p < 0.001$). For total cancer mortality rate vs. backround radiation, $r = -0.300$ ($p = 0.05$). Thus, cancer mortality rates were significantly *lower*, on average, in regions of higher radiation than in lower radiation areas.

This inverse relationship was also reported[8] for populations of Guandong Province in China. Such evidence is incompatible with Cohen's "loss of life expectancy" datum. Extensive evidence appearing in over 1,000 reports published over the last century has shown that ecologically realistic low levels of ionizing radiation are, on average, stimulatory and physiologically beneficial rather than hazardous.[6,7,10] To use a more popular expression, it appears that "a little radiation is good for you." Radiation therapy is, of course, well known.

Also in his Table 10, Cohen asserts that smoking a cigarette leads to a loss of life expectancy, on average, of 10 minutes. Insofar as I am aware, *scientifically valid proof* of smoking-causality, as for lung cancer, is highly questionable or nonexistent. That a positive correlation exists between cigarette smoking and lung cancer mortality risk or rate is not in question. However, inference of causality from correlation is one of the hoariest and most popular of the widespread abuses and misuses of statistics!

By analogy, consider that use of insulin is correlated with the presence of diabetes mellitus. Essentially all persons using clinically prescribed insulin are diabetics. Are we to conclude from this association that "insulin causes diabetes, because of the correlation"? Of course not! Insulin usage is *symptomatic* of diabetes, not the cause of it.

Also, persons taking prescribed antibiotics are usually afflicted with an infectious disease. Does this mean that antibiotics "cause" infectious diseases "because of the correlation"? Obviously not! Antibiotic usage is usually *symptomatic* of an infectious disease, or the suspicion of one. Further more, many regular consumers of aspirin tend to be inflicted with headaches or arthritis or certain other ailments. Does this mean that aspirin "causes" headaches and related aches and pains "because of the associations"? Not at all. Aspirin usage is *symptomatic* of headache and related discomforts.

Furthermore, insulin, antibiotics, and aspirin are all *therapeutic* agents that usually provide health benefits. As a matter of principle, a statistical correlation, no matter how strong, *cannot distinguish cause from symptom*. Since the problems are biological, the distinction must be made biologically. Is it possible, rejecting personal opinion, popular vote, conventional wisdom, and misuse of statistics, that cigarette smoking is *symptomatic* of a physiological deficiency among smokers, such as in biogenic monamine neurotransmitter hormones (such as epinephrine), that nicotine tends to *alleviate*? The pharmacologic effects of nicotine are described in modern textbooks of pharmacology.

The hypothesis that smoking is symptomatic of a physiological deficiency, among smokers that nicotine tends to alleviate has been presented.[11,12] As was noted,[11] R.A. Fisher (a former president of the Royal Statistical Society, London) warned long ago that statistical methods, properly used, can *reject* a hypothesis on the ground that it is incompatible with observed data, but that statistics alone can *never* establish that an hypothesis is certainly true. This principle has been widely ignored in many biomedical and medical articles. Furthermore, cancer is obviously a *biological, not a statistical problem*!

If one suspects cancer, he or she would certainly not visit the neighborhood statistician! Also, another former president of the Royal Statistical Society, G.U. Yule, warned, long ago, that statisticians deal with highly complex problems of multiple causation. Further, it may be easy to find that the data are in accord with an hypothesis favored by an investigator, but it is *essential* to establish that all competing hypotheses are excluded *scientifically*, and that the favored hypothesis is the *only one* that conforms to all of the facts.[11] This requirement has been widely ignored or "overlooked" by many who are convinced, on the basis of personal opinion, that smoking causes cancer.

Air Pollution

What about air pollution? A number of multivariate statistical epidemiological studies have been published over the 15 years or longer that have shown highly significant relationships between atmospheric concentrations of common air pollutants (like SO_2, NO_2, SO_4, and so on) and mortality rates for several classifications of cancer and heart disease.[11,12] Curiously, Surgeons Generals' reports on smoking and health have often "overlooked" or downplayed the implications of the correlations between air pollutant chemicals and mortality rates from cancers and other chronic diseases.

If smoking is symptomatic of a physiological deficiency that nicotine tends to alleviate among smokers,[11, 12], then, for smokers, low-level nicotine could be expected to be beneficial. In the present emotional and ideological states of affairs, such a notion, threatening some if correct, might be labeled instantly as heresy on the basis of "judgment," without objective evaluation. Is the concept correct? Have scientists such as R.A. Fisher, Joseph Berkson, Jacob Yerushalmy, P.R.J. Burch, and a few others been correct all along in warning that the beliefs that smoking causes cancers may be erroneous?

If smoking causes cancer, what are the *proven* molecular biological mechanisms? Also, rejecting rhetoric, rationalizations, opinion, and misuses of statistics and of science, what are the *scientific* explanations for the facts that many smokers do not develop lung cancer, and that some nonsmokers do?

As noted recently,[13] the prospect of the imposition of federally designated "official science," such as that extrapolation is good science, on individuals who apply for research grants from federal agencies (involving *public* funds), if they hope to have the applications approved and funded, was raised by Bross.[14,15] The "official science" in question concerns health effects of low-level ionizing radiation, with certain federal agencies relying on the fallacy of extrapolation to claim that all levels of radiation are hazardous.[9,13] Another form of "official science" could involve designation of inference of causality from correlation as federally approved.[11,12] Examination of public literature indicates that "correlation means causation" is accepted as valid in some federal agencies even though it is an elementary fallacy.

As was reported[11], the Surgeon General's report of 1964 on smoking and health[16] states: "Statistical methods cannot establish proof of a causal relationship in an association. The causal significance of an association is a matter of judgment which goes beyond any statement of statistical probability." Thus, according to the Public Health Service, the fallacy of inferring causality from correlation is accepted as correct "science." It is, of course, pseudoscience, or false science. Personal opinion cannot be equated with objective fact.

Situations such as these lead to regrettable and unacceptable alternatives: (1) If administrators and staff of an organization find extrapolation of observed high-level dose-response data downward toward zero exposure, through the ecologically realistic low-level exposure region where effects measurements are difficult to obtain, to be scientifically acceptable for "determining" low-level "effects," there would be a problem of scientific incompetence;[9] (2) if the personnel are aware that such extrapolation is bogus "science" and is based on opinion rather than on fact, but still adhere to it for personal or political reasons, there is then, evidently, a problem of deception; and (3) if public funds are expended in support of such deception, and if personnel are required to accept the extrapolation fallacy as correct science, if they wish to remain employed, then there would appear to be a problem of fraud[9] and mismanagement.

Since there appear to be no other alternatives, clearly none of (1), (2), or (3) is acceptable. Each is detrimental and degrading to biomedical science.

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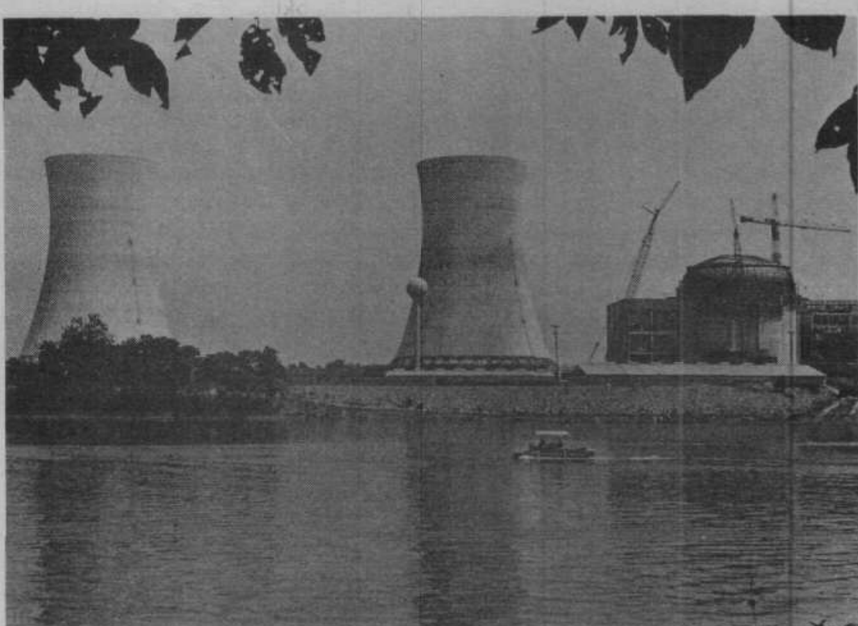

Metropolitan Edison Company

"A little radiation is good for you," the evidence shows. Here, Three Mile Island in construction.

Viewpoint

The Future of Astrophysics

by Dr. Luis Carrasco

Astrophysics is really important as a science because almost any possible physical process that we can imagine, that we can dream of, is likely to take place somewhere in the universe, and is taking place already.

In fact, we should recover our historical background. Physics was started by learning processes that were taking place in the universe; that is what Kepler did. He inferred laws that were controlling the motion of planets around the Sun, and he inferred a process from there. That is the way science makes progress.

I emphasize this point because there is a strong tendency in astrophysics now to try to impose on the universe things that we do not really understand. Our rather imperfect knowledge of things is forced. Somehow we have fallen behind, to a certain extent, and we are making an effort to deny that there are a number of things that are occurring in the universe that we can observe, but that we don't understand. Because we don't understand them, we try to deny that they are taking place!

Some astronomical objects, for example, are very familiar to most of us, yet have lots of open problems. Consider this photo of a hydrogen transition on the Sun (Figure 1). The Sun is an astronomical object very familiar to every one of us; we see it every day. On the upper left is a prominence, which is an eruption—an eruptive process on the surface of the Sun.

Most of the dynamics of the process of eruption are not well understood. Nevertheless, we try to understand them, and we fail over and over again, as long as we use incompetent theories to explain them.

This prominence is obviously a hydromagnetic phenomenon. Associated with this process, there are strong magnetic fields, acceleration of particles to very high energies. In fact, we can detect with our satellites the increase in cosmic ray particles that is always associated with this type of eruption, X-ray emissions—a whole collection of high-energy phenomena. We don't have a good theory to explain that.

Here is the Sun again in Figure 2, with a photo showing some smaller-scale phenomena. These are always connected with the magnetic activity of the Sun, areas that are preferentially heated or overheated in the surface of the Sun. In fact, they by themselves defy what is called the Second Law of Thermodynamics.

Defying the Second Law

Thermal theories would predict that the surface of the Sun should have a roughly uniform temperature, except perhaps at the poles. But when we look in close detail at the Sun, we see that it is not uniform, that it is composed of a lot of vortical structures. By having rotational action, these combine with electrical charges and then automatically have the appearance of magnetic fields.

Dr. Luis Carrasco is a professor of astrophysics at the University of Mexico in Mexico City. This viewpoint is adapted from his presentation at the Krafft Ehricke Memorial Conference, June 15-16, sponsored by the Fusion Energy Foundation and the Schiller Institute.

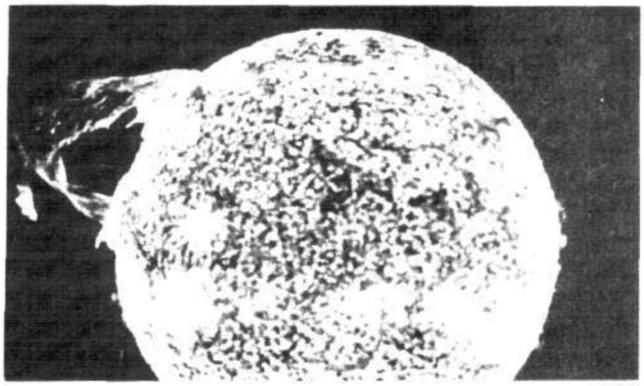

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Figure 1
SOLAR PROMINENCE
Solar prominences, like the one at upper left, are obviously hydrodynamic phenomena.

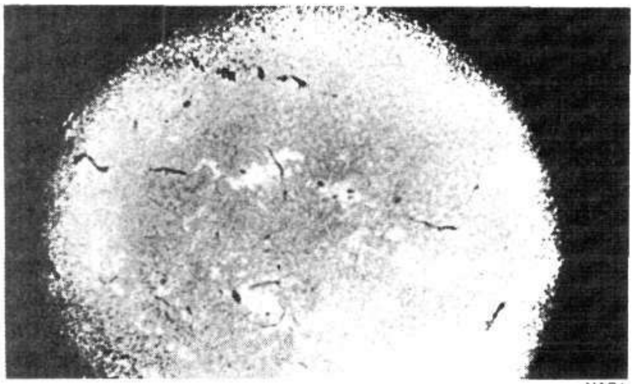

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Figure 2
HYDROGEN TRANSITIONS ON THE SUN
Smaller scale phenomena like these are related to the magnetic activity of the Sun and defy the Second Law of Thermodynamics.

These are essentially least-action units, which work for themselves and are long-lived processes. They cannot be treated just as simple perturbations of the process, but in fact they define the process itself.

Take another example that is also a familiar object to most people—the Crab Nebula, which is a star that exploded about 1,000 years ago and was recorded by Chinese astronomers in the year 1054 (Figure 3). When we look at the sky in that place now, what we see is a mass of very hot plasma, expanding at very high speed—about 10,000 kilometers per second. All the structural features that we see—the rings, the filaments—are apparently magnetic, self-confined plasma structures, probably similar to some of the filaments observed in a plasma focus fusion device.

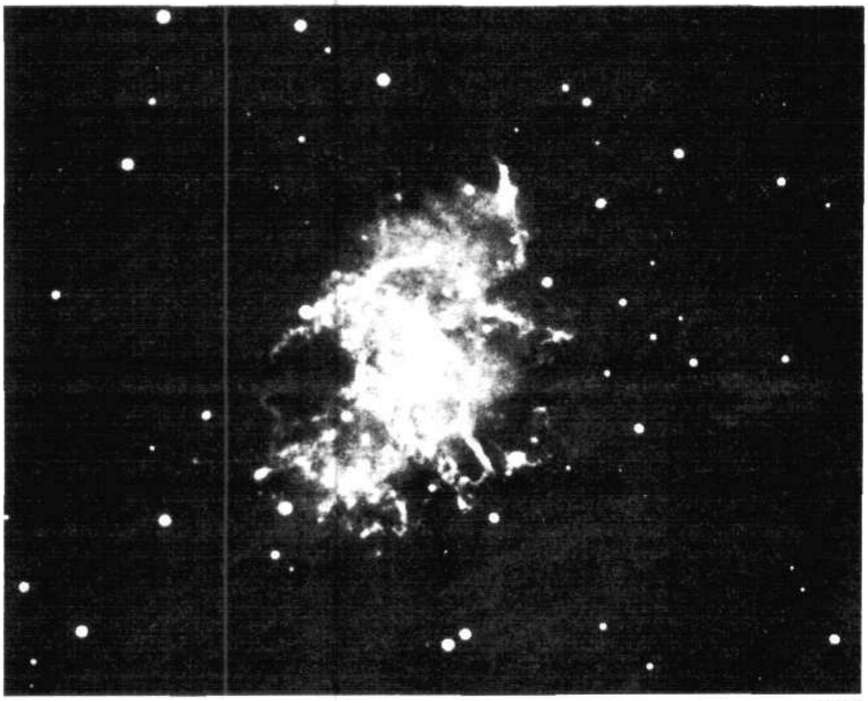
Another problem to deal with is the structure and morphology of galaxies. What is a galaxy? A galaxy is a compound of stars. But stars are being formed all the time, and the geometrical site at which new stars are being formed all the time is a spiral structure. We have some idea as to what is happening: The gas that is the raw material to form new stars is piled up, swept, and compressed into a spiral-shaped structure, where magnetic processes are also very efficient in actually providing the proper physical conditions for stars to form.

The details of the physics that we can learn by studying this sort of process certainly should enlighten our concepts for any future local application of universal physics.

In an elliptical galaxy, which is different from a spiral galaxy, what has happened is that the star formation process in the past was so efficient that most of its gas was transformed into stars at a very early stage. We have some evidence, in fact, that this is the basic difference between spiral and elliptical galaxies—the rate at which these different objects consume, or transform, their gas into stars.

A New Physics

What's the future of astrophysics, in terms of space programs, in terms of what should be done in the near future?



NASA

Figure 3
CRAB NEBULA IN TAURUS
The filamentary structures in the Crab Nebula in the constellation Taurus are similar to the filaments created in the plasma focus device.

First, we need space telescopes, for several reasons. As you can easily imagine, Earth's atmosphere—which contains oxygen that is vital for life—is not so good for astronomy and astrophysics. It essentially blurs the image. The information we get from outer space becomes distorted when it gets across the atmosphere, and this distortion blurs the image: We get a foggy picture of what the universe really looks like. Perhaps the most spectacular and important results in the near future will come from apparently very small structures. These contain very high energy density phenomena that, because of this blurring, we cannot properly study from ground-based observatories. So, one thing that we should have—and we will have very soon—is the Space Telescope.

However, this is only one experiment, one observation instrument, and one is too few. It figures that if every competent astrophysicist in the world would ask for observing time, each would not have more than a couple of hours within the next five or ten years of operation of the satellite. So, certainly, we need more Space Telescopes.

Of course, the moment we have at least two of these telescopes in orbit, then we can begin to think about what is called aperture synthesis: We can place two telescopes in orbit, look at the same object, and by playing certain tricks, in terms of space resolution, in terms of how small an object we can see—we can mimic a telescope of the size of the Earth! This, in fact, would then allow us to see and study many—very many—of the small-scale, compact phenomena in the universe, including, the nuclear regions of galaxies, where some very impressive phenomena are taking place.

We know, for instance, that a number of galaxies, at very early stages of

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News Briefs

Argonne National Laboratory

Argonne's magnet is lowered into place at the ALEX facility.

ARGONNE NATIONAL LAB OPENS LIQUID METAL FACILITY

The world's largest facility for studying the effects of magnetic fields on flowing liquid metal has begun operation at Argonne National Laboratory in Illinois. The facility is called ALEX, for Argonne Liquid Metal Engineering Experiment. "We know that magnetic forces can alter the flow patterns of liquid metals that move through magnetic fields, but there has been very little research to tell us what those patterns will be for the magnetic field conditions of a fusion reactor," said Richard Mattas, manager of the facility. The goal is to determine the behavior of liquid metals flowing through different shapes and sizes of pipes surrounded by magnetic fields of varying intensities, he said. Experiments will study a mixture of liquid sodium and liquid potassium as it flows through a magnetic field as strong as 2.0 tesla, about 50,000 times the strength of the Earth's magnetic field.

CONGRESS AND SENATE PROPOSE TO SLASH FUSION BUDGET FOR 1986

The House of Representatives seeks to cut $5 million from the U.S. Department of Energy magnetic fusion budget proposal of $390 million for fiscal year 1986, while the Senate has proposed an $8 million cut. The $390 million proposal put forward by the Reagan administration was already a significant reduction from that of fiscal year 1985 for $440 million, which had been cut to a level of about $437 million last year. This new round of cuts will close down several fusion experiments and slow down the rate of progress in others. The Princeton Plasma Physics Laboratory's TFTR tokamak, for instance, is capable of demonstrating fusion energy breakeven within a year, but this will not be done because of funding cutbacks.

AFRICA NEEDS NEW TECHNOLOGIES, FREEMAN TELLS HUNTSVILLE GROUP

"Why build Africa with 100-year-old transport, energy, and agricultural equipment?" Marsha Freeman, *Fusion* Washington editor, asked a group of civil rights and community leaders Huntsville, Ala., on a recent tour of space facilities sponsored by the Schiller Institute. "To do it quickly will require resource data from satellites, magnetically levitated trains, nuclear-powered industrial complexes, plasma steel-making, and laser processing." The audience included 100 clergy, college students, and community and civil rights organizers from Alabama and Georgia who were given a tour of the Alabama Space and Rocket Center led by some of the German rocket scientists who built the U.S. space program.

Historically, civil rights leaders have been told that the money spent on space developments and military technology "took money away" from funds available in the federal budget for "poor people," Freeman said. The Schiller Institute sponsored the tour to demonstrate that only exploration of the frontiers of space and science—the directed energy beam defense program—can create the conditions for developing both the advanced sector and Africa.throughout the universe.

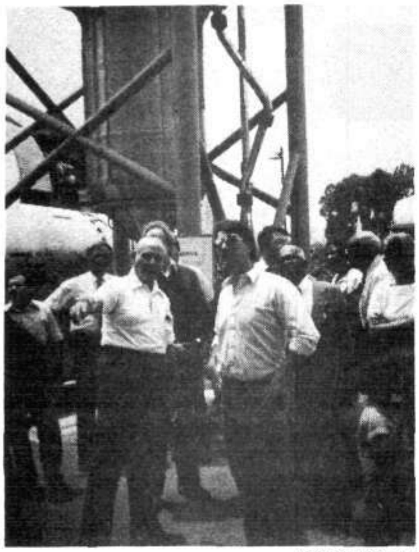
Leo Scanlon

Medaris: "Fundamental constitutional issues at stake."

GEN. MEDARIS HITS 'PERSECUTION' OF GERMAN-AMERICAN SCIENTISTS

The Justice Department Office of Special Investigations has carried out a campaign of persecution against leading American scientists, and Congress must conduct an oversight review of the agency's activities, General John Bruce Medaris, (ret.), told a July 23 press conference in Washington, D.C. Medaris warned that the tactics used by the Office of Special Investigations in the persecution of NASA scientist Dr. Arthur Rudolph, have "created a second-class citizenship for naturalized citizens."

"I am concerned about this issue not only because Dr. Rudolph is a great personal friend of mine," said Medaris, "but because there are fundamental constitutional issues at stake here. . . . These procedures arbitrarily deny constitutional rights to naturalized citizens . . . and it is important to note that naturalized citizens maintain and carry forward the cutting edge of our technology. . . . Most of the Nobel Prize winners from America have been naturalized citizens! We have not been able to create the educational conditions which duplicate this ability . . . so this is an issue which affects not only the SDI, not only our vital national defense, but all of our science and thus our way of life."



Marsha Freeman

Space scientist Konrad Dannenberg (left) leads tour of the Alabama Space and Rocket Center.

SOVIETS BOYCOTT ERICE MEETING ON SDI AND ARMS RACE

Although a top-level Soviet delegation was scheduled to attend the fifth international conference in Erice, Sicily, no Soviet scientists showed up, nor was there a message explaining their absence. This year's topic at the week-long science meeting was "The SDI, Computer Simulations, and New Proposals to Stop the Arms Race." The Soviets had promised Prof. Antonio Zichichi, who hosts the conference, a delegation led by laser specialist E.P. Velikhov and including two Nobel Prize winners, N. Basov and Aleksandr Prokhorov. President Reagan's message to the conference noted that "Our aim in this research program is not to achieve superiority, but to maintain and enhance the essential strategic balance which has kept the peace for 40 years. This is especially important in light of Soviet activities. For over two decades, the Soviet Union has not only pursued its well-known offensive nuclear build-up, but has also pursued a wide range of strategic defensive efforts. The Soviets currently have the world's only deployed antiballistic missile system, and have a long-standing and intensive research program in many of the same areas the U.S. is not exploring."

PENNSYLVANIA HEALTH DEPT. SAYS TMI DID NOT INCREASE CANCER

A Pennsylvania State Health Department study released Sept. 5 said that it has found no evidence of increased cancer among area residents due to the 1979 accident at Three Mile Island. State Health Secretary Dr. Arnold Muller called the report "the first scientific analysis of cancer among those living within a 20-mile radius of the plant," and said that the latency period for most cancers would have made an earlier effort "premature." The study also found no evidence of an increase in new cases of leukemia, which has a shorter latency period. The study covered cancer deaths recorded from January 1974 through December 1983 within 20 miles of the plant, as well as new cancer cases found in four areas "downwind" of the plant. The study also included a critique of a survey alleging a dramatic rise in cancer deaths in the area, which was conducted by local environmentalists and widely publicized. The allegations in that study are "contrary to scientific findings," the Health Department said.

LOUSEWORT LAURELS TO ACADEMY OF SCIENCES DIETARY COMMITTEE

This month's Lousewort Laurels award goes to the dietary allowances committee of the National Academy of Sciences for its draft report recommending lower levels of some vitamins and minerals in the American diet. According to a confidential draft of the committee's report publicized in the press, the allowances for vitamins A, C, and B-6, and for magnesium, iron, and zinc should be cut significantly. "The majority of scientists who reviewed the report" favored higher levels than those the committee recommended, according to press reports. Several reviewers expressed concern that the lowered allowances would be used to justify reductions in school lunches, food stamps, and other food programs. Honorable mention in this month's award goes to committee chairman Dr. Henry Kamin, a biochemistry professor at Duke University. Kamin commented on the criticism of his committee's forthcoming report: "Ours is a scientific report. How it is used in setting policy is out of our hands and out of our competence."

Fine Structure Found in X-Ray Spectrum

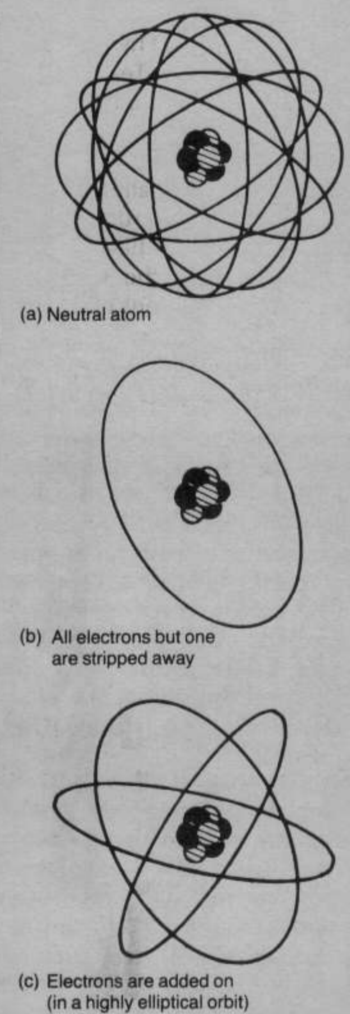
A new type of X-ray lasing medium has been achieved that makes possible an X-ray laser operating at much shorter wavelengths than otherwise attainable. In this recombination X-ray laser, electromagnetic radiation is used to strip away most of the electrons of a heavy element like gold. The highly ionized atom then recaptures (that is, recombines with) electrons whose excited state provides the basis for X-ray lasing.

Using the higher-energy inner electrons is what produces the shorter wavelengths, which are important for both military and scientific research applications.

Adequate manipulation of the recombination process to achieve X-ray lasing—and make it efficient—depends on understanding the spectrum and energy levels of the highly stripped ions. Dr. M. Klapisch of the Racah Institute of Physics at Hebrew University, Jerusalem, has pioneered research into these spectra. Klapisch and collaborators have employed a small, infrared glass laser to produce a plasma of the heavy element under study. A small number of the plasma ions produced in this way are highly stripped.

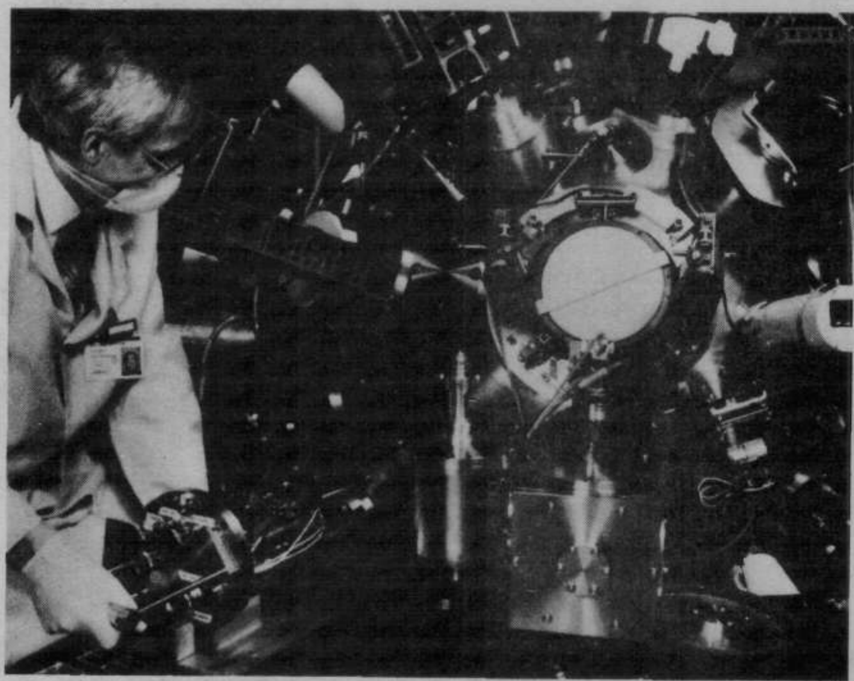
Klapisch has developed techniques to isolate the spectra of these few from the general plasma background. He reports that these highly stripped ion spectra have significant fine structures indicating that energy processes of the inner-orbit electrons of heavy elements involve highly nonlinear processes. These inner orbits therefore cannot be understood on the basis of simple quantum mechanical models, such as those developed for the single-electron hydrogen atom.

Recent experiments at the University of Rochester Laboratory for Laser Energetics have confirmed Klapisch's findings. The new results are important because they were achieved with the powerful Omega glass laser, which can achieve a far greater number of highly stripped ions.



SCHEMATIC OF RECOMBINATION X-RAY LASER

Most of the electrons of a heavy element are stripped away using electromagnetic radiation (a) and (b). The highly ionized atom then recombines with a few electrons that occupy excited states of the available orbits. To establish stable occupancies, the recombined electrons shed energy by emitting X-rays.



LLE

The high-power Omega glass laser University of Rochester's Laboratory for Laser Energetics was able to achieve a large number of highly stripped ions. Shown here is a researcher working with Omega's diagnostics.

Princeton TFTR Fusion Reactor Gears Up

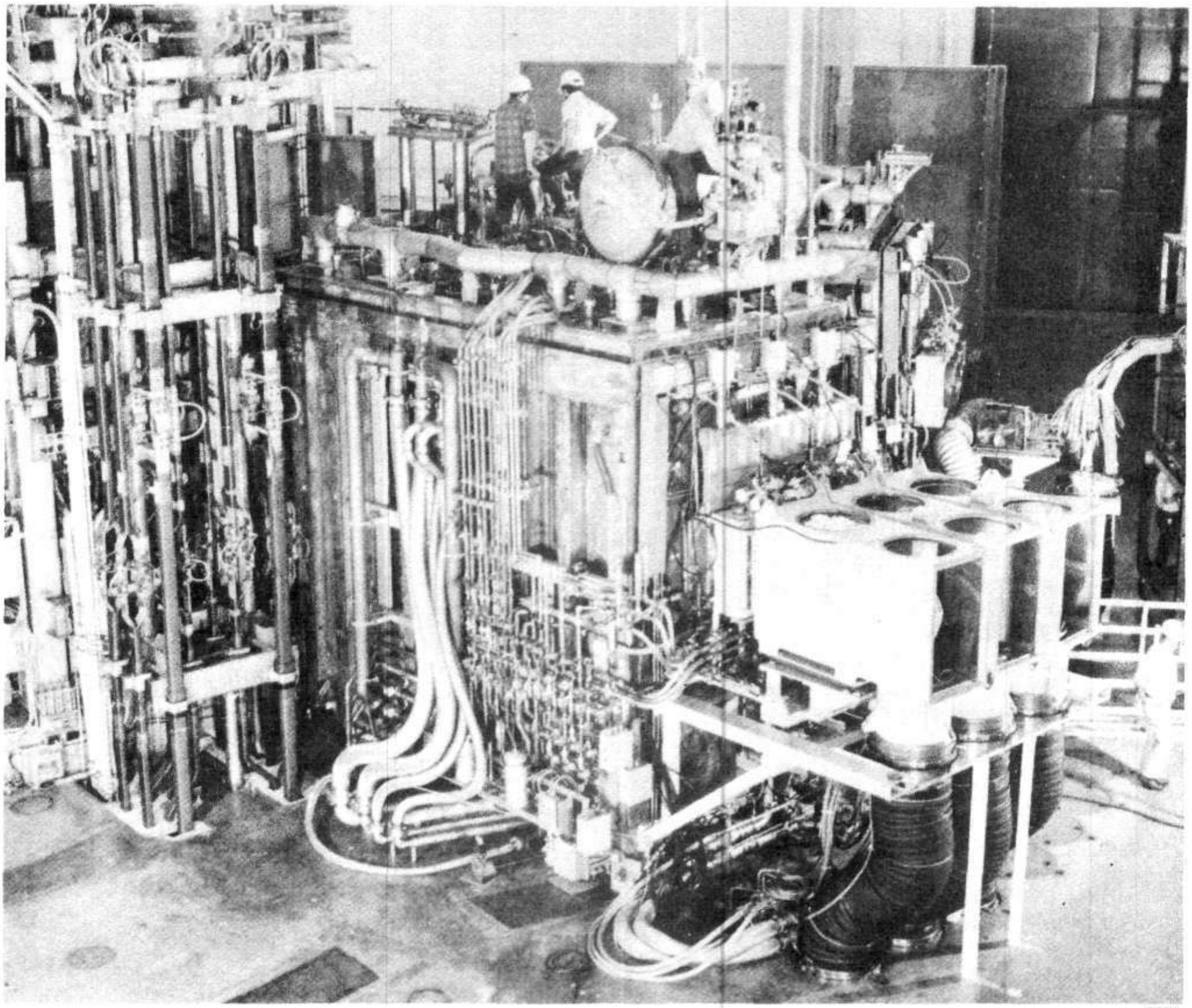
The Princeton Plasma Physics Laboratory's Tokamak Fusion Test Reactor (TFTR) in New Jersey is adding two neutral beam heaters to the existing two, bringing the TFTR up to the operational capability originally planned. The TFTR is scheduled to run with actual tritium fusion fuel in 1988.

Over the next year, the TFTR will demonstrate the conditions of plasma density, temperature, and confinement time needed to produce net energy. The TFTR researchers plan to take the device significantly beyond the original design capabilities with higher magnetic fields and plasma currents.

One significant yet inexpensive upgrade—using the radio frequency (RF) heating capabilities developed for the Princeton PLT tokamak—is not currently planned because of cutbacks in the U.S. magnetic fusion budget. The PLT's multimegawatt RF generator outputs could simply be transferred to the TFTR through waveguides.

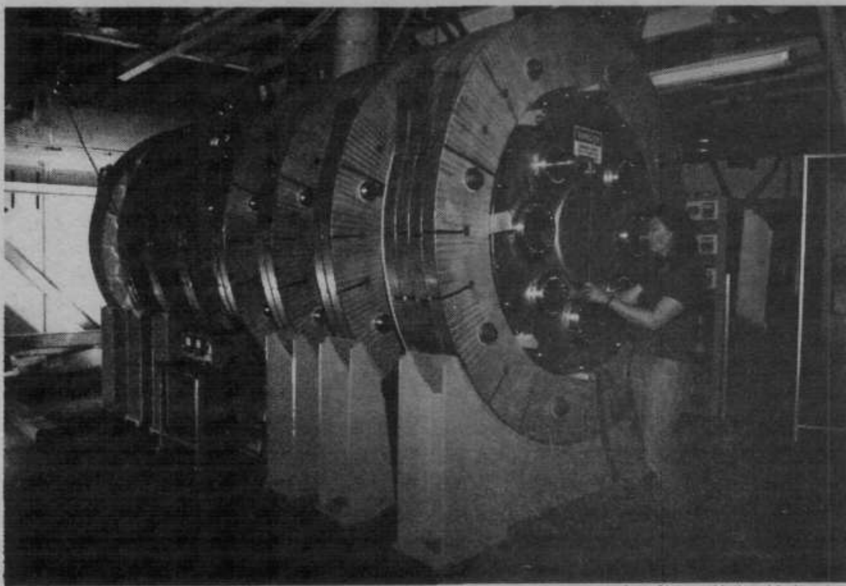
The use of radio frequencies to heat fusion plasmas has proven to be just as effective as neutral beam plasma heating. RF heating can also be used to extend the plasma current pulse and therefore the experimental lifetime of the plasma being studied.

The RF capability on the European JET tokamak nearly guarantees that it will achieve full fusion plasma ignition—where the fusion energy output itself sustains the burning plasma at fusion conditions without external heaters.



PPPL

Princeton's TFTR will demonstrate the conditions of plasma density, temperature, and confinement time needed to produce net energy over the next year. Shown here is the neutral beam assembly. Two more neutral beam heating units are being added.



The CTX spheromak at Los Alamos National Laboratory has reached plasma discharges lasting more than 8 milliseconds—well beyond previous microsecond discharge times for spheromaks.

Spheromak and Compact Torus Score Major Advances

The leading candidates for advanced magnetic fusion power reactors, the spheromak and compact torus, have scored major experimental successes recently, despite continuing budget cutbacks.

After demonstration of principle, the Princeton Plasma Physics Laboratory's S-1 spheromak will be upgraded with a new "flux core" permitting achievement of much higher plasma currents—in the 500 kiloampere range. This is expected to provide the means for attaining much higher plasma electron temperatures, in the neighborhood of 200 electron volts (2.2 million degrees Celsius).

Construction of the University of Maryland Spheromak (MS) is now complete. Since it will operate with a magnetic field strength on the order of 20,000 gauss, compared to roughly 5,000 gauss for previous spheromak experiments, experimental results are eagerly awaited.

When tokamaks went to high field strengths, as did the MIT Alcator in 1974, entirely new plasma and confinement regimes were accessed. A similar transition may now occur with the spheromak.

The Los Alamos National Lab's CTX spheromak, a dynamically self-organized magnetic plasma, has recently demonstrated significant increases in plasma duration with injection of magnetic helical flux. Plasma discharges lasting more than 8 milliseconds have been attained. That is in the range achieved on early tokamaks and well beyond the microsecond discharge times previously characterizing spheromaks.

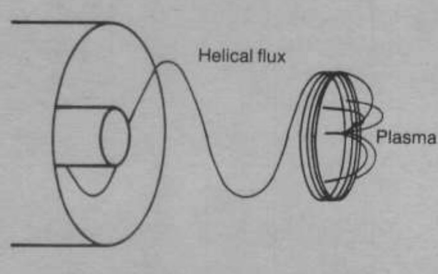
In the CTX, the magnetic helical flux is generated by leaving the plasma formation gun on. As magnetic flux is produced, it is absorbed by the self-confined CTX spheromak. An apparent dynamo action converts this helical flux into a distribution of magnetic field most appropriate for maintaining the plasma configuration.

This helical flux injection opens up the prospect of spheromaks operating continuously, instead of in pulsed mode as previously thought necessary. The resulting steady-state operation will greatly decrease the cost of power reactor operation.

Compact Torus Advances

The University of Washington's compact torus has recently begun operation. Unlike the spheromak, which has both poloidal and toroidal magnetic field components, the Washington self-organized compact torus is based on a theta pinch and has only a poloidal field. The addition of a transformer within the core has proven successful in increasing this poloidal flux. Impurities in the plasma from the vacuum chamber wall, however, are apparently leading to an early end to the discharge. New wall materials are expected to solve the problem.

New methods of stabilizing this type of theta-pinch-generated compact torus are being sought at Los Alamos. Professor Y. Nogi of Nihon University in Japan replaced the quadrupole, Jaffe-type bars in his NUCTE experiment with a helical type of winding and reported increased stability. Experiments at Los Alamos aimed at duplicating this result on the RFX-C have so far failed to do so at low plasma currents.



THE SPHEROMAK CONFIGURATION

The plasma gun (left) creates a ball of plasma (right), and then feeds to it a helical magnetic field. The field lines wrap themselves around the plasma ball in a distribution most appropriate for preventing the ball from dispersing, thus opening the possibility for continuous, instead of pulsed, spheromak operation.

Experiments Broadened in Reversed Field Pinch

Now that the Los Alamos National Laboratory's ZT-40 reversed field z-pinch device has successfully reached confinement times on the order of 40 milliseconds, work on this type of device is beginning to move beyond a fairly small number of experiments that focused on primary issues of plasma confinement.

General Atomic in San Diego, for example, is experimenting with elongated plasma cross sections to see if they lead to even higher beta—the efficiency with which a given magnetic field confines a plasma.

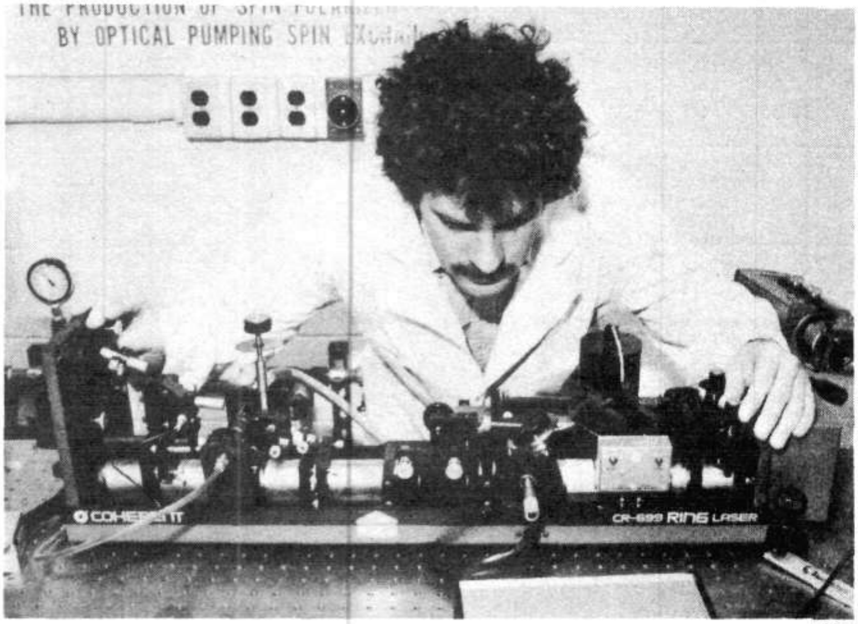
Other experiments at General Atomic and the University of Wisconsin are directed at finding the best method for forming an outer boundary for the plasma. At present the vacuum chamber wall is the plasma boundary—as with the early tokamaks. The experiments seek to find whether limiters or electric and magnetic fields could be substituted. Early tests with a rail limiter on the ZT-40 failed to produce the desired results.

Nova Laser Will Experiment with Polarized Fuel

Lawrence Livermore National Laboratory has launched a crash program to determine the effects of spin polarization on rates of laser fusion reactions in fusion experiments with the new 130-trillion-watt Nova glass laser system. Nova, which was dedicated in March 1985, is the most powerful laser in the world.

Computer simulations carried out over the past two years have shown that polarization of the fusion fuel can increase the fusion energy gain by as much as a factor of 7 in inertial confinement. The primary reason is that spin polarization of the fuel in spherical targets leads to asymmetrical fusion burn waves that are more effective in burning up the cold outer fuel layers.

Experiments will begin in the near future with cryogenic deuterium-deuterium (D-D) targets on the 10-beam Nova glass laser. Although deuterium-tritium (D-T) fuel is projected as having far greater energy gains for both polarized and unpolarized inertial confinement targets, the difficulties in preparing spin polarized D-T have led Livermore scientists to first explore the much more easily prepared D-D spin-polarized targets.



PPPL

Polarization of the fusion fuel can increase the fusion energy gain by as much as a factor of 7 in inertial confinement. Here a researcher at the Princeton Plasma Physics Laboratory aligns the tunable ring dye laser used in the optical pumping production of spin-polarization.

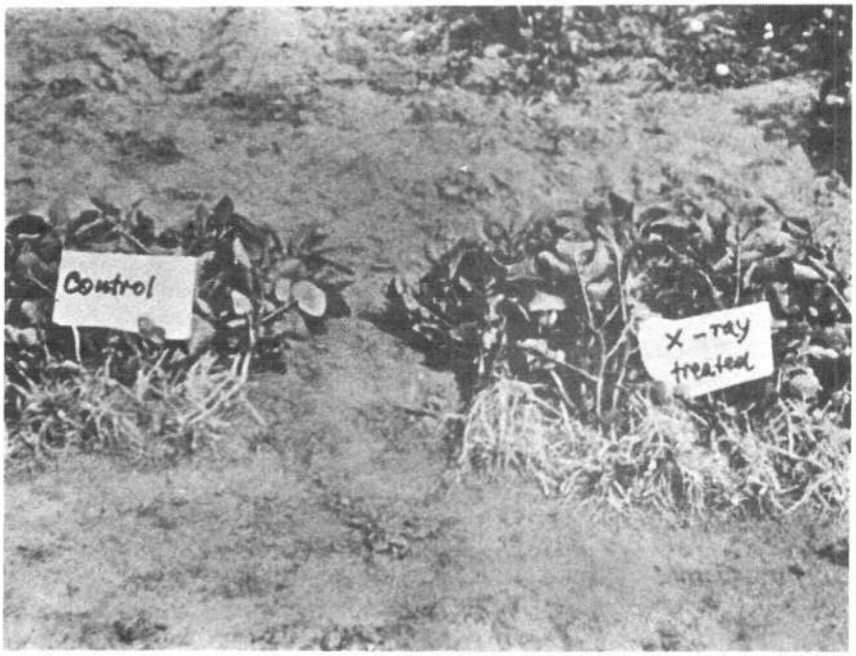
The D-D Debate

The experiments with D-D may also resolve a major theoretical debate concerning the D-D fusion reaction. Some scientists have held that the D-D reaction can be suppressed if a particular spin alignment is utilized. This could be extremely significant, for in the case of the deuterium-helium-3 reaction, if the D-D reaction could be suppressed, a fusion reaction without neutrons could be attained. This would make engineering and applications of fusion energy to industry far easier and much more economical. Other scientists have held that D-D cannot be suppressed by spin polarization.

The argument revolves around interpretation of experimental data from both the United States and the Soviet Union for D-D beam-target reaction cross-sectional measurements. A deuterium beam is injected into a cold target of deuterium, and measurements of the rate of fusion reactions are made. Soviet experiments seemed to indicate that spin polarization could be used to suppress the D-D reaction rate.

But the Soviet data have been presented in a form that is ambiguous and difficult to directly interpret. More recent U.S. experiments have seemed to indicate that the reaction cannot be suppressed, and careful examination of the experiments has led some to believe that the beam may undergo depolarization before the reactions take place.

—*Charles B. Stevens*



Courtesy of Ionizing Energy Company of Canada Limited (IEC)

Treatment with low-dose radiation from an X-ray source produced the increased growth seen in the potato tops at right.

HORMESIS:

Reaping the Benefits Of Low-Level Radiation

Contrary to uninformed public opinion, minute doses of ionizing radiation seem to improve fertility, growth, health, and longevity in all species of plants and animals examined so far.

Hormesis, the phenomenon of stimulation by low doses of radiation—as well as by other potentially harmful agents—has been known for at least eight decades. The phenomenon has been demonstrated for insecticides, arsenic, cadmium, bacterial toxins, X-rays, and gamma rays. All of these agents demonstrate beneficial effects, such as stimulation of immune function at low doses, and toxic to lethal effects at high doses.

What emerges from the massive literature on hormesis is the hypothesis that there is not only a level at which these agents become nontoxic, but that there is apparently a level at which they become positively beneficial. Furthermore, in the case of ionizing radiation, the lack of exposure at this level can be potentially harmful.

Bigger and Better Plants

There has been extensive work done on the effects of low-level radiation on the yield of agricultural plants. An enormous literature, much of it from Eastern Europe, indicates that low doses of X-rays or gamma-rays (100 to 200 rad) produce substantial increase in quantity and quality of crop yields. These effects are dependent on a number of factors, such as seed type, time between radiation and planting of the seed, dose rate, and growing conditions, among others.

An example of the results of radiating seeds with appropriate levels of ionizing radiation is provided by a study on cucumbers at Lvov University in Russia. Radiated seeds produced 19 to 38 per cent more cucumbers than controls, and the vitamin C content of these cucumbers was 20 percent higher than the unirradiated controls.

A great deal of work has been done on irradiating potatoes in Russia because they are a major source of vitamin C in the Russian diet. In one variety of potato, irradiated tubers produced of 39.4 percent more vitamin C, representing an increase in both the numbers of potatoes and the vitamin C concentration in the potatoes.

This stimulation of growth is a result of multiple factors. One is an increase in the rate of cell division in the sprouts and rootlets. Cell division is stimulated by low-dose radiation and inhibited—and ultimately stopped—by higher doses. Low-dose radiation also stimulated an increase in the amount of auxins, hormone-like chemicals that stimulate plant growth.

Photosynthesis is increased from 18 to 40 percent over that of control levels in plants grown from irradiated tubers, resulting in production of more than twice as many plant products from irradiated plants.

Similar results have been demonstrated in animals, ranging from insects and mice to food animals like chickens and salmon. Egg production was increased in irradiated hens and embryo development was increased in irradiated eggs. Radiation of trout sperm reduced embryo mortality and radiation of salmon eggs or young increased viabilty of these fish. All these effects occur within a specific dose rate, and disappear at higher or lower doses.

In rats and mice, low-level radiation at the time of fertilization increases the size of litters and the percentage of healthy offspring. This has implications for increasing livestock production in general and promises to be a fertile research area, especially since other evidence indicates that low-dose radiation enhances the ability to survive and develop in suboptimal environments.

Stimulating the Immune System

Studies in animals varying from fruit flies to salmon to mice have shown an approximately 120 percent increase in average lifespan for low-dose irradiated animals compared to unirradiated controls. Preliminary studies in humans suggest increased average life expectancy in areas with higher than average background radiation.

For instance, studies in China showed that cancer mortality rates in areas of Guandong province where there is high background radiation *were signficiantly lower than rates in* areas of the same province that had low background irradiation rates.

Similar results have been reported from Tibet and from a study of 43 urban areas in the United States. In an analysis of atomic bombing effects, the *Encyclopedia Britannica* reports that Japanese who received between 11 and 120 roentgen of radiation in the 1945 atomic bombings appear to live longer than those who received more—or none.

The basis of this decreased mortality appears to be an increased resistance to disease, resulting from stimulation of the immune system. Animals subjected to low-dose irradiation show increase in a number of components of the immune system, including the thymus hormone, which stimulates growth of T-cells, the cells that are damaged in the AIDS disease.

Irradiated animals also produce increased antibodies, compared to unirradiated animals, and these antibodies *are more effective.*

A U.S. Conference on Radiation Hormesis held in Oakland, Calif., Aug. 14-16, is expected to provide a forum for publicizing more widely the research on hormesis that could revolutionize food production and medical treatment.

—John Grauerholz, M.D.

India Commissions World's Largest Nuclear Research Reactor

India's indigenously designed and built Dhurva nuclear research reactor at the Bhabha Atomic Research Center in Bombay went critical Aug. 8. "This is a landmark in the country's atomic energy program," said Dr. Raja Ramanna, chairman of India's Atomic Energy Commission, in announcing the event.

The new 100-megawatt (MW) research reactor will have important medical and industrial applications, for example, increasing the production of isotopes like iodine-131 and chromium-51.

Dhurva is twice as large as the Canadian-built Cirus reactor at the research center and it will replace the aging Cirus as a source of plutonium fuel for India's fast breeder reactor, now under development at the fast reactor research center at Kalpakkam.

A 40-MW test fast breeder reactor is scheduled to come on line in December, and the 500-MW prototype fast reactor is already under construction at Kalpakkam. India has some of the largest reserves of thorium in the world, and the thorium-fueled fast reactor is envisioned as the workhorse of the country's future atomic power program.

Within days of Dhurva's start-up, India's Nuclear Power Board announced the commissioning of the second unit of the Madras atomic power station. The Madras station, India's third atomic power plant and the first that was fully indigenously built, consists of two 235-MW heavy water reactors. The newly commissioned reactor incorporates certain improvements over the first unit, and power production is expected to begin in October after a series of tests.

—Susan Maitra

Viewpoint

Continued from page 7

their evolution, become extraordinarily bright in their nuclear regions. Just to give you an example of our knowledge so far, we understand, for instance, that in the nuclear regions of galaxies, at one point in time, a region comparable to the size of the Earth's orbit around the Sun is capable of producing, of liberating, energy equivalent to 1,000 times the entire luminosity of the whole galaxy later on.

Whether or not we need entirely new physics to understand these objects is an open question. It is my belief that *we do need a new physics.* The possible explanations are, in a sense, now taken out of science fiction books. We have to look and make better and more detailed observations of these types of objects, and this will be possible only if we put more telescopes in orbit, and do aperture synthesis.

Another need, certainly, is the establishment of astronomical observatories on the Moon, because then we will have all the advantages of ground-based *astronomy—in* the sense of having the stability, the ability of carrying on observations for very long periods of time, of a single object—without the problems of Earth's atmosphere.

It's a pity: When I was a child, and later on, when I began working in astronomy, about 20 to 25 years ago, I always dreamed that one of the first things that was going to happen was the establishment of an observatory on the Moon. Yet, it hasn't happened! And it just has to happen, because otherwise, the rate at which we are acquiring knowledge is slowed down.

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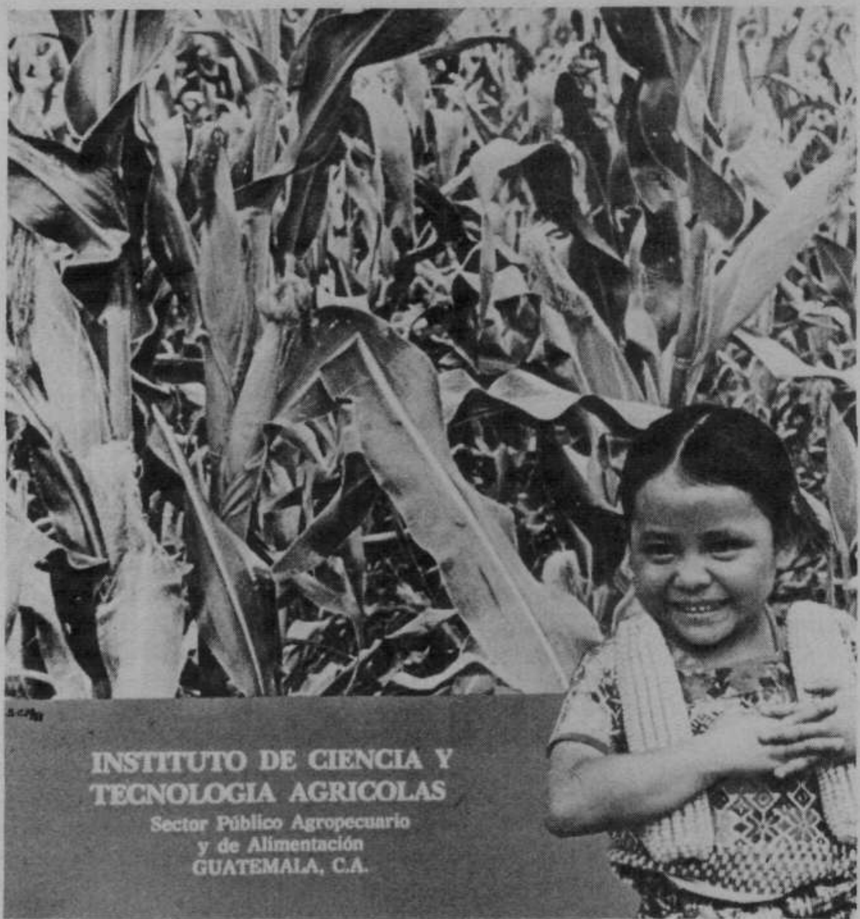


Courtesy of Dr. Edwin T. Mertz, Department of Biochemistry, Purdue University

High-lysine corn could end malnutrition in areas where children are dying for lack of lysine in their diets of normal corn and beans. Here a Guatemalan publication advertising the merits of growing high-protein corn.

New Technologies to Develop Protein-Rich Grains

Protein-rich grains that can help reverse the effects of severe protein deficiences are now being developed using new plant breeding technologies.

Although Americans are accustomed to consuming high-grade animal proteins—beef, pork, poultry, milk, and eggs—today cereals still provide 70 percent of the world's total protein intake. Unfortunately, these cereals are not complete proteins because they are deficient in essential amino acids.

A complete protein is one that contains the essential amino acids in a ratio necessary for the healthy growth of muscles, nerves, and other tissues; the healthy function of the immunological system; the healthy development of human cognitive powers. Although the body can manufacture a few amino acids, a great number of essential amino acids must be ingested for the human to survive.

The best ratio of essential amino acids for healthy growth and development is found in animal proteins like milk, steak, or eggs. Cereals contain plant proteins, but they are so deficient in some of the essential amino acids that a person surviving on a primarily cereal diet acquires a protein-deficiency disease called kwashiorkor.

Kwashiorkor commonly hits the weaning-age child in association with measles, diarrheal diseases, and, in Africa, also malaria and parasitic problems. It is characterized by edema (swelling or bloating of the limbs with excess body fluids), growth failure (including weight loss), muscular wasting (as the body consumes itself in order to acquire some protein), anemia, dyspigmentation of hair, and psychomotor behavioral changes (including whining, lethargy, or withdrawal).

Recent developments in agricultural technology have made it possible to produce grains whose proteins are close enough to complete proteins to clinically allow for the recovery of a child suffering from kwashiorkor by feeding the child a diet primarily of these enriched grains.

The Promise of DNA Technologies

The pace of cereal improvement is expected to quicken as researchers overcome some of the obstacles preventing the use of recombinant DNA techniques to produce protein-enriched grains. Two major bottlenecks exist. First, plant hormone development and cell tissue culture must become something more than the fledgling science it currently is, so that the cells from grain tissue culture can be regenerated back into a complete plant. This plant tissue culture is possible with most dicots (vegetables), but not with monocots (grasses, including cereals), which evolved later with more efficient photosynthetic systems, and thus may well have more sophisticated systems for tissue development.

Second, current vectors for inserting DNA into monocots must be developed. The techniques being explored include *lipsomal fusion*, in which the DNA is encapsulated in membrane lipids (fats) that will fuse with the cell membrane, releasing the DNA into the cells; *electrofusion*, in which low electrical currents help get encapsulated or unencapsulated DNA into the cells; *lasers* or *microinjection*, in which holes are poked through the membrane to insert the genetic material; and particle guns, in which tiny 1-micron particles of relatively inert tungsten coated with DNA are shot into the monocot cells.

Using currently available plant breeding techniques, some superior grains are now available:

Corn. Standard hybridization techniques have been used by a research group at Purdue University in West Lafayette, Ind., to develop a corn rich in the essential amino acid lysine. This high-lysine corn was developed and tested in Guatemala and Colombia and has been shown to be effective in eliminating kwashiorkor.

Scientists studied the genetic control over the biochemical pathways in corn that convert simple sugar into starch and proteins. In the many varieties and hybrids of high-lysine corn, the synthesis of the usual lysine-poor corn protein is deliberately depressed in favor of the synthesis of glutulins rich in lysine and trytophan, another amino acid. Glutulins are a protein found in many grains; in fact, the high-protein wheat flour used for bread is glutulin-rich.

Thus far, genetic modification to produce high-lysine corn has generally meant the production of a corn that is less resistant to disease and other crop stresses like drought. In addition, it has caused a slight to large depression in the yield a farmer obtains by planting the high-lysine corn. In the next 10 years, however, it is expected that these problems will be eliminated by further crop breeding.

A similar breeding project is just beginning to develop high-lysine sorghums. Sorghum is a grain grown in very dry areas, particularly in Africa and Asia.

Wheat. Although these same plant breeding techniques cannot be used to develop a high-lysine wheat, scientists have begun to use cell tissue culture, specifically, the culture of the wheat-callus, the growth area of the wheat plant, to breed a high-lysine wheat. This work is taking place under the direction of Dr. Rollin Sears at Kansas State University in Manhattan, Kan.

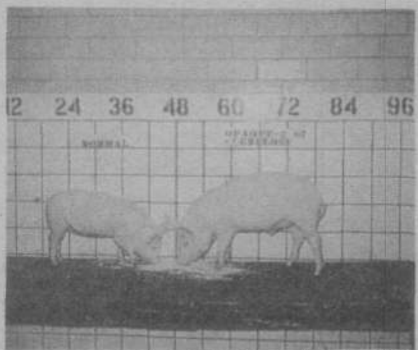
Ordinary plant-breeding techniques take a large amount of space and roughly 10 years to develop a new plant variety. Cell tissue culture, however, allows researchers to screen millions of potential wheat plants for a desired trait in a very small area, and to develop a new plant variety over a period of five years or less. By adding the chemical S-2-aminoethylcysteine (AEC), which mimics the chemical action of lysine in the wheat's biochemical pathways, researchers are able to screen for plants that have extra biochemical pathways and unusually great production of lysine.

Utilizing this technique, researchers were able to increase lysine production by 100 percent in the local wheat strain they used. Now they are trying the same technique on a specific high-yield spring wheat that is widely adapted to global climatic conditions. Over the next five years, they expect to bring this wheat up close to the Food and Agricultural Organization standard of 5.3 percent lysine. A similar cell tissue culture project is beginning to increase the methionine (another amino acid) content of rice.

Meanwhile, the somewhat more expensive synthetic lysine, like that now produced in Japan, could be added to wheat when it is milled, in the same way that U.S. wheat flour is enriched with B vitamins.

Potato. Although not a cereal, the potato ranks directly under rice, wheat, and corn as the fourth most important global crop. Dr. Jesse Jaynes of Louisiana State University in Baton Rouge is using the most advanced technology, recombinant DNA, to produce a complete-protein, high-protein potato. His research group is simultaneously working on white potatoes, sweet

Continued on page 64



The Saturday Evening Post, Dec. 1983

Which twin had the high-protein corn? The larger pig, fed high-lysine corn, gained five times more weight in a 45-day period than his twin, who was fed regular corn.

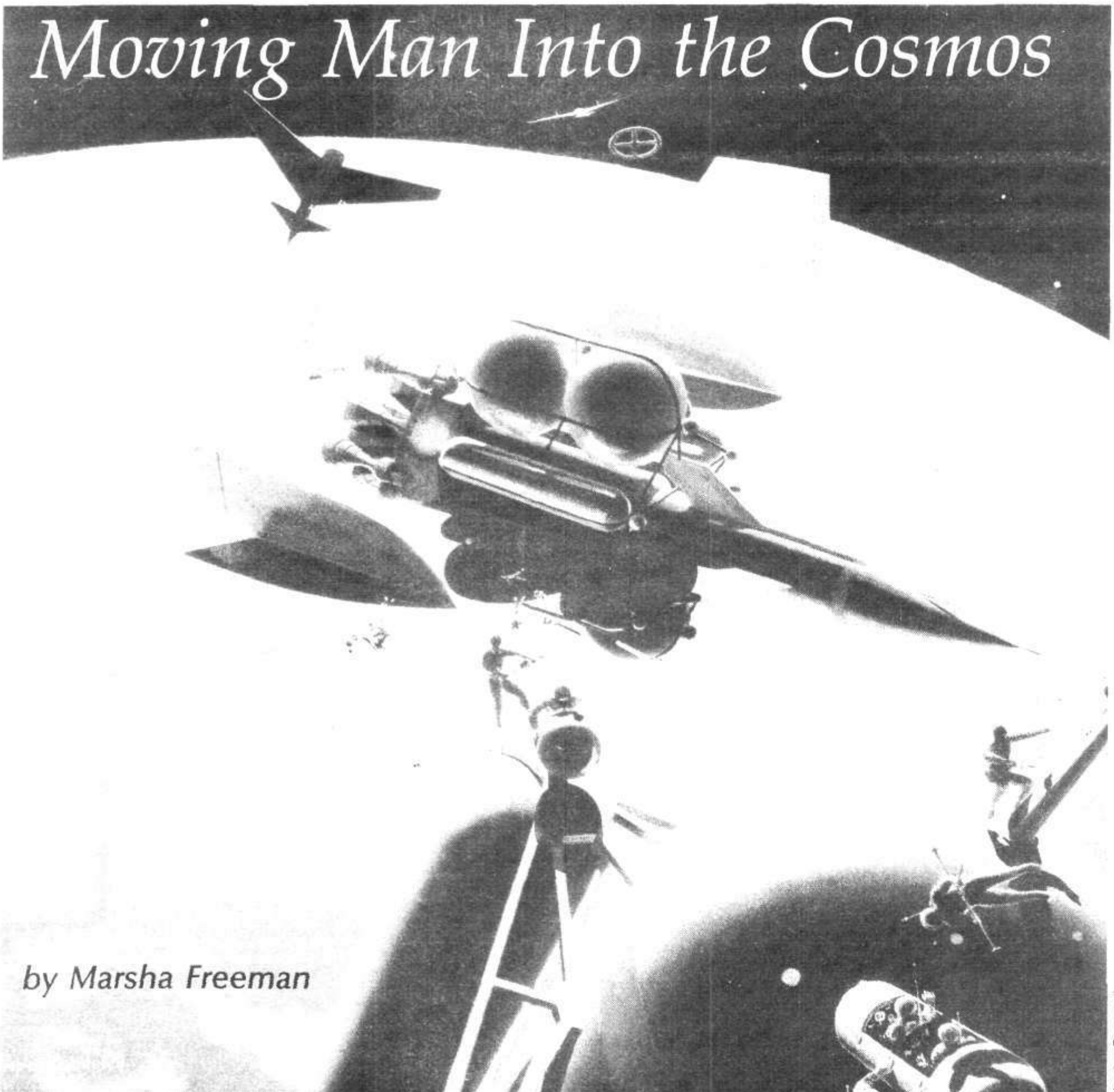
HIGH-PROTEIN GRAINS COMPARED TO REGULAR GRAINS

Type of Grain	Percent protein	Protein digestibility	Lysine (Grams/100 grams protein)
Wheat Purdue 4930 (high protein)	17.3	85.5	2.9
Wheat (regular)	12.1	85.5	3.0
Maize (high lysine)	10.5	85.8	4.6
Maize (regular)	10.5	85.8	2.7
Sorghum (high lysine)	18.5	60.0	3.3
Sorghum (regular)	13.1	60.0	1.8
Rice BP 1761 (high protein)	15.4	83.8	3.4
Rice (regular)	6.9	83.8	3.7

Colonizing MARS

Moving Man Into the Cosmos

by Marsha Freeman



© Chesley Bonestell

Colonizing the planet Mars is not science fiction. It is the logical goal of a 50-year mission that establishes a permanent manned space station, moves on to the Moon, and uses this as a jumping off point to Mars—and beyond. This article, the first in a series on Mars, focuses on how we will travel to our neighboring planet.

The manned landings on the Moon were a moment of great national achievement for the American people and all of mankind. Once again it was demonstrated that with a goal-oriented crash program we could achieve the seemingly impossible. Yet, the promise of putting man on the Moon has not yet been really fulfilled. As Hermann Oberth and other space pioneers well knew, a Moon landing is only the stepping-stone for man's conquest of all of space. Such a conquest will be accomplished only in terms of the grander plan to turn planets that are now uninhabitable into man's garden.

The United States is now committed to building a functioning space station by the early 1990s. At the same time, plans by space scientist Krafft Ehricke and others for industrializing the Moon are now being reconsidered by NASA. Neither venture will succeed, however, unless it is seen as part of a comprehensive program to colonize Mars in the next 50 years. The colonization of Mars presents the proper framework in which the technologies necessary for the nearer-term tasks can be optimally accomplished.

This 50-year perspective was precisely the approach taken as early as 1948 by Wernher von Braun, the man who made it possible for the United States to accomplish a Moon landing.[1] Von Braun knew that the Moon would have to be explored first, but to him the promise of Mars—a planet with an atmosphere, water, and possibly life—was that it could be a new home for man. Von Braun designed his "Mars Project" so that man could go there to answer the century-old question: Is there life on Mars? (Figure 1).

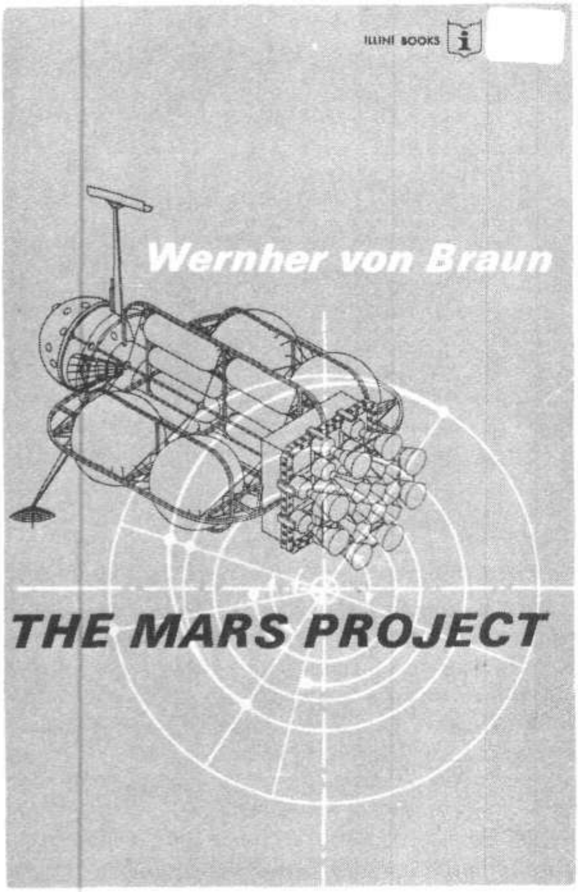


Figure 1
VON BRAUN'S MARS PROJECT
The Mars Project, *written by von Braun in 1948, was the first comprehensive plan for a manned mission to Mars. The book itself, a fictional account of such a journey, has never been published: Only the technical appendix, shown here, is available.*

How to Get to Mars

In order to colonize Mars, it is necessary to have a rocket propulsion system capable not only of transporting man there, but also of transporting along with him the means to support a stay on the planet long enough to begin the process of transforming the planet to support human life.

In 1948, when von Braun proposed the colonization of Mars, the only rockets that had flown anywhere in the world were derivatives of the A-4 rockets (better known as V-2) developed by the scientific laboratory at Peenemünde in Germany during World War II. After the war, the von Braun group settled in the United States, where they helped develop U.S. ballistic missiles. Although their rocket work in Peenemünde as well as their early work in the United States had a military goal, the primary commitment of these space scientists was to realize the vision of space pioneer Hermann Oberth—that within their lifetime man could reach the Moon and beyond. Oberth, the father of the German rocket program, in 1923 had outlined steps for the relatively straightfoward trip to the Moon.

Mars presents a far greater challenge than the Moon. Not only is it 35 million miles away at its closest opposition to the Earth (compared to the less than 250,000 miles to the Moon), but Mars is only in the right position in its period of revolution around the Sun about once in every two years [Figure 2 (a)]. For the Moon, this opportunity exists once a month.

If you leave the Earth at its closest opposition to Mars, by the time you travel the at-least 35 million miles to get to the planet, Mars would no longer be where it was when you left. Therefore, the path of least energy is to leave Earth-orbit at a point when Mars is about 44 degrees ahead of the Earth, and to intersect Mars's orbit about 260 days later, after traveling more than 700 million miles. This opportunity presents itself every 25 to 26 months.

The distances and motions of the planets in the solar system are organized in harmonic relationships, as Kepler understood. In order to travel on a path other than an orbital trajectory—that is, across orbits—requires energy, to do work against the motion of the solar system. This is the problem posed in developing propulsion systems to take

Wernher von Braun envisioned a flotilla of spaceships leaving Earth's orbit for Mars. In this painting by space artist Chesley Bonestell, the ships are being assembled by astronauts in orbit. An Earth-to-orbit shuttle vehicle is shown top left being unloaded by astronauts; a wheel-shaped space station is at the top center.

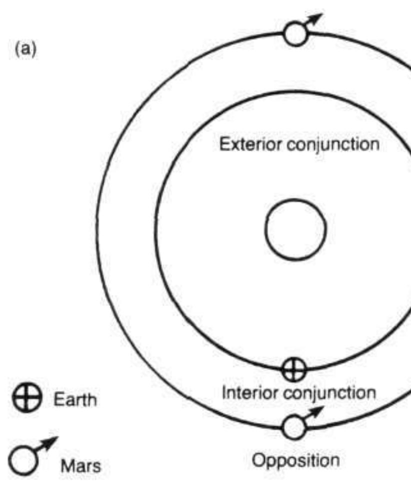
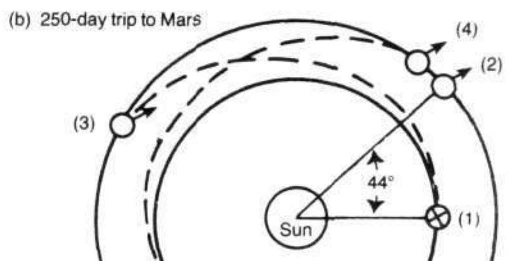


Figure 2
THE MARS LAUNCH WINDOW AND HOHMANN ORBITS

At the point of opposition, the Earth and Mars are at their closest distance. However, because it takes Mars almost two Earth-years to revolve around the Sun, such opposition occurs only that often. Thus, the journey to Mars can begin only about once every two years. The orbits are shown (a) as circles, not ellipses.

Since it takes time to get to Mars, the spacecraft cannot leave at the point of opposition, for by the time the crew arrives, Mars would have moved along on its orbit. In 1925, Dr. Walter Hohmann designed the minimum-energy transfer orbits shown in (b). The crew starts out when the Earth (1) is 44 degrees ahead of Mars (2) in its orbit. The astronauts intersect Mars in its orbit at point (3), having traveled about 250 days. After spending more than a year on Mars, the astronauts leave Mars's orbit (4) and arrive back on Earth, another 250 days later, at point (5) in Earth's orbit around the Sun.



spacecraft from the Earth to Mars: Nothing in the solar system travels naturally from one planet to another.

The fuel requirements for interplanetary trips and the minimum-energy flight paths to accomplish them were worked out in 1925 by the German scientist Walter Hohmann. The so-called Hohmann transfer orbits are Keplerian ellipses, which lie in the plane of the ecliptic, travel in the same direction as the general rotation of the solar system, and touch at least two planetary orbits, as seen in Figure 2b. These trips require a boost out of Earth-orbit and then continue on a "cruising," unpowered ballistic trajectory until arrival at Mars.

Once on the planet, a 400-day-plus waiting time is mandatory before the Earth-Mars system allows a minimum-energy return trip, which is again 260 to 300 days. Thus, if the trip to Mars must rely on unpowered travel, the crew must be prepared for a 950-day mission.

The trip could be shortened considerably by increasing the initial velocity, accelerating along the way, and crossing rather than intersecting the orbit of Mars. But this would require additional energy as it violates the path of least action of Keplerian ellipses. Also, more energy—more fuel—to reach a higher velocity and to slow the spacecraft for capture into Mars's orbit would be required. As long as the trip relies on chemical propulsion, the weight penalty of carrying along extra fuel results in too much of a trade-off against the amount of payload that can be taken on the trip. The propellant weight increases exponentially with linear increases in velocity.

When von Braun sat down to write *The Mars Project* in 1948, the only option available, based on then-current chemical propulsion technology, was the Hohmann transfer orbit. His only computational tool was a slide rule. Although he could certainly envision the development of "atomic" propulsion, von Braun aimed to prove that the manned mission to Mars could be done with the technology of that day.

'Grand Scale' Exploration

Interplanetary exploration "must be done on the grand scale," just like the exploration of America, von Braun remarked in the technical appendix of *The Mars Project*—the only part of the book that has been published. In his scheme, since the trip was to take nearly three years, safety for the passengers was provided by redundancy, or taking multiples of everything.

Von Braun planned a flotilla of 10 interplanetary ships that would be assembled in space while orbiting the Earth (frontispiece, p. 00). A fleet of 46 space shuttles (ferry vessels) would transport each spacecraft module to orbit. At that time, von Braun did not envision a permanent space station in orbit. Instead, these shuttles, making 950 trips back and forth to Earth-orbit, would build and fuel the vehicles for the crew of 70. Of the 10 interplanetary ships, 7 would carry people, and 3 would carry cargo. Each would weigh nearly 4,000 tons.

Three of the seven passenger ships would have "landing boats" in order to descend to the surface of Mars, while the others remained in orbit around Mars. These three landing ships would deliver 50 men and 149 tons of material to the surface of Mars for the 400-day exploration of the planet. At the end of the Mars surface stay, two of the three landing boats would rejoin the interplanetary ships in orbit and head back to Earth, where the crew would transfer to orbital ferry vehicles to land on Earth.

For all of his space vehicles—Earth-to-orbit three-stage ferry vehicles, interplanetary ships, and Mars landing boats—von Braun assumed that the fuel would be hydrazine with a nitric acid oxidizer. He used this combination because the technology to handle more energy-dense liquid hydrogen had not yet been developed, although von Braun stated that it surely would be by the time mankind set off for Mars.

In the introduction to *The Mars Project*, von Braun wrote, "There is scarcely any branch of science which has no bearing upon interplanetary flight, and this little booklet will have achieved its objective if it stimulates some of its readers to find, in their own particular specialties, contributions which may fill out one or more of the many gaps still existing in the scientific extrapolation of a voyage to a neighboring planet."

By 1956, when von Braun coauthored *The Exploration of Mars* with Willy Ley, confidence in space systems had increased to such a point that the revised Mars plan called for a crew of only 12. The other advances were just as dramatic. Each interplanetary spacecraft, using a more advanced chemical fuel, would now weigh only 1,870 tons (not 4,000) and would be assembled in Earth-orbit by 400 (not 950) shuttle missions. Six years later, in 1962, when von Braun wrote a preface to the second edition of *The Mars Project*, he stated that the single greatest advance since his original mission outline was the availability of liquid hydrogen fuel. This leap in propulsion technology was created by space scientist Krafft Ehricke, another veteran of Peenemünde, who had left the original von Braun team to go to General Dynamics to build the Centaur—the first liquid hydrogen upper stage rocket.

With liquid hydrogen, the exhaust velocity of the combustion products jumped to 4,200 meters per second, compared to the less energy-intense hydrazine, which had an exhaust velocity of 2,800 meters per second. This increase in exhaust velocity results from the higher combustion temperature, and it increases the specific impulse of the propulsion system (see box).

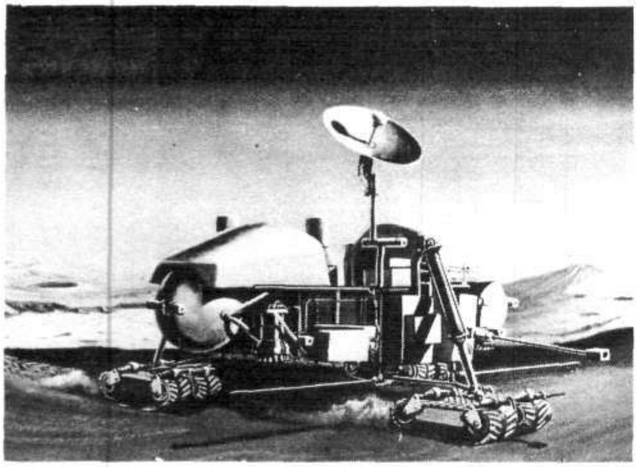
By the early 1960s, scientists could envision still further advances in technology, and NASA set to work to develop the postchemical generation of propulsion techniques, planning an array of nuclear-derived technologies that would become available over the next decade.

Comparing Propulsion Systems

The speed at which the propellant is expelled from the rocket largely determines the specific impulse of the propulsion system. The specific impulse—the impulse per unit weight—is measured in seconds. The higher the specific impulse, the more efficient the propulsion system and the greater the potential rate of acceleration of a spacecraft.

In addition to specific impulse, every rocket engine has a specific thrust, or force produced by the exhaust. The ideal propulsion system would combine a high-temperature, high-velocity exhaust, (specific impulse), with enough exhaust mass for a high-thrust push. Most existing and near-term propulsion systems trade one off against the other.

For example, a liquid hydrogen chemical rocket has a high thrust, by spewing thousands of tons of propellant out the back of the engine in a matter of seconds. But the maximum specific impulse obtainable is about 450 seconds because of the temperature of chemical combustion. Ion propulsion systems, on the other hand, which could have much greater exhaust velocities by high rates of acceleration of ions, would produce very low thrust, and therefore low rates of acceleration because of the small mass of material being expelled.



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Unmanned robotic systems will be important, as predecessors to a manned Mars mission, to continue the exploration of our neighboring planet. This 1976 NASA design for a Elastic Loop Mobility System is an improvement on the Lunar Roving Vehicle used in the Apollo program. NASA designed these mobile systems as the next step after the Viking landers, which were immobile. The continuous elastic-loop track device would distribute the vehicle weight uniformly over a large area and allow heavy scientific equipment to be moved about the Martian surface.

Going to Stay, or Just to Visit?

After the 1969 triumph of man's first lunar landing, scientists naturally assumed that the Moon would be developed as a great resource and scientific base from which man would continue on to Mars and beyond. As early as 1962, Ernst Stuhlinger, a Peenemünde veteran, and his coauthor, Joseph King, discussed electrically propelled vehicles for Mars from that standpoint:

> It seems reasonable to predict that detailed design studies on the necessary vehicles will begin toward the end of this decade. This prediction is based on the

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The thin atmosphere of the planet creates a weather system, which, from time to time results in dust storms. At the top of the extended boom of the Viking lander is the package of meteorological instruments that monitors the atmospheric pressure, temperature, wind velocity, and wind direction.

> theory that the Mars expedition will be the natural follow-on project to be undertaken after the lunar program reaches enough maturity that lunar surface operations are being carried out more or less routinely.[2]

The most important conceptual development during the past 30 years of planning manned Mars missions was Krafft Ehricke's work during the late 1960s. Ehricke put forward the detailed evolutionary plan of using space stations and the Moon as the jumping off point for Mars, and he developed an entire family of space vehicles to permanently move human civilization outward from Earth.

One important judgment that had to be made in evaluating different propulsion possibilities during the 1960s, was whether it would provide more crew safety—in terms of system reliability, exposure to radiation, and physiological effects of zero gravity—to try to complete the manned Mars mission as fast as possible, although quick trips would sacrifice scientific return.

One concern that continues today is the observed deteriorating effect zero gravity has on bone calcification as well as its possible cardiovascular effects. Vigorous exercise on the way will ameliorate some of the symptoms, and when advanced nuclear and later fusion technologies are ready, trip time will be significantly cut down—ultimately to a few days. Also, once on Mars, the increase in gravity to 38 percent of that on Earth should significantly slow down or even reverse any effects from the trip.

In deciding how to go to Mars before advanced propulsion techniques were ready, the question came down to the choice between using the Hohmann transfer orbits (synodic missions) or faster systems that made use of higher specific impulse systems. The former were lengthy but gave the crew plenty of time on Mars and could be achieved with available chemical fuels. The higher specific impulse systems, on the other hand, would get the crew there faster but would not allow large payloads or long stay-times.

At the dawn of the era of manned space flight two decades ago, few scientists could envision the wealth of data about other worlds that would be gathered by robotic flyby missions and probes. They planned to fulfill this purpose with short-transit and short-stay-time manned missions to Mars to gather information. These brief reconnaissance forays, they expected, would then enable scientists to make decisions about whether it would be possible for man to work on Mars.

By the mid-1960s, however, unmanned Pioneer and Mariner spacecraft had revealed fantastic pictures of new worlds in space. Krafft Ehricke then decided that the earlier concept of getting man to Mars as quickly as could be projected with the technologies of the next decade would offer too limited stay-times at the planet. In a 1970 paper, he remarked:

> The explorers at the planet will act as individuals and as extensions of the scientific community of Earth in real time, just as the unmanned probes that preceded them. They need time at the planet to consult with their peers and plan details of their exploration as they proceed. This way scientists and engineers on Earth can participate in real time in a truly manned exploration of the solar system. It appears that *exploration in depth* should be viewed as the primary engagement of future manned missions into the solar system.[3]

Ehricke's work outlined in great detail the requirements for industrializing the Moon. Included in this plan were the next-generation transport vehicles, like nuclear shuttles, which would lay the basis for going to Mars. As he planned it, industrial production on the Moon, including finished metal products and liquid oxygen for propulsion, would provide a less expensive source of materials for Mars-bound travelers than the same products made on Earth. The industrialization of the Moon would provide the enabling technology for the colonization of Mars.

Bringing Civilization to Mars

What Ehricke put forward in 1970 was a 12-year manned Mars base program to start the process of settling Earth's neighboring planet. He replaced quick-transit propulsion proposals, which only allowed short visits to the planet's surface, with synodic missions where scientists would have the opportunity to work on Mars for more than a year.

Ehricke's manned missions to Mars involved several stages. First, the astronauts would take a reusable shuttle to a low-Earth orbiting space station. From there, they would transfer to a nuclear-propelled Interstation Transfer Vehicle, which would bring them to a Geospace Shuttle Station. This station would be located in a highly elliptical orbit, with a perigee meeting the low-Earth orbital station and an apogee at a distance from Earth that was 98 percent of geosynchronous orbit (see Figure 3).

The value of this intermediate orbital step, according to Ehricke, is that the gross mass of the large interplanetary Mars Delivery Vehicle could be reduced by about 62 percent, raising the gross payload that can be taken to Mars by about that amount. Unlike the Earth-to-orbit shuttle, the Interstation Transfer Vehicle will have to traverse the Earth's Van Allen radiation belts, and therefore, must be heavily shielded. Ehricke envisaged that the Geospace Shuttle Station could also function as a repair and maintenance facility.

The huge interplanetary spacecraft, or Mars Delivery Vehicle, would be assembled at the Earth-orbital space station, mated with the crew at the Geospace Shuttle Station, and boosted from there by a Trans-Planetary Insertion vehicle. This booster would be fueled and checked out at the Geospace Shuttle Station.

At Mars arrival, one of the interplanetary spaceships would function as a Mars Orbital Station. This orbiting command center would control a series of Martian orbiting subsatellites, surface landers, rovers, and sample return vehicles that would make unmanned forays to the Martian surface before the crew landed. Ehricke proposed that the Mars

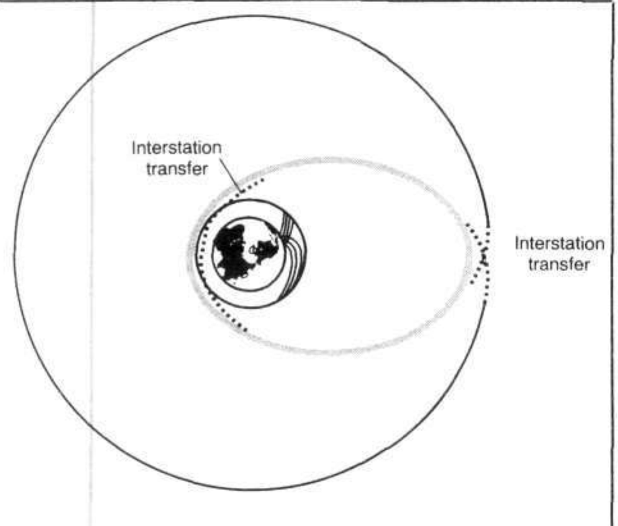
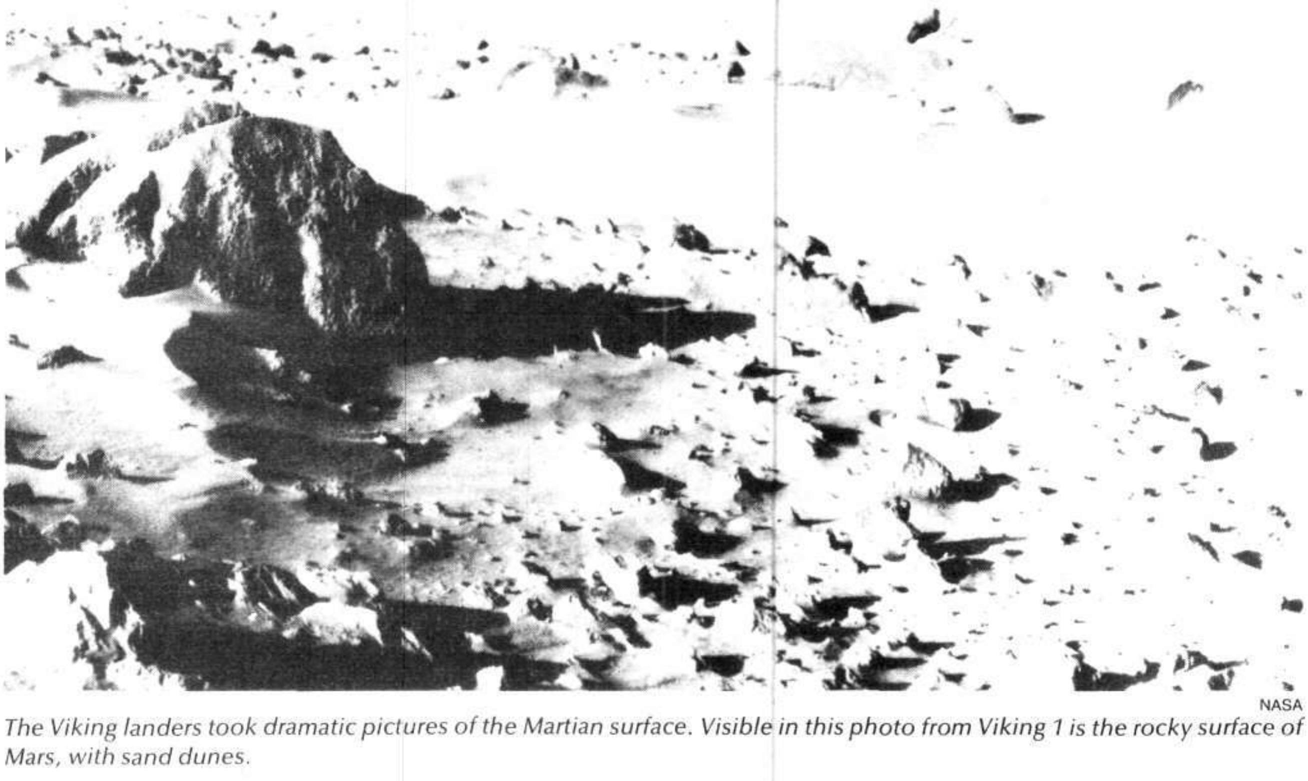


Figure 3
EHRICKE'S INTERMEDIATE SHUTTLE STATION BETWEEN NEAR-EARTH AND GEOSYNCHRONOUS ORBITS

Krafft Ehricke designed this intermediate, highly elliptical transfer stage between low-Earth orbit and the boost toward Mars, making it possible to increase the payload the crew can take to Mars by 80 percent. In the Earth-orbit transfer station (left), the crew boards a nuclear-propelled Interstation Transfer Vehicle that takes them to a Geosynchronous Space Station (right).



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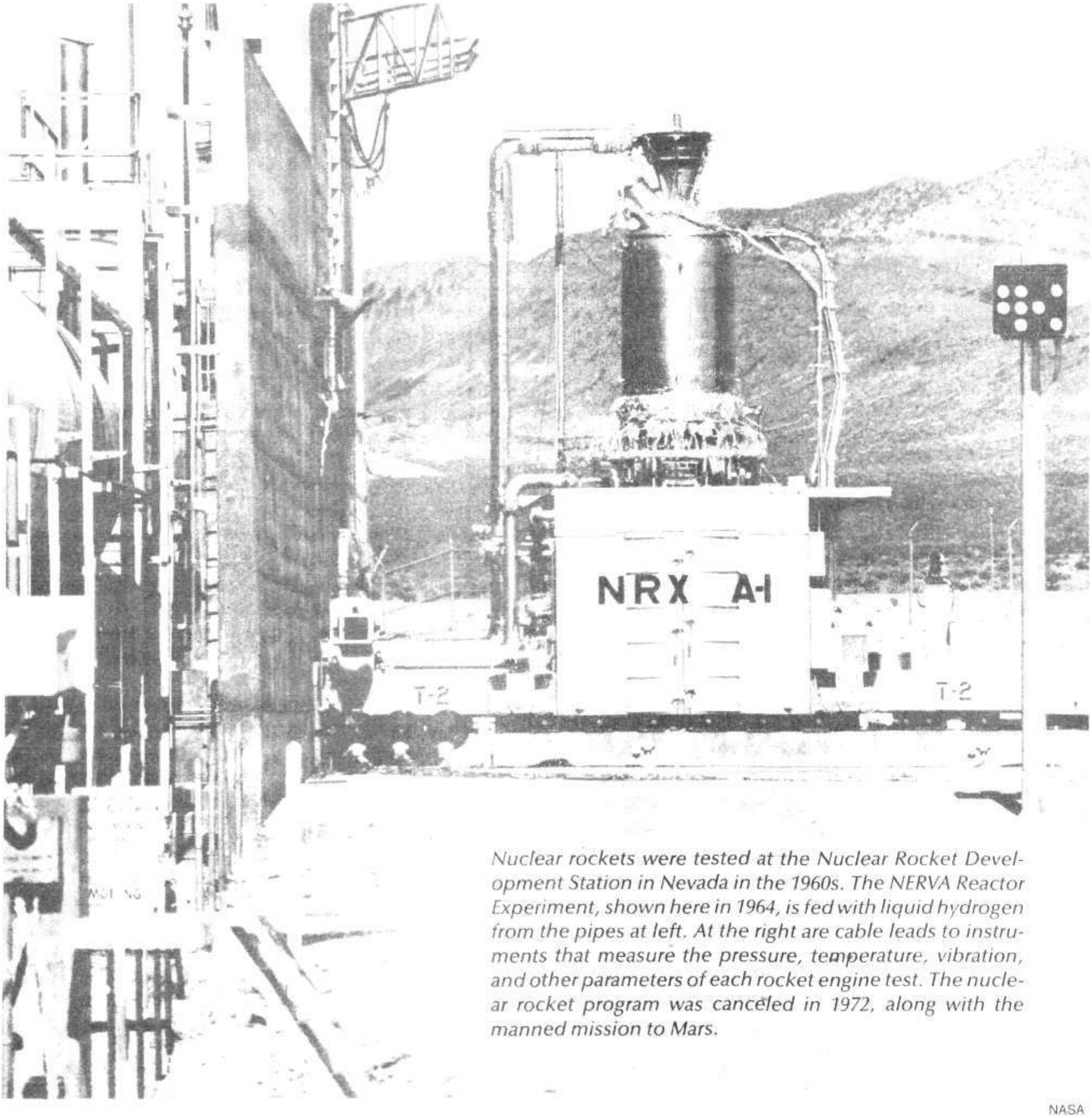
The Viking landers took dramatic pictures of the Martian surface. Visible in this photo from Viking 1 is the rocky surface of Mars, with sand dunes.

Orbital Station might contain plants and even animals that have made the long voyage from Earth. When crews began to land on the planet, the Mars Orbital Station would be the control center for Mars Excursion Vehicles as well.

In addition to providing safety by sending a "convoy of at least two manned vehicles," Ehricke wished to increase both the scientific return of the mission and the safety and comfort of the crew by sending them to Mars *without* sufficient fuel for their return trip. All previous mission profiles, from von Braun's in 1948 through other plans in the 1960s, provided for the crew to carry the fuel for its return journey, leave it in orbit around the planet while the manned exploration proceeded, and use it on the way back.

However, Ehricke asked, if the crew is going to stay on Mars for a year, why leave that fuel in orbit to evaporate or possibly be hit by meteors? On a chemical or even low-thrust nuclear propulsion basis, using the long but energy-efficient Hohmann transfer orbit, the crew cannot leave Mars until the Earth-Mars system allows it. As he put it, "Return propulsion absorbs mass that does not contribute to the crew's safety, because with the limited propulsion energy available, emergency transfer to Earth is not feasible until the next window comes around. . . . Crew survival probability, therefore, is directly proportional to the payload mass available to them for the duration of the synodic capture period."

Why not send the Mars Delivery Vehicle off on its mission with twice the payload, and half as much fuel? Ehricke asked. Doubling the payload means the crew can have luxurious living quarters compared to conventional designs, signifi-



Nuclear rockets were tested at the Nuclear Rocket Development Station in Nevada in the 1960s. The NERVA Reactor Experiment, shown here in 1964, is fed with liquid hydrogen from the pipes at left. At the right are cable leads to instruments that measure the pressure, temperature, vibration, and other parameters of each rocket engine test. The nuclear rocket program was canceled in 1972, along with the manned mission to Mars.

NASA

cantly more scientific equipment and research facilities to make their stay at Mars more worthwhile, and increased safety from "defense-in-depth" against vital equipment failures. The situation is not that different from the scientific expeditions that last a year in Antarctica, where travel from the base is virtually impossible in the winter. Those in the expedition must have everything with them that they might need.

How then does the crew return to Earth? When the next launch window opens, a small, relatively high-speed Crew Pick-Up Vehicle leaves from Earth. Carrying mostly fuel—since only that plus life-support provisions for the pick-up crew and the returning Mars expedition are needed—the small vehicle goes on its pick-up mission. It could also take back a crew module already in Mars orbit, to house the travelers on the return flight.

Ehricke points out that the safety of the return is enhanced by the relative newness of the return vehicle—a ship that has been in operation for only 160 to 190 days, (depending upon the propulsion technique), compared to nearly two years. Another benefit is that the stay of the astronauts on Mars is extended by the 160 or so days they are waiting for the Crew Pick-up Vehicle to come for them.

In the 12-year Mars development scenario Ehricke laid out in 1970, the pick-up vehicle would also drop off a fresh crew to Mars during its brief 10-day Mars stopover. In this Multiple-Flight Synodic Mission Mode, there is a step-wise build-up using the five launch windows that are available during a 12-year period of time. If the first crew had found severe problems for the Mars colonization effort, they would be returned to Earth and not replaced. If things went according to plan, the second mission would accomplish a one-for-one exchange of the 12-person crew. Resupplies and some new scientific equipment would be brought along in the pick-up vehicle. Propellant for reusable Interorbital Excursion Vehicles to visit the Martian moons Deimos and Phobos would be delivered as well.

On the third trip, the crew size would be increased to 18, and a shelter for extended surface stays and two Mars shuttle vehicles would be included in the delivery. By the fourth mission, the base would increase in size to 24. At the same time, assembly and repair facilities for the Mars Orbital Station, resupplies for the station itself, a third Mars shuttle vehicle, and equipment for exploiting Martian resources for growing base autonomy would be delivered.

By the end of the 12 years and five trips to Mars, the Ehricke plan provides for the possibility that crew members could stay for a second tour of duty. Surface and flying vehicles were designed by Ehricke for the small but growing Martian community. Thus in barely more than a decade, humanity could establish a permanent foothold on another planet in the Solar System.

Advanced Propulsion Technology

It was clear to Ehricke as well as other scientists, that the way to get to Mars faster and without the handicap of a heavy fuel load, was to go with nuclear propulsion. Nuclear-fueled rockets were planned much the same as the nation planned on nuclear-fueled submarines and nuclear power plants.

The Rover program was begun in 1955 by the Atomic Energy Commission, before NASA even existed, to develop a nuclear rocket. A progression of solid-core nuclear reactors and rocket engines were built in a highly successful effort. In 1968, the Phoebus reactor ran for 12 minutes at above 40,000 megawatts of power. It was the largest nuclear rocket engine ever built, delivering 250,000 pounds of thrust.

In 1969, however, the U.S. cut back on the Apollo program and decided to stop the production of Saturn V launch vehicles. These were the only rockets big enough to allow the nuclear engine to be flight-tested; they would have launched an operational nuclear engine to Earth-orbit, where it would be fired up to send men on their way to Mars.

When he planned his Mars mission just after the Saturn V liquid hydrogen rocket had proved itself man-worthy in the Apollo program, Ehricke had conservatively estimated that only first-generation nuclear propulsion would be available when the manned Mars program started. During the mission's 12-year duration, he expected propulsion technology to continue to advance. Ehricke explained how the progression from chemical to first-generation solid-core nuclear propulsion, which doubles the specific impulse of the system, allows a reduction by 50 percent in the weight of the interplanetary vehicle launched from the Geospace Shuttle Station. Lighter vehicles would greatly reduce the time it would take to assemble them in orbit as well as the number of Earth-to-orbit shuttle flights required. They would also allow a larger payload per unit of propulsion weight.

With the use of fully nuclear two-stage Mars Delivery

NASA

This full-scale mockup of the Nuclear Engine for Rocket Vehicle Application (NERVA) allowed engineers to observe component orientation and limitations on spatial arrangement. The mockup was constructed by Aerojet-General Corp.

Vehicles, Ehricke estimated that the payload that could be carried to Mars would be increased between 60 and 80 percent. It is even possible, in the longer term, that the nuclear stages that boost the Mars Delivery Vehicle out of the near-geosynchronous orbit could be reusable nuclear-propelled shuttles, which would detach from the delivery vehicle after boost, return to the Geospace Shuttle Station, and wait for their next assignment. These would be similar to the tug boats that guide huge ships out of a harbor although, of course, working at greater speed. It would allow the series of boost stages to be decoupled from the remainder of the mission.

The characteristics and capabilities of families of propulsion technologies, all of which will have their own "windows of opportunity" and applications for missions to Mars, are summarized in the table. After the successful development of liquid-hydrogen-fueled rockets, the next-step increase in propulsion capability was the solid-core nuclear reactor, not that different from ground-based power plants. With a specific impulse double that of chemical propulsion, the solid core nuclear reactor had the potential to decrease total travel time, although within the parameter of a short stay at Mars.

By 1971, the nuclear rocket engine concept and feasibility (this was known as NERVA for nuclear engine for rocket vehicle application) had been demonstrated. The Ground Experimental Engine had been test-fired 27 times in one hour, with a peak run of 200 seconds, producing over 57,000 pounds of thrust at over 1,000 megawatts of power. NERVA was a nuclear-thermal engine that used the heat of the fission reaction to raise the temperature—and therefore, the exhaust velocity—of liquid hydrogen to about 25,000 feet per second, or double chemical exhaust velocities. In 1971, von Braun estimated that a NERVA-type rocket could be ready for flight by the mid-1980s.

Some rocket scientists had proposed nuclear designs that were different from NERVA in the late 1950s. Their idea was that nuclear energy would not directly heat a propellant, but would be converted to electrical energy to ionize and accelerate a propellant, such as mercury, which would be expelled from the engine. These high specific impulse designs, nonetheless, were low in thrust or pushing power. It would take a long time for the ship to reach a high rate of acceleration; therefore, the relative positions of the Earth and Mars would still be a major constraint in stay-time at Mars.

Another constraint to the relative efficiency of nuclear-electric drives is the efficiency of conversion from heat to electricity. Current studies at the Jet Propulsion Laboratory in Pasadena, Calif., indicate that nuclear electric propulsion will, however, be very promising for future deep-space unmanned planetary probes.

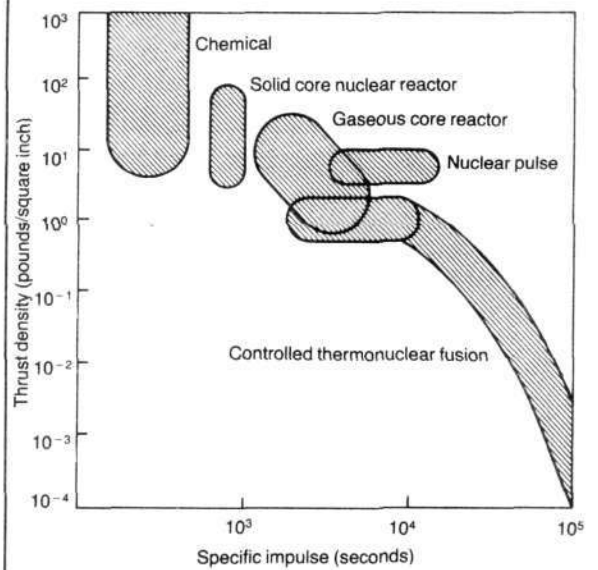


Figure 4

THRUST DENSITY VERSUS SPECIFIC IMPULSE

The advantages of of progressing to more energy-dense forms of propulsion are shown in this figure from Ehricke's 1970 Mars design. The chemical category at left, is today's class of liquid hydrogen rockets. Although the thrust, measured in pounds per square inch, is high, the specific impulse, and therefore rate of acceleration, is slow. The solid core nuclear reactor doubles the specific impulse. The gaseous core reactor moves into the region of thousands of seconds of specific impulse, gaining efficiency and acceleration. The nuclear pulse system, which would consist of small atomic bomb bursts, pushes into the thousands of seconds range, and controlled thermonuclear fusion, potentially is at least an order of magnitude higher.

Electric, solar, and other low-density propulsion systems would not be able to maintain the thrust levels shown here; the thrust density of these systems is less than 0.01 pound per square inch.

SDI Opens the Technology Window

Next-generation nuclear systems, under development until the early 1970s cancellation of the Mars mission, are

GENERAL PARAMETERS FOR SPACE PROPULSION SYSTEMS

Propulsion Type	Specific Impulse (seconds)	Mars Trip Time (days)	Mars Stay Time (days)
Liquid hydrogen	450	520	450
Nuclear electric	5,000	443	29
Solid core reactor (thermal)	800-1,200	400	40
Gaseous core reactor (thermal)	2,000-3,000		40
Laser/thermal	1,500	NA	variable
Only for low-Earth orbit to geosynchronous orbit			
Nuclear pulsed	2,000-10,000	variable	variable
Laser fusion	10,000-600,000	30-100	unlimited

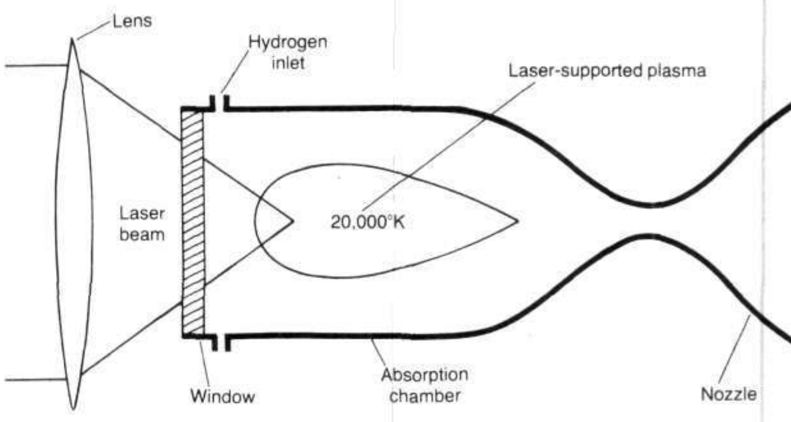


Figure 5
HIGH-POWER LASER PROPULSION DESIGN

These laser-heated engine thrusters are being developed at the Marshall Space Flight Center. A high-power laser, either on the ground or in Earth orbit, would beam its energy through a window at the front or side of the rocket. This would create a high-temperature plasma in the center. Liquid hydrogen would flow in from the inlets at top and bottom and would be heated by the plasma. The hydrogen propellant would go through the nozzle at right, and then be expelled, creating the thrust for the spacecraft.

now being resurrected because of the propulsion requirements for the Strategic Defense Initiative (SDI). The need to orbit large space components, develop megawatt or gigawatt directed-energy devices, and develop space-based nuclear electric systems, is reopening the technology window for what will be available to the manned missions to Mars after the year 2000.

Next-generation nuclear propulsion. The SDI Office announced in June 1985 that it will be funding a consortium of scientific researchers "to study innovative approaches for space power, utilizing improved nuclear reactor technology." The purpose of the program is to develop *multi-megawatt* reactors, and the research will include development of more efficient gaseous core nuclear power plants. Taking the fission processes to the gaseous state can potentially produce rocket engine specific impulses up to three times those of the NERVA solid core reactor. This advantage comes from the fact that the gaseous fission reaction takes place above 2,000 degrees F., whereas the solid core system operates at less than 1,000 degrees F.

As the table indicates, the gaseous core reactor would potentially decrease the Mars transit time. Greater velocity changes during the different phases of the trip would be possible, because of the higher power density of the system. New and potentially lighter materials will need to be developed for the higher-temperature gaseous nuclear system. Replacing heavier metal alloys with partially stabilized zirconium and other rugged materials on the horizon may even improve the total payload-to-mass ratio.

Laser propulsion. There is little question that the SDI program will push the development of lasers into the multimegawatt and even gigawatt power ranges. With lasers of this power level, either in space or on the ground, thermal *laser-plasma propulsion will become possible.*

At the Marshall Space Flight Center in Huntsville, Ala., a laser propulsion facility has been established to develop a rocket engine that would use laser energy to create a high-temperature plasma. The plasma would transfer energy to a hydrogen propellant, creating a 1,500-second specific-impulse drive. The NASA researchers state that although large lasers are not likely to be developed purely for these propulsion systems, lasers for directed-energy kill systems would be the system's enabling technology.

The attractiveness of this system is recognized by the Air Force Office of Scientific Research, which is funding laser propulsion development. In 1968, this office funded an evaluation of advanced propulsion technology by Krafft Ehricke. The major use of laser-thermal propulsion would be between low-Earth orbit and geosynchronous orbit, where the payload could be tripled by eliminating the use of a chemical upper stage from the Space Shuttle. In the laser system, the power supply is no longer on the vehicle, and only the hydrogen propellent must be carried along.

It might also be possible to use ground or Earth-orbital lasers for transit to the Moon, if high-powered, short-wavelength lasers become available. For travel beyond that distance, the dispersion of the laser and size of the optics needed would make the system unwieldy.

Pulsed fission and fusion propulsion. The real breakthrough in propulsion technology will come when small fission and then thermonuclear fusion explosions can be used in pulsed configurations. These most intense energy releases will create specific impulses in the tens to thousands of seconds. A Nuclear Pulse Drive engine that would use small nuclear explosive charges stored in the vehicle was designed by Krafft Ehricke in 1968. The explosives would be ejected and detonated at some distance behind the vehicle. The high-velocity plasma debris from the explosion would intercept a "pusher plate," which, after moderation, would propel the vehicle. The velocity would be determined by the frequency of detonations, and a "push power" three times gravitational acceleration would be possible. At this level of specific impulse and rate of acceleration, the distance traveled on the way to Mars becomes less significant. Least-energy Hohmann transfer orbits and waiting-out synodic cycles would finally be superseded.

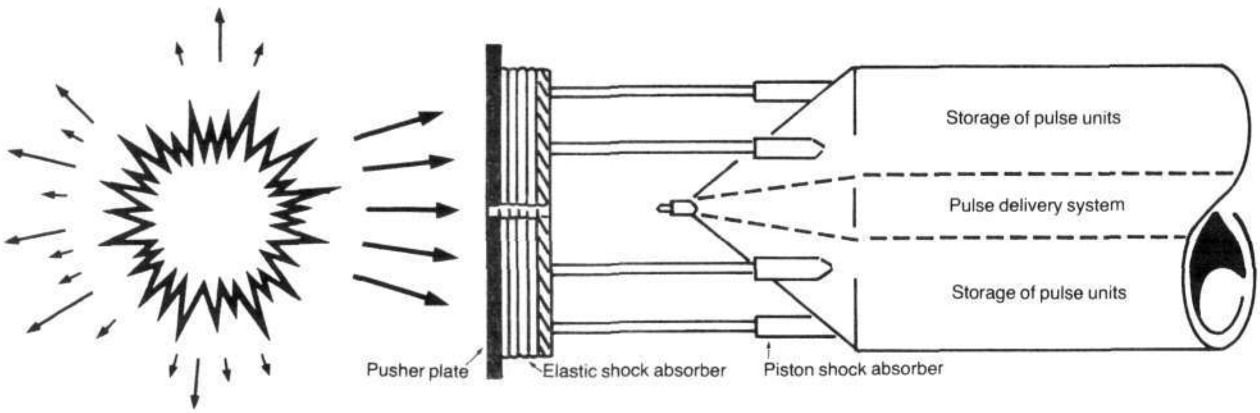


Figure 6
EHRICKE'S DESIGN FOR AN EXTERNAL NUCLEAR PULSE ENGINE

Krafft Ehricke designed this nuclear pulse engine in 1970. The pulse units, made up of nuclear fuel, are propelled out of the rear of the vehicle and detonated at some distance from the spacecraft. Part of the small blast would hit the pusher plate. Shock absorbers would moderate the pulse, and the ship would be pushed forward, at a rate perhaps as fast as three times gravitational force, or 3g. This would make possible trip times to Mars of weeks, rather than months.

At exhaust velocities in the range of thermonuclear fusion, the specific impulse and high thrust could bring the crew to Mars in just days. Work at Lawrence Livermore National Laboratory and that done by fusion scientist Friedwardt Winterberg in laser and other inertial fusion designs demonstrate that fusion is the enabling technology not only to Mars, but also to the stars.

Many varieties and combinations of advanced energy production and conversion technologies can be designed to optimize each step that Krafft Ehricke outlined for the colonization of Mars. Since the Mars mission was not carried out in this decade as the original timetable had envisioned, we now have the opportunity to skip the first-generation chemical and nuclear propulsion technologies and aim for the more advanced and flexible systems.

The Challenge

Over the past 10 years, when nearly all of this research was in the deep freeze, few scientists and engineers were working on solving the myriad problems in power plants, materials, and basic physics that remain today. Unfortunately the popular research topics have been the various schemes to use "low technology" and nonnuclear "solar" systems, derived from the Gerard O'Neill "tin can" school of space colonization, which have dominated the research and development work of young scientists and engineers.

Exactly the opposite is necessary if mankind is going to bring human civilization to its neighboring planet, Mars. Such exploration will have to be carried out the way exploration of new worlds has been done historically—with the leading-edge technologies at the frontiers.

Information confirmed by the mid-1970s Viking Lander missions have opened up the possibility of using the existing resources on Mars to make a base self-sustaining earlier in the colonization picture. "Mining" the atmosphere of the planet, processing the raw materials, melting parts of the polar caps for water, and developing Mars-specific industries will create a new society—not just an "outpost" away from Earth.

The dreams of generations will begin to become reality when man picks up the challenge former senator Harrison Schmitt put before Americans when he left the Moon on the last Apollo mission: Man must put his footprint on more distant bodies in the solar system.

Marsha Freeman is the director of industrial research for the Fusion Energy Foundation and writes frequently on the space program.

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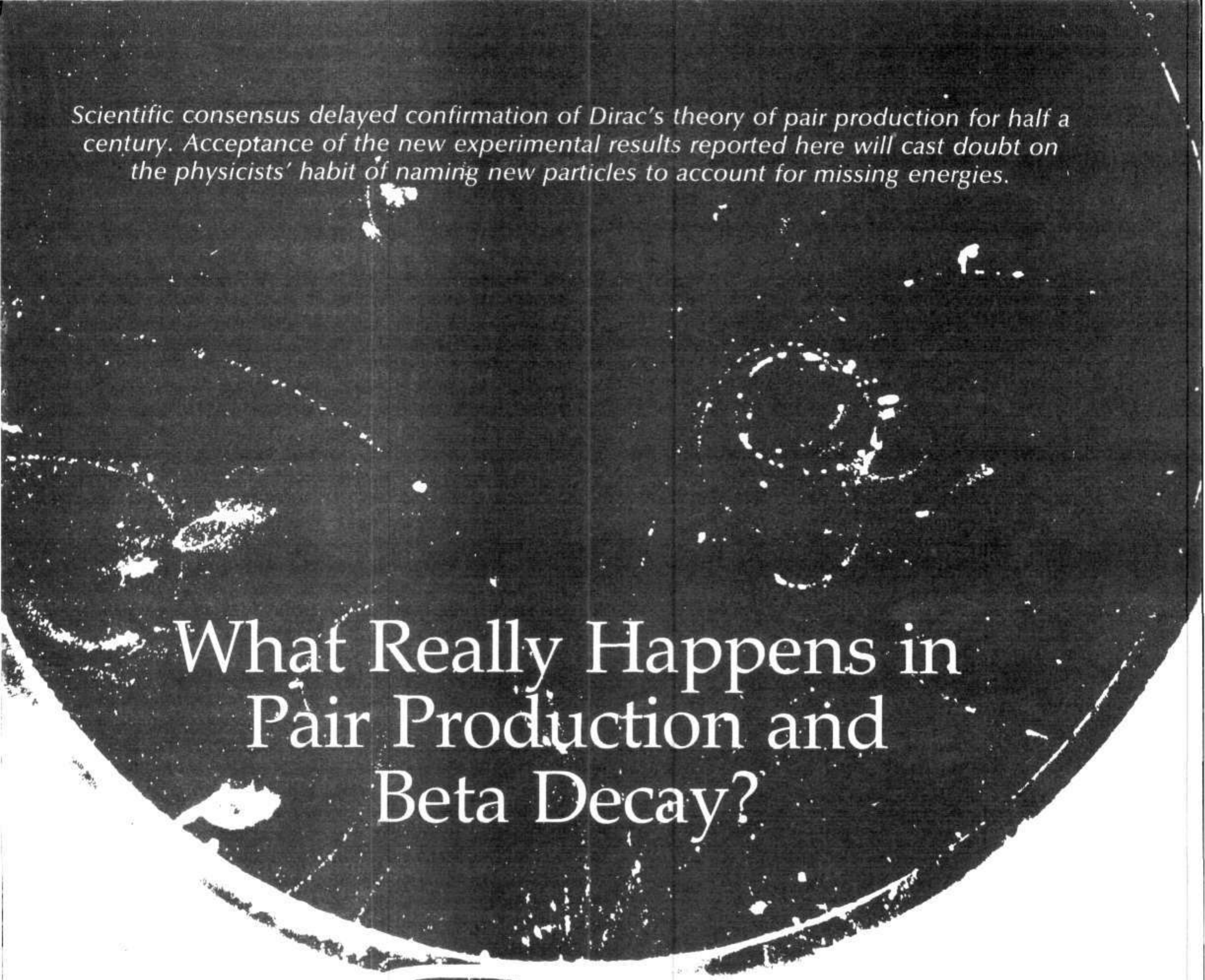

Scientific consensus delayed confirmation of Dirac's theory of pair production for half a century. Acceptance of the new experimental results reported here will cast doubt on the physicists' habit of naming new particles to account for missing energies.

What Really Happens in Pair Production and Beta Decay?

Why Neutrinos Don't Exist

by Erich R. Bagge

Our story does not take place in the time when Kepler and Galileo had to consider the brute force of an orthodoxy as they wrote. Rather it occurs, with some sad parallels, in the present. Indeed, the story is not yet over. We are midcourse in a development in which the yet undetermined fate of a physical theory inspires the most intense interest.

The story begins in 1932. In that year, while investigating cosmic radiation—the high-energy radiation from space that penetrates the Earth's atmosphere—the American physicist C.D. Anderson discovered the existence of positrons. Positrons are positively charged particles that have the same mass and the same amount of electrical charge as electrons. For the experimenter, they are distinguished from electrons only by their positive charge. In nature, they do not occur as long-term, stable structures.

The discovery gained Anderson a Nobel Prize and brought joy to another Nobel Prize winner, the English theoretician P.A.M. Dirac. Dirac had developed a relativistic theory of the electron in 1927, which wonderfully fit the experimental evidence of nuclear physics. It has since become one of the best established theories of modern physics. For many physicists, however, Dirac's theory has an extremely disturbing characteristic: It defines positive and negative *energies* of electrons (independent of their positive and negative *charges*). Surprisingly, states of positive and negative energy play equal roles in this theory, even though energy as such continues to be thought of in terms of positive quan-

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English theoretical physicist Paul Dirac, who developed a relativistic theory of the electron in 1927 that defined positive and negative energies of electrons, independent of their positive and negative charges. Negative energies proved necessary to account for observed physical processes.

tities. In certain situations, with strict solutions of the Dirac equation, it even turns out that this negative energy is inextricably involved in physical processes.

Negative Energy in Nuclear Physics

Negative energies are really nothing unusual in modern nuclear physics. When weighed, an atomic nucleus is always lighter than the sum of the weights of its components.

For example, the nucleus of uranium-238, which contains 92 protons and 146 neutrons, weighs only as much as 236 such nucleons. The forces that hold these particles together have an effect on the nucleus either like negative energy or, according to Einstein's relativity theory, like an equivalent negative mass. This has long been accepted by physicists as self-evident; it is actually nothing but the addition of a negative energy to the positive energy of the nucleons. Of course, these negative energies of the nuclear mass deficiency constitute only about 1 percent of the total energy, and therefore have little significance for weight in macroscopic physics.

We can rejoice in this, because this condition makes it possible for us to live on the Earth: A percentage of this negative energy is normally involved in the creation of nuclei from nucleons in the stars and in our Sun, and only this small fraction of the energy content of the nuclear components is released as heat energy. At the level of the temperatures of stars, this process takes place slowly, giving life

FIGURE 1
THE THEORY OF PAIR FORMATION AS USED BY BETHE-HEITLER

An electron in the negative energy state $E_{\bar{e}} = -|E_{\bar{e}}|$ is raised into a state of positive energy E^- by a high-energy gamma quantum $h\nu$ (h = Planck's Action Quantum; ν the frequency of the quantum). The hole produced in the previously completely occupied Dirac Sea appears in the world of positive energy states (the upper world) as a positively charged positron of energy E^+. The conservation postulate for energy is thus: $h\nu = E^+ + E^-$. The conservation of momentum is expressed by the equations:

$$h\nu/c = p^+ + p^- \; (p^+ = p_{pos};\; p^- = p_{el} \text{ and } p^+ = p_{\bar{e}}),$$

where c is the velocity of light.

The part played by the relatively massive nucleus in pair production can be ignored, since it absorbs almost insignificantly little energy from the gamma quantum and its momentum, p^+, changes only with respect to direction. Total momentum hardly changes at all.

on Earth time to develop from its first beginnings in protein molecules up to *Homo sapiens*.

World and Antiworld in Dirac's Theory

Negative energies actually manifest themselves in Dirac's theory of the electron in a much more dramatic form in another connection.

Dirac's theory had the Special Theory of Relativity as its point of departure and took its fundamental features from it, including the fundamental postulate that positive and negative energies are equally warranted. This heritage, together with the fact that positrons normally do not occur in nature as stable—that is, as permanently existing particles—was the basis for Dirac's formulation of his famous Hole Theory.

Dirac postulated that our physical world has a kind of double structure with positive and negative electron energy states. The positive energy state is the condition in the observable "upper world," while the negative state is in the "netherworld"—or "antiworld," the term used in English-language literature—and is initially unobservable. For electrons, such an assumption is physically intelligible if we assume that all antiworld states are fully occupied, and that is Dirac's assumption. We human beings, who can only observe the phenomena of the "upper world," move around simultaneously within the "upper world" and also within this fully occupied "antiworld" ("Dirac Sea") as though the latter did not exist. Given the full occupation of negative energy states, it can be demonstrated mathematically that the interactions of all electrons exactly compensate for one another.

The Theory of Pair Production

The experimentalist finds cases of a high-energy gamma quantum that appears to "turn into" an electron and a positron, each taking a path at an angle to the original gamma quantum trajectory. Hence the name "pair production." Dirac reasoned that if an electron from the antiworld is hit by a highly energetic photon (gamma quantum) of the upper world, the electron can absorb the photon's energy by interaction in the electron's electromagnetic field. The electron then appears in the upper world. Simultaneously, a hole appears in the antiworld that represents a disturbance of the condition of full occupancy. This deficit in negative charge in the antiworld is observed in the upper world as a positron (Figure 1).

With conceptions developed in this manner, Dirac explained the production of electron-positron pairs by gamma quanta (high-energy light quanta), and simultaneously explained why a positron of the upper world can vanish when an electron from the upper world refills the hole in the antiworld, with both particles then becoming unobservable. Both processes are today easily observable in physical experiments.

Calculations of Sauter, Heitler, and Bethe

Dirac's interpretation of pair production and annihilation automatically gives the quantum theoretician a rule for calculating the frequencies of the corresponding processes. Following preliminary work by the theoretical physicist F. Sauter in 1933, and calculations by Sauter and W. Heitler, these computations were done in an extremely comprehensive and detailed investigation by H. Bethe and W. Heitler. Their results, the Bethe-Heitler theory, have played a major role in modern physics.

This theoretical work decisively advanced the development of our conceptions of the nature of cosmic radiation and elementary particles. Their results are incorporated today in the design of measuring devices in high-energy physics.

The work of Sauter, Heitler, and Bethe was the first successful step in the right direction, which seemed, with a not overly critical examination, to fit well with experience. Therefore, it found immediate recognition and was used as the foundation for new theories, for example, the theory of extensive air showers of cosmic radiation in the atmosphere.

Such cosmic ray showers involve the lightning-like appearance of swarms of electrons and positrons produced by a single, high-energy proton penetrating the Earth's atmosphere in a series of interactions with the atmosphere's nuclei. The study of these atmospheric showers is today one of the experimental pillars of the physics of cosmic radiation. The interpretation of these showers follows fairly well from the theories mentioned. Completely new phenomena of astrophysics have been discovered as a result; for example, the extraordinarily high-energy gamma quanta emanating from the double-star system Cygnus X-3, discovered by Samorski and Stamm in Kiel in 1983.

Energy Spectrum of Electrons in Pair Formation

It is no accident that the Bethe-Heitler theory produced this result. It employed the postulate of conservation of energy very strictly for the process of pair production, setting the energy of the arriving light quantum equal to the

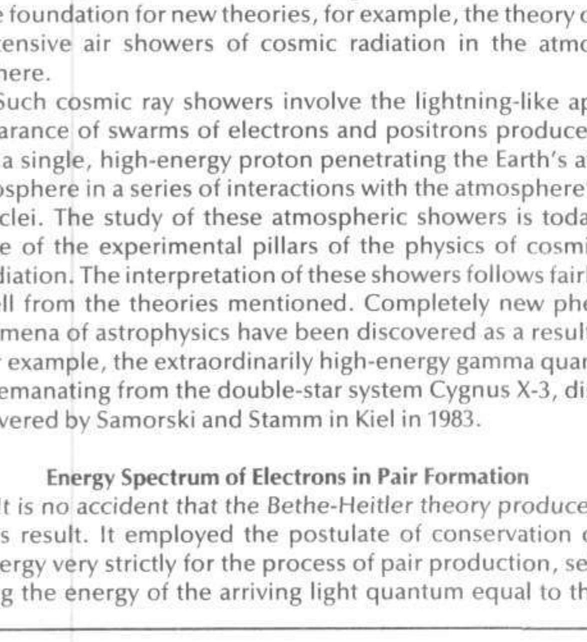

Figure 2
PREDICTED ENERGY SPECTRA ACCORDING TO THE BETHE-HEITLER THEORY
Predicted energy spectra for positrons and electrons of pair production in the Bethe-Heitler theory are shown for gamma quantum energies of 3.02, 4.04, and 5.05 MeV. Both positrons and electrons are supposed to appear with these same distributions of kinetic energies.

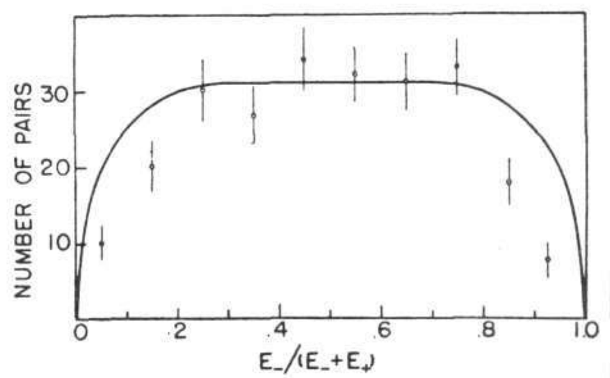

Figure 3

AGREEMENT BETWEEN PREDICTION AND THE 1937 FINDINGS OF DELSASSO, FOWLER, AND LAURITSEN

The points and probable error ranges are the electron energy spectrum found by Delsasso, Fowler, and Lauritsen in 1937, using a lead foil 320 microns thick. The pairs were produced by 17 MeV gamma quanta. The solid line is the corresponding prediction from the Bethe-Heitler theory. Only electrons were measured.

The authors wrote: "The deviation at the low and high end are to be expected because of the great probability that a pair is not measured as such if the energy division is very unequal. This systematic error is not included in the probable errors indicated. The agreement with the theory is entirely satisfactory."

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Nobel Prize winner Hans Bethe, who published a theory of cosmic ray phenomena with W. Heitler in 1934. Partly because their theory proved so useful, it was not subject to doubt until the 1982-1984 work of Egyptian scientist Ahmed Abu El-Ela. Bethe is shown here just after World War II.

sum of the energies of the positron and electron. In this way, there can be no gross falsification of the energy balance, even if the conservation law for momenta in the interaction of the gamma quantum and antiworld electron is disregarded. This assumption, although not strictly correct, has the convenient consequence that the formula for energy distribution between the two charged particles is beautifully symmetrical. Bethe and Heitler state that neither of the two particles can appear with all of the available kinetic energy or with none of it. The most probable outcome is that the two particles will share the available energy equally (Figure 2).

When physicists L.A. Delsasso, W.A. Fowler, and C.C. Lauritsen sought to test the Sauter, Heitler, Bethe theory in 1936 and 1937, naturally these considerations were known to them. They also knew that positrons and electrons were supposed to have identical energy distributions (energy spectra), which meant, of course, that only one of the two particles had to be investigated. Additionally, according to the theory, extremely low-energy particles were not to be expected.

Theoretical derivations from the Bethe-Heitler theory demand a considerable amount of work, which the experimenter—merely because of considerations of time, but also because of the complicated mathematical apparatus—cannot complete in every detail. The experimenter is well advised to leave this work to the theoretician. Likewise, experimenters are extremely reluctant to make any criticism of theoretical work in quantum electrodynamics.

As a result, Delsasso, Fowler, and Lauritsen adjusted their experiment to the theoretical predictions of the Bethe-Heitler theory to allow the most favorable observation of the phenomena being investigated.

They used a Wilson cloud chamber to make the positron and electron trajectories visible. Two Helmholtz coils produced a homogeneous magnetic field in the cloud chamber of 2,580 gauss for determination of the energy of the observed particles. The cloud chamber was covered on one side by a lead foil 320 microns thick, at which gamma radiation of 17 million electron volts (MeV) from an accelerator was aimed. This radiation released electron-positron pairs in the lead collector, as well as Compton electrons when there were direct hits on electrons in the lead atoms. (A Compton electron is simply an upper world electron that scatters when the impact of a high-energy photon endows it with kinetic energy.)

Both processes produce easily interpretable tracks in the cloud chamber. Measurements on positrons were not reported in the work; clearly this was the case because the authors assumed that the energy spectra of the positrons and electrons were necessarily identical.

The authors were fortunate; they obtained an electron energy distribution in agreement with that calculated by Bethe and Heitler. Since they had also found a good agreement between experimental results and the theory of quantum electrodynamics earlier in a similar investigation on Compton electrons, they and the physicists who read their work were convinced that the Bethe-Heitler theory best fit

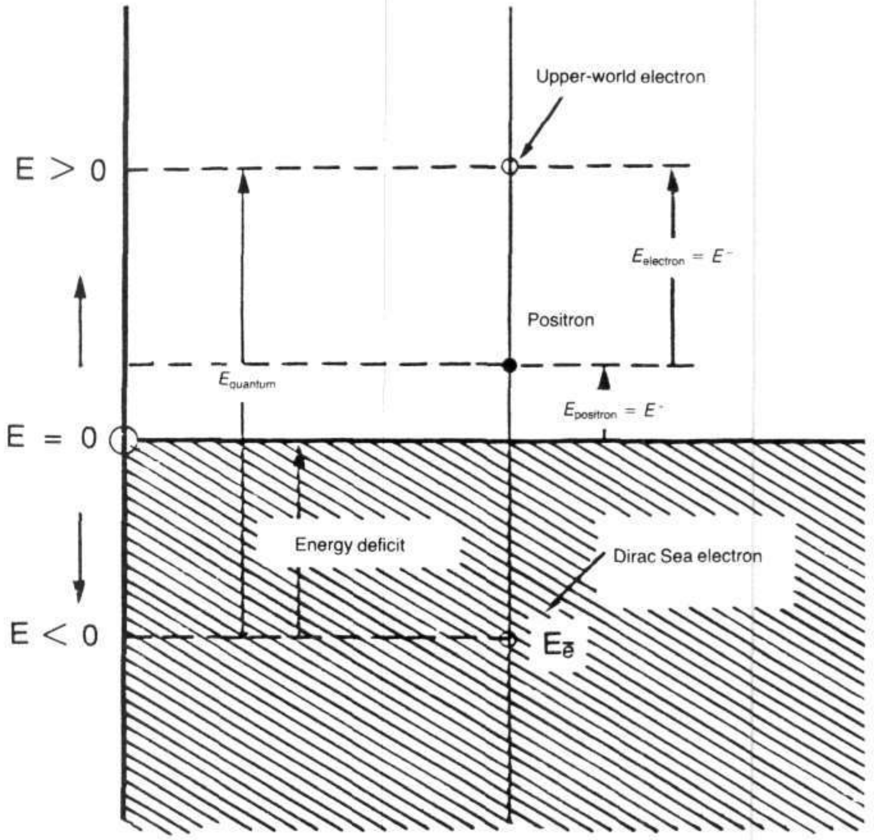


FIGURE 4
STRICT INTERPRETATION OF DIRAC'S VIEW OF PAIR FORMATION

The Dirac Sea electron with energy $E_{\bar{e}} < 0$ is lifted into the upper world by a high-energy gamma quantum of energy $E_{quantum}$ in an energy state of $E^- > 0$. The negative energy value $E_{\bar{e}}$ is thus lost to pair production in the upper world. The energy difference $E_{quantum} - |E_{\bar{e}}|$ is divided according to the conservation of energy and momentum equally between the positron and electron. Thus, the following hold:

energy postulate:

$$E_{quantum} - |E_{\bar{e}}| = E^+ + E^-$$

and vectored momentum postulate:

$$(\boldsymbol{E}_{quantum}/c) + \boldsymbol{p}_{\bar{e}} = \boldsymbol{p}^+ + \boldsymbol{p}^-.$$

The part played by the nucleus can again be ignored for the reasons mentioned in Figure 1. Energy and momentum postulates are strictly obeyed.

physical experimental results (Figure 3).

And there the matter remained, practically up to 1984. It was, however, a great illusion, as we will show.

Energy Spectrum of Electrons in Beta Decay and the Conservation Postulates

The author had his first doubts about these discoveries in the context of beta decay. In beta decay, a neutron decays to produce a proton and an electron, while the energies and momenta of these products are not sufficient to satisfy the conservation laws. He noticed that the deficit of electron energy in this process can be explained very simply using Dirac's conception of the antiworld and upper world. It must be assumed that the beta-decay electrons do not spontaneously come into existence in the nucleus but are carried by the nucleus from the antiworld to the upper world. They are already present and were in an unobservable state of negative energy before their appearance in the upper world. These negative energies represent exactly the energy deficit of the beta electrons. If they are taken into consideration, we not only gain the proper energy spectrum of the beta continuum but the theory gives the right decay time for the beta-unstable nucleus from its own internal logic, without recourse to newly introduced ad hoc "natural constants."

This method works only if the conservation-of-energy postulate used in the Bethe-Heitler theory is refined by allowing for the negative exit energy of the electrons. We must consider that the electron of the antiworld has, along with its negative energy, a vectored momentum. It was this that Bethe and Heitler were able to disregard in 1933 in their elegant treatment of pair formation. It greatly simplified their calculations without introducing any gross distortion into the results.

For beta decay, if the experiment is to be properly described theoretically, not only conservation of energy must be considered—with inclusion of the negative exit energy of the electron—but also conservation of momentum. This is analyzed in work by the author (see bibliography).

The conservation postulate for energy and momentum is very closely and fundamentally related to the Kirchoff-Noether postulate of classical physics. Therefore, neither of these conservation theorems can be ignored with impunity in theoretical work. This is very clearly the case with nuclear beta decay.

The energy deficit in beta decay is thus more effectively accounted for in this manner than by introducing the unphysical notion of a massless, chargeless neutrino. Wolfgang Pauli made a fitting confession on his 60th birthday concerning his neutrino concept. He said he had done what

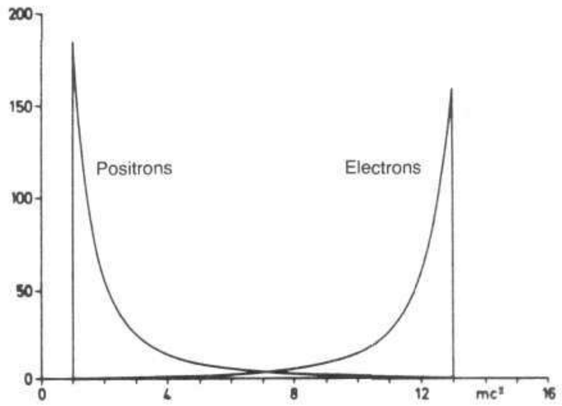


Figure 5
PREDICTED ENERGY SPECTRA OF POSITRONS AND ELECTRONS UNDER THE STRICT INTERPRETATION OF DIRAC
The theoretical energy spectra of positrons and electrons according to the strict Dirac conception of pair formation. The positrons have primarily low, the electrons primarily high kinetic energy. The graph is valid for gamma quanta of 7.07 MeV = 14 mc^2 (m = mass of electron; c = speed of light).

a physicist should never do—explain the unknown by means of the unobservable! Pauli's confession and warning are fully relevant today.

Momentum Exchange Between Gamma Quanta and Antiworld Electrons

It was therefore obvious that pair formation should be interpreted in strict accord with Dirac's conception, using both conservation postulates (Figure 4).

The rather extensive calculations necessary to expand the original Sauter-Heitler-Bethe investigations were undertaken by the author in 1976-1977, and a very surprising result emerged. The energy spectra for positrons and electrons were not in the least congruent, but were actually fundamentally different (Figure 5). While positrons for the most part received little or no kinetic energy during pair formation, the exact opposite was true for the electrons. They mostly took on high energies, up to the highest theoretical values.

This shockingly contradicted not only the 1937 results of Delsasso, Fowler, and Lauritsen, but also other, later measurements by various authors. A critical study of these later efforts showed that the apparent confirmation of the Bethe-Heitler spectra is not conclusive in practically every case. But the Delsasso-Fowler-Lauritsen work of 1937 with its apparently conclusive results remained.

Since, on the other hand, the observations of beta decay

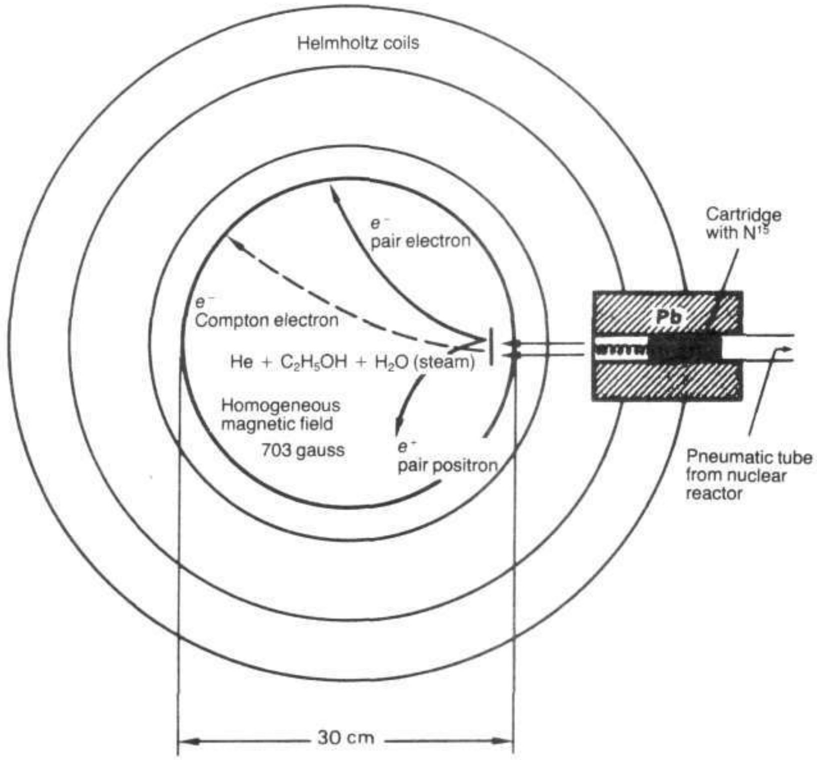


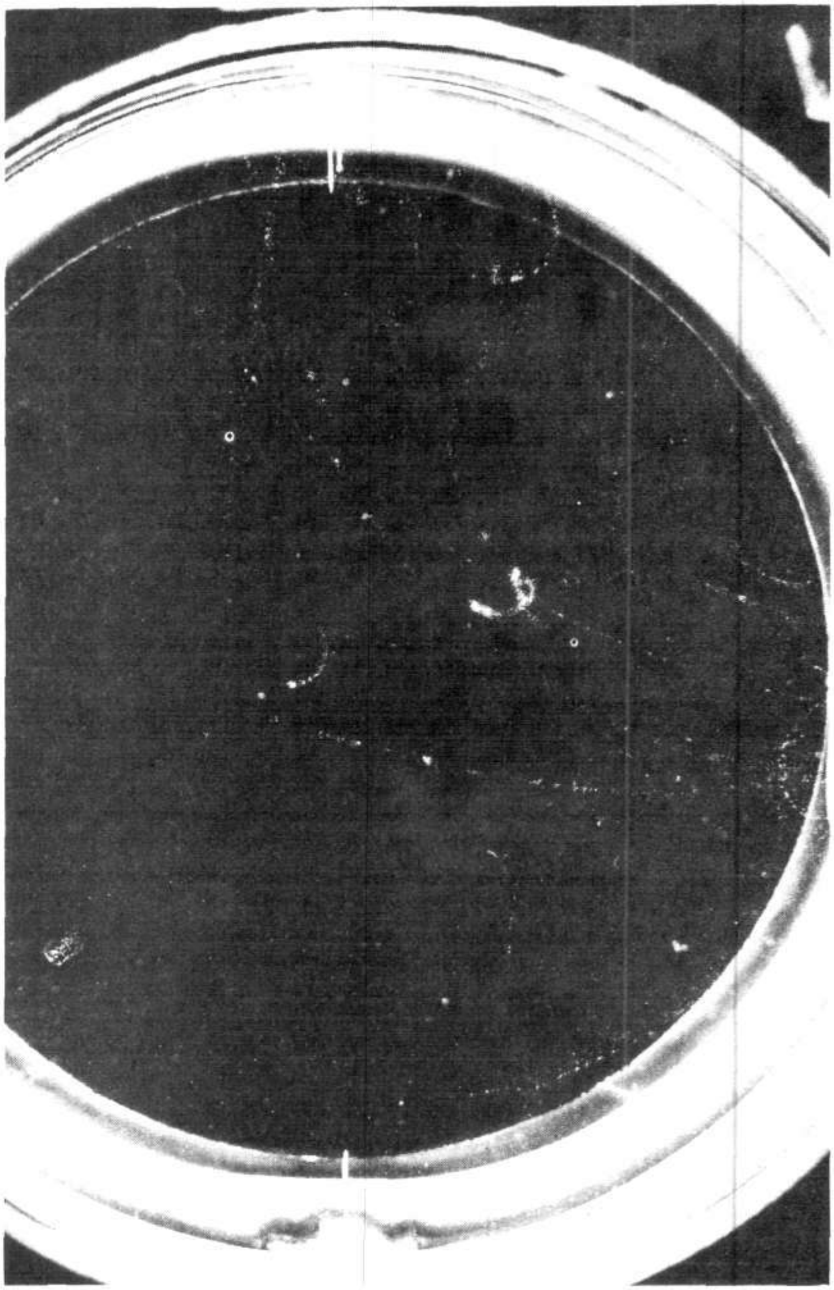
FIGURE 6
SCHEMATIC OF WILSON CLOUD CHAMBER AT GEESTHACHT
The Wilson cloud chamber, shown here, is filled with helium, and is equipped with two Helmholtz coils for production of a homogeneous magnetic field of 703 gauss. At the right, the end of the pneumatic tube shielded with lead in which the cartridge filled with N^{15}/urea is enclosed. The cartridge is irradiated in the Geesthacht reactor and shot by pneumatic tube 6 m to the cloud chamber each time the chamber is expanded.

of nuclei were equally convincing, there was only one way to clarify the situation: repeat the experiment in the cloud chamber under improved conditions. This was done during 1982-1984 at Kiel and at the research reactor at Geesthacht-bei-Hamburg.

The Kiel-Geesthacht Cloud Chamber Experiments

Egyptian physicist Ahmed Abu El-Ela, studying in Kiel, was given the problem for his dissertation project: to measure at Geesthacht the energies of electrons and positrons arising from pair production. With a Wilson cloud chamber in a homogeneous magnetic field of 703 gauss, the energy spectra of positrons and electrons were to be determined separately. The gamma quanta were emitted from excited O^{16} nuclei and sent to a gold-foil target in the cloud chamber.

As El-Ela had already learned from his university work in Cairo, the first step was a thorough study of all former work on the subject. He gave a lecture on his investigations, concluding that it was simply pointless to carry forward this line of research. He had rediscovered the cloud chamber measurements of Delsasso, Fowler, and Lauritsen, which supposedly proved that the Bethe-Heitler predictions had been confirmed. He therefore proposed to work on a com-



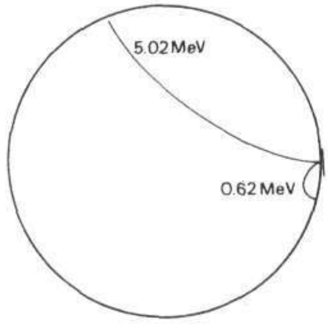
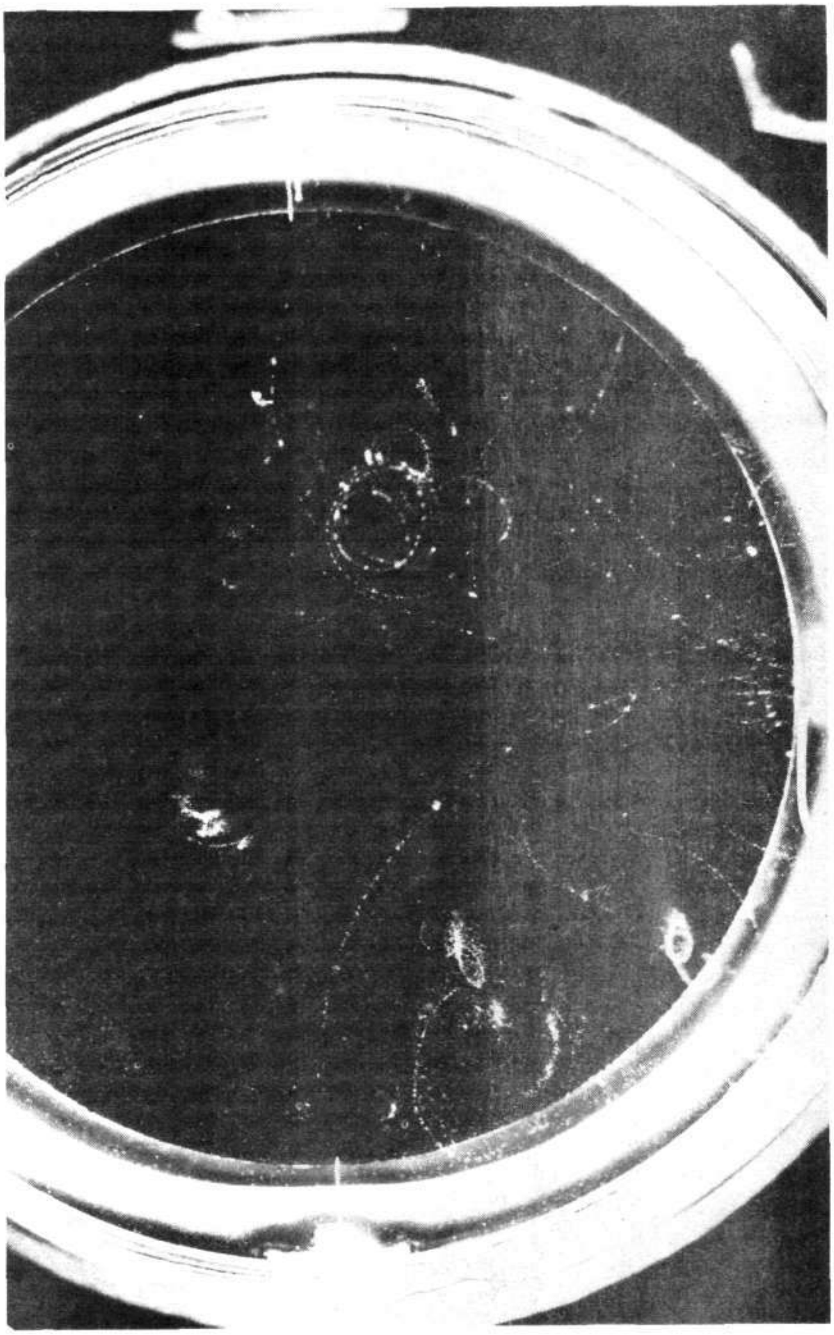


FIGURE 7
TRAJECTORIES OF A PAIR IN THE WILSON CLOUD CHAMBER

The electron exits upward, with energy of 5.02 MeV, the positron downward with 0.62 MeV. Under the Bethe-Heitler theory, the two energies were supposed to be nearly equal in most cases.



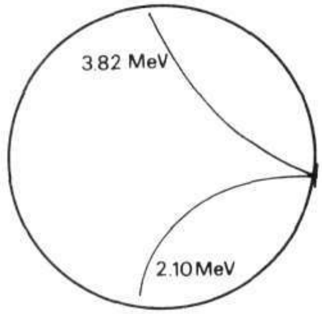


FIGURE 8
A PAIR WITH AN UNUSUALLY ENERGETIC POSITRON
In this relatively rare case, the positron, below, with 2.10 MeV, received almost half the energy of the electron, above, with 3.82 MeV. The sum of the energies of the two, 5.92 MeV, when compared to the emission energy of 6.14 MeV, gives an energy deficit of only 0.22 MeV. This particle pair obviously must have been produced immediately before the end of the cloud chamber expansion, since the tracks are so sharply defined.

pletely different problem. Fortunately, however, he was persuaded to take on the project.

To improve the conditions for measurement, the cloud chamber was to be filled with helium rather than air, making possible tracks of greater length for less energetic particles, and therefore easier and more precise measurements. Instead of a lead foil 320 microns thick, a gold foil of only 25-micron thickness was used for pair production, so that even low-energy particles could penetrate (Figure 6).

Despite the advantages of this design, El-Ela was convinced that new measurements could only have the result of reconfirming the Bethe-Heitler theory (Figures 7 and 8). El-Ela desired assurance that he would be awarded a degree if the work were carried out carefully, no matter what the results.

After some months passed, El-Ela submitted his first observations. He was somewhat disturbed by the fact that, remarkably, he had found too many low-energy positrons and too many high-energy electrons. He felt like an insignificant dwarf caught between two giants—one or the other would necessarily destroy him. On one side, were the authorities in the literature on pair production; on the other side, the author, his dissertation adviser. The only thing that kept him from complete despair was the consolation

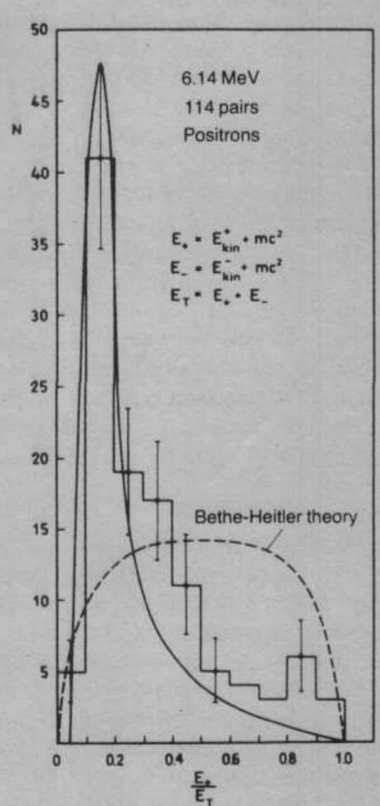
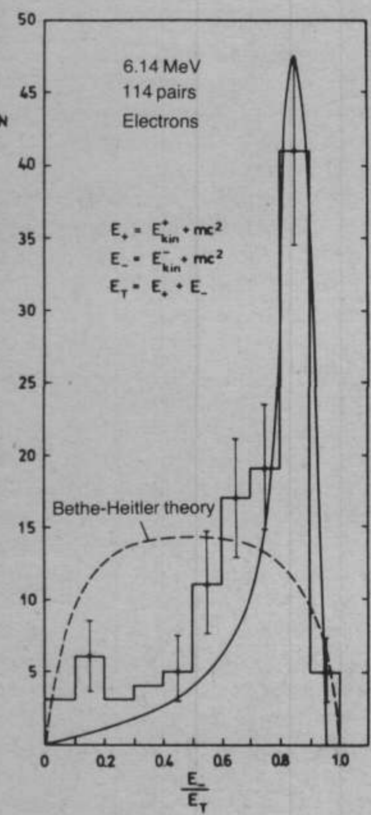


FIGURE 9
ENERGY SPECTRA OF PAIRS OBSERVED AT KIEL-GEESTHACHT

The two diagrams show the Kiel-Geesthacht results of Ahmed Abu El-Ela and Saad Hassan for 114 positron-electron pairs produced by 6.14 MeV gamma quanta emitted by excited oxygen O^{16}. These nuclei were produced by radiation of N^{15} with thermal reactor neutrons. Initially, an N^{16} nucleus is formed, which undergoes beta decay with a half-life of 7 seconds to an excited O^{16} nucleus.

The energy spectrum for positrons is on the left, for electrons on the right. The histograms show the observed values. The solid lines show the values expected from the strict Dirac conception; the dotted lines show the distribution predicted by the Bethe-Heitler model.



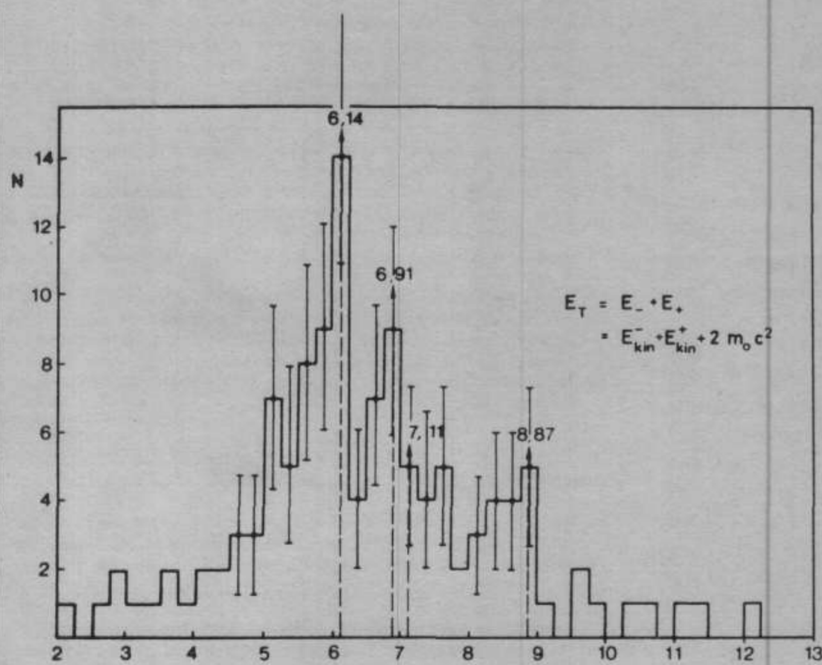


FIGURE 10
ENERGY SPECTRUM FOR PAIR-TOTALS OBSERVED AT KIEL-GEESTHACHT

The observed energy-total spectrum of 122 positron-electron pairs is shown; that is, the frequency of energy-totals for the two particles produced by gamma quanta emitted by excited O^{16} nuclei. Of particular interest here is the energy total at 6.14 MeV and the lines of lower intensity at 6.91, 7.11, and 8.87 MeV. The latter three show in principle the same behavior as the 6.14 line, but because of the lower frequency of the pairs measured so far, they are less interesting for the purposes of this article.

Note the relatively gradual increase of frequencies to the maximum of the 6.14 MeV line and the sharp fall beyond this maximum. In the low-energy part of this spectrum to the left of the maximum, the energy deficits are apparent in pair formations originating from electrons of negative energies.

that nothing but establishing the truth could possibly help him move forward. And so he continued his investigations until he was able to submit two calibration curves, one for the positron spectrum and one for the electron spectrum. The curves quite clearly showed that it was not the unified Bethe-Heitler curve, but the two different distributions predicted by using Dirac's unmodified conception of pair production that actually fit the facts (Figures 9 and 10).

The measurements also showed that the electrons from the antiworld would not allow their past as particles of negative energy to be ignored. These negative energies were lacking for the positron-electron pairs in the upper world. In fact the energy total for pair members showed a deficit of the proper order of magnitude.

Figure 11 shows the frequency distribution of energy totals for positron-electron pairs produced by 6.14 MeV quanta. The histogram shows a sharp decrease in frequency above the energy $h\nu = 6.14$ MeV, but only a gradual decrease toward lower energies. This would indicate that there are relatively frequent energy totals for which the negative energy of the exit electron reduces the energy total of the pair in the upper world.

Thus Dirac's old theory of pair production, after being declared dead for a half century, underwent resurrection. The electrons of the antiworld with their negative energy and momenta gained a higher degree of reality than almost any contemporary theoretician wished to grant. There is, of course, still a slight chance that some theoretical physicist will now assert that slow positrons can be understood in terms of the old Bethe-Heitler theory, but that is very remote. The energy spectra predicted by the Bethe-Heitler theory are simply too different from those of the Dirac theory, and the measured spectra fit the latter too well.

The Thick Lead Foil of 1937 and the False Energy Spectrum

The predominance of slow positrons in pair formation was implicit in Dirac's theory long before it was confirmed by experiment, but scarcely any notice had been taken of it.

That is not really surprising. Most physicists belong to internationally organized schools of thought. They harmonize their views in highly specialized workshops and then hang on to the agreements reached for good reasons. This explains why it is so difficult to establish a reinterpretation—or even argue for one—that runs counter to deeply ingrained academic opinions already organized into conceptual schemes. For the most part, such interpretations are passed over with polite silence and then forgotten. This is the modern form of burning Giordano Bruno at the stake for advocating that the stars are nothing but distant suns (the year was 1600); it is more humane than that hideous practice, but just as effective. New theories that fail to conform to ruling academic opinion simply disappear into the abyss.

What was really wrong with the Delsasso-Fowler-Lauritsen experiment, which so misled the physicists? The answer is extremely simple in view of the experimental facts now established. The lead foil of 320 microns was far too thick. To pass right through the foil, a positron needs at least approximately 0.8 MeV; even from an arbitrary point of origin within the foil, an average value of 0.4 MeV is still needed. But such positron energies are only rarely present in pair formation.

For that reason the experimenters were not able to tell whether pair formation had taken place or not. For many pairs they found a high-energy electron only, and took this for a Compton electron, which could be ignored.

There were, accordingly, far too few high-energy electrons from pair formation in their evaluation and far too many Compton electrons. As accident would have it, the the resulting energy spectrum for pair electrons fit the Bethe-Heitler theory fairly well. No one thought it necessary to carefully examine this apparently very satisfying result that confirmed the theory. And so it stood until the Kiel-Geesthacht experiments of 1983-1984 brought the exact opposite to light.

Dr. Erich Bagge, a student of Werner Heisenberg and Arnold Sommerfeld, is a pioneer of the nuclear energy industry in West Germany and the designer of the world's first nuclear-powered commercial vessel, the Otto Hahn. *He is director of the Institute for Pure and Applied Nuclear Physics at the University of Kiel, director of the Geesthacht Reactor Station, director of the Society for the Application of Nuclear Energy to Shipping, and a member of the West German Atomic Energy Commission.*

John Chambless translated this article from German.

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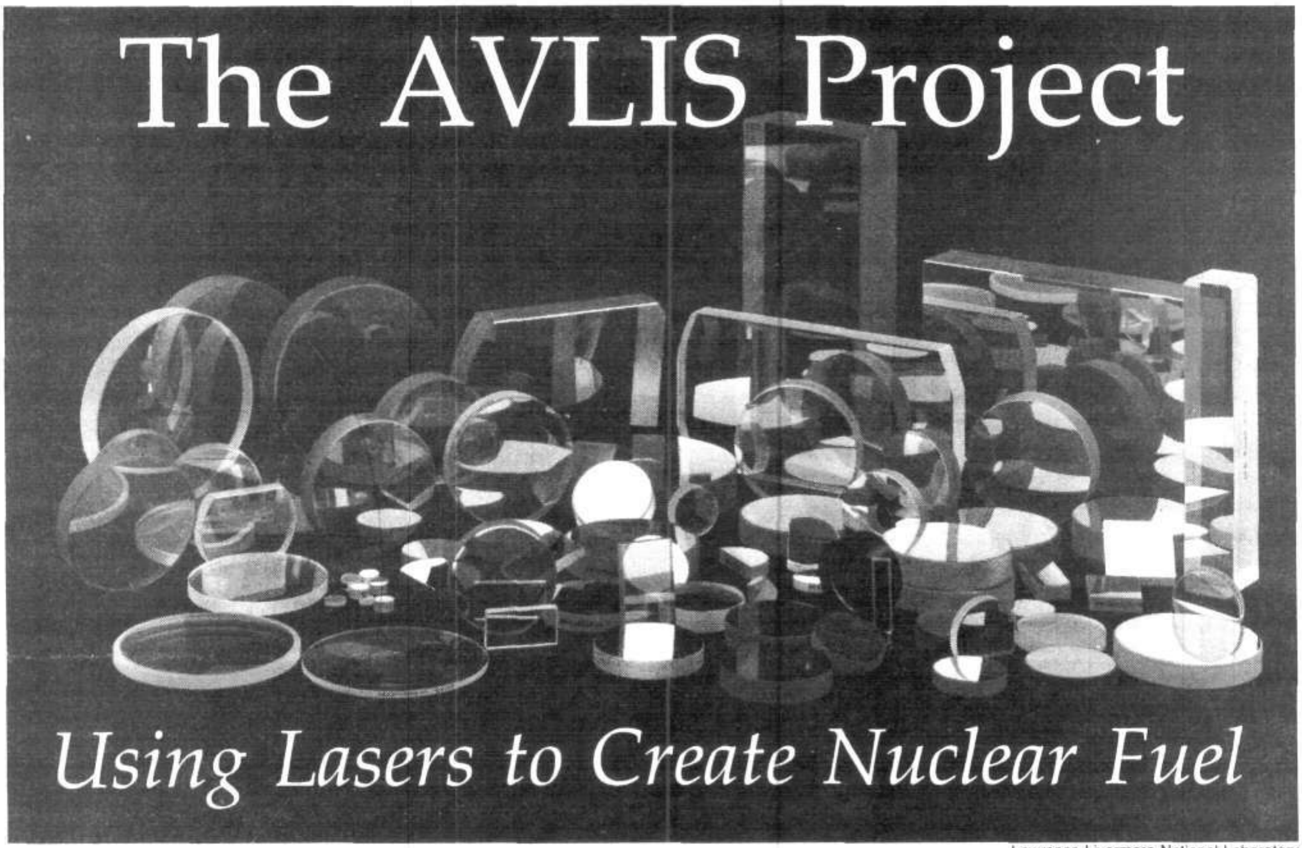
The AVLIS Project



Using Lasers to Create Nuclear Fuel

Lawrence Livermore National Laboratory

One of the most exciting commercial uses of lasers—isotope separation—will soon demonstrate how to cut the cost of enriching uranium. The new Atomic Vapor Laser Isotope Separation program at Lawrence Livermore National Laboratory also opens the way to "tailoring" new isotope products for a broad range of industrial applications.

EDITOR'S NOTE: Cheaper fission fuel using laser isotope separation may be the shot in the arm that the U.S. nuclear industry needs to reverse its precipitous decline. It will help regain U.S. utility customers who have turned elsewhere for enriched uranium because of the high cost of current U.S. enrichment processes. And it also can supply the enormous demand for fission fuel that will come if the nation follows through on the "Atoms for Peace" program of the 1960s, using nuclear energy to industrialize the undeveloped sector. Most important, pushing forward with the most advanced technologies like laser isotope separation reestablishes the key principle of the American System economics that built this country. With the return of this economic outlook—cultural optimism—we have a chance to complete the long-delayed plans for America's second generation of nuclear technology: the fast breeder, fuel reprocessing, the high temperature reactor, the fission/fusion hybrid, and beyond. Without such a revival, there is no way to supply the energy required to reindustialize the advanced sector and develop the rest of the world.

The applications of this new technology are mind-boggling in scope. Laser isotope separation is to industrial materials what genetic engineering is to agriculture—an incredible technological tool to increase productivity and efficiency, moving man into the 21st century. In the nuclear industry alone, isotope separation could expand the variety of materials that can withstand a nuclear environment and could cleanse nuclear waste, turning it into valuable heavy metal and gas isotopes, leaving only a minute quantity of highly radioactive material. Both applications could revolutionize the nuclear industry and the coming fusion power industry.

The United States took a step in this direction in June 1985, when the Department of Energy gave the go-ahead to

Above, some of the more than 4,500 optics used to transport light through the laser isotope separation system. Developed in a cooperative effort with 30 major U.S. optics companies, the high-quality optics are about 100 times more efficient in reflecting light than a bathroom mirror.

the Atomic Vapor Laser Isotope Separation (AVLIS) program at Lawrence Livermore National Laboratory, after a DOE economic assessment showed AVLIS to be significantly cheaper than current processes to enrich uranium. In the previous 18 months, the laboratory had accelerated construction of the AVLIS facility, proving that a production-scale commercial plant could be built now, making use of existing U.S. technology and industrial suppliers.

Working around-the-clock for the past several months, the 400 employees in the laser isotope separation program at Lawrence Livermore, along with an additional 400 contract workers and technicians, completed a new $60 million laser system as well as a $24.5 million new separator demonstration facility in record time. The AVLIS system was tested successfully in April and May 1985 using the smaller, existing Mars separator, and the lab expects AVLIS to move to full commercial demonstration conditions for enriching uranium with the new separator facility by 1987.

This article was written by researchers in the AVLIS program at Lawrence Livermore National Laboratory.

* * *

In the short time since the flash of the first ruby laser in 1960, laser technology has undergone explosive growth. Hundreds of different materials—gases, liquids, solids—have been used as lasers. Lasers or laser systems can be as small as a grain of salt and as large as a football field. They emit light from X-rays to microwaves, including all of the visible colors. Some lasers operate continuously, and others emit pulses that can be shorter than a quadrillionth of a second.

Laser technology has expanded rapidly, with a multitude of applications in diverse fields, including energy, communications and radar, manufacturing and materials processing, weapons, medicine, precision instruments, data processing, photochemistry, holography, art, and entertainment.

This article discusses Atomic Vapor Laser Isotope Separation, AVLIS, a system developed at the Lawrence Livermore National Laboratory over the past 12 years to refine materials that consist of mixed isotopes.

The AVLIS program pioneers the first large-scale industrial application of lasers to material refining, one that will soon provide a low-cost means of producing enriched ura-

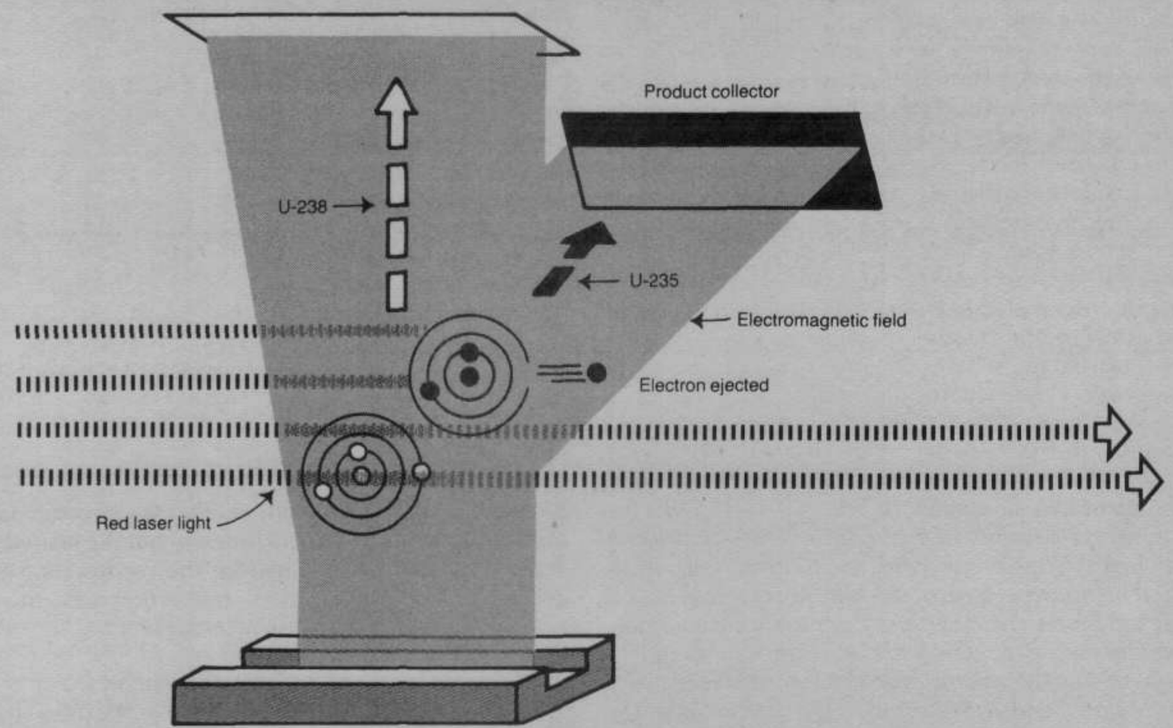


Figure 1
SCHEMATIC OF THE AVLIS ISOTOPE SEPARATION TECHNIQUE
Red laser light is tuned to the electron energy levels of uranium-235, but not uranium-238. The uranium-235 atom absorbs the precisely color-tuned laser energy and ejects an electron (photoionization). The uranium-235 atom left with a net positive charge is diverted by an electromagnetic field, while neutral uranium-238 moves on unaffected.

nium fuel for light-water reactors. Although efforts have concentrated on this primary application to date, the advanced laser technology already developed in the program can be extended to a broad range of applications.

The Emergence of Laser Technology

The operation of a maser (microwave laser) in the 1950s and of the laser in 1960 triggered a stream of inventions and new science, and a number of Nobel Prizes. The rapid growth of this technology has continued for two and a half decades. Its products now generate billions of dollars in sales in the United States with applications in many fields.

After the first red flash from a ruby crystal in 1960, the race was on with attempts to make every form of material lase: crystals, glasses, and semiconductors; atomic, ionic, and molecular gases; and liquids containing dyes of every color. The materials were made to pulse, to emit a continuous stream of pulses, or to operate continuously.

In the first decade after invention of the laser, applications concepts abounded. Laser communications systems, radars, designators, welders, cutters, precision instruments, and surveying tools were moderately successful. Inhibiting factors were the limited commercial availability of durable lasers engineered for specific tasks and the lack of technological infrastructure needed to support these applications. Optical components, electrical power supplies, and control systems were not yet adequate to meet the new needs. Mechanical agility, precision, and stability requirements were beyond the state of the art. In spite of these difficulties, lasers tracked satellites, precisely measured the distance to the Moon, welded automobile bodies, balanced jet engine rotors, and performed surgery.

The real applications explosion began in the 1970s when the laser system components began to appear as commercial catalog items. Laser devices were relegated to component status in complex systems. Laser radar tracked and imaged satellites at thousand-kilometer ranges. Development was started to use laser fusion to generate electricity from seawater. Home video and audio recorders used lasers. Supermarkets automated their check-out and inventory based on technology derived from lasers. Computer-controlled manufacturing machines used laser diagnostics. Lasers became a new growth industry.

It was in this environment that atomic vapor laser isotope separation was first demonstrated and its development begun. The AVLIS process uses lasers to separate uranium-235, for light-water reactor fuel, from inert uranium-238, the predominant isotope in naturally occurring uranium. After extensive systems analysis and laboratory trials, copper-vapor lasers and dye lasers were chosen to drive the process. Again, advances in optics, controls, power supplies, electron beams, and, in this case, liquid metal handling, were needed to make the process economical. Supported by a strengthened commercial base, these technologies advanced rapidly. By the early 1980s, this new application of lasers had been demonstrated on a large scale.

To give an idea of the scale of this application, an AVLIS enrichment plant contains about 1,000 lasers and costs about $1 billion. Several plants are needed to replace existing U.S. enrichment capacity and to meet the new U.S. reactor fuel demand. The Soviet Union, France, Japan, and Israel are also investigating the AVLIS process, but the United States is the only country prepared for the construction of production plants. This process should dominate the world enrichment market because of its lower cost.

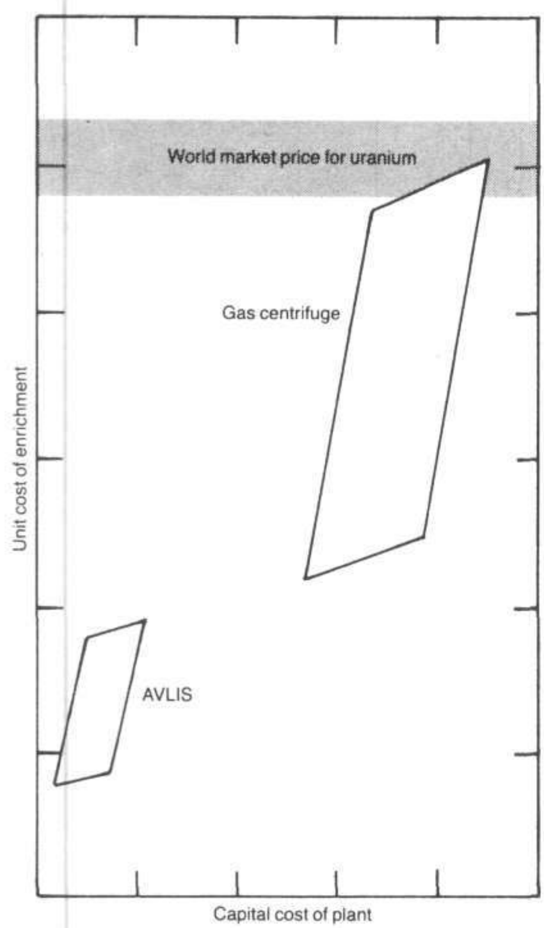


Figure 2
COMPARISON OF ENRICHMENT COSTS
Both the unit uranium enrichment cost and plant capitalization cost are far lower for AVLIS than for the gas centrifuge.

Isotope Separation

Atomic Vapor Laser Isotope Separation is inherently more efficient than conventional separation processes. AVLIS is based on the fact that different isotopes of the same element, while chemically identical, have different electronic energies. As a result, different colors of light are absorbed by each isotope, such that each has its own distinct color signature. When illuminated by a laser beam containing the color signature, an atom of the selected isotope emits an electron and becomes a positively charged ion. The ion can then be separated from the neutral atoms of the other isotopes by an electromagnetic field.

Conventional isotope separation techniques—gaseous diffusion and gas centrifuge—depend on differences in mass of the isotopic species. The most commonly used technique, gaseous diffusion, operates on the principle that lighter molecules move faster than heavier ones. The lighter uranium-235 can be separated from uranium-238 by using a cascade of porous barriers through which the lighter uranium-235 is statistically more likely to pass. The separation per barrier pass is small, which results in the need for multiple stages in very large plants (hundreds of acres) and large requirements for power consumption (billions of watts).

The gas centrifuge spins a gaseous uranium compound in a rotating cylinder, throwing the heavier isotope to the cylinder wall where it is scooped away from the lighter isotope. This process requires significantly less power than does gaseous diffusion but equally as large a plant.

The mass differences on which gaseous diffusion and gas centrifuge depend are about 0.01 for uranium. In contrast, fundamental selectivity of the AVLIS process by means of the color signature process is extremely high—greater than 10,000. This means that for each 10,000 ions of the desired isotope, only 1 ion of the undesired species is generated. So AVLIS has a fundamental selectivity advantage greater than 1,000,000. As a result, AVLIS can achieve a high degree of isotopic enrichment on a single pass and requires relatively little equipment to achieve the enrichment. The bottom-line result is low capital and operating cost.

Atomic Vapor Laser Isotope Separation

The AVLIS process developed at Lawrence Livermore includes two major component systems: a laser system and a separator system. In the separator, unenriched metallic uranium is vaporized by means of an electron beam that creates an atomic U-235/U-238 vapor stream moving rapidly away from the uranium melt. At the same time, dye lasers produce beams of red-orange light precisely tuned to the colors that will selectively photoionize U-235 isotopes. Powerful copper-vapor lasers emit beams of green-yellow light that energize dye lasers. This configuration produces powerful beams of tuned red-orange light to illuminate the uranium atomic vapor inside the separator.

U-235 isotopes absorb the tuned red-orange light, but U-238 isotopes do not. The excited U-235 isotopes eject electrons (photoionized) and retain a net positive charge. The U-235 ions then may be moved preferentially by an electromagnetic field to condense on the product collector. The U-238 isotopes, remaining uncharged, pass through the collector section to condense on the tails collector. Thereafter, the separated uranium condensates are cast and stored in metallic form for later use.

AVLIS is not a single-market technology limited to separation of U-235 from U-238. The periodic table (Figure 4) shows that nearly every element can be separated in this way. Separation of uranium isotopes, which now bears great economic benefits, is an obvious application for AVLIS. However, as the technology improves, as costs decrease, and as demands for the new isotope products increase, new markets will appear. For example, markets may develop for modification of the isotopic blend of mercury (to improve fluorescent lamp efficiency); for separation of gadolinium (to use in power reactors); for isolation of radioactive xenon (to use as a respiratory diagnostic); and for separation of plutonium isotopes (to solve problems in handling radioactive materials).

The AVLIS Production Plant

The AVLIS plant design is based on laser/separator modules assembled in a system to provide the desired enriched uranium production rate. A plant capable of providing a product in excess of a million kilograms of enriched uranium per year is planned.

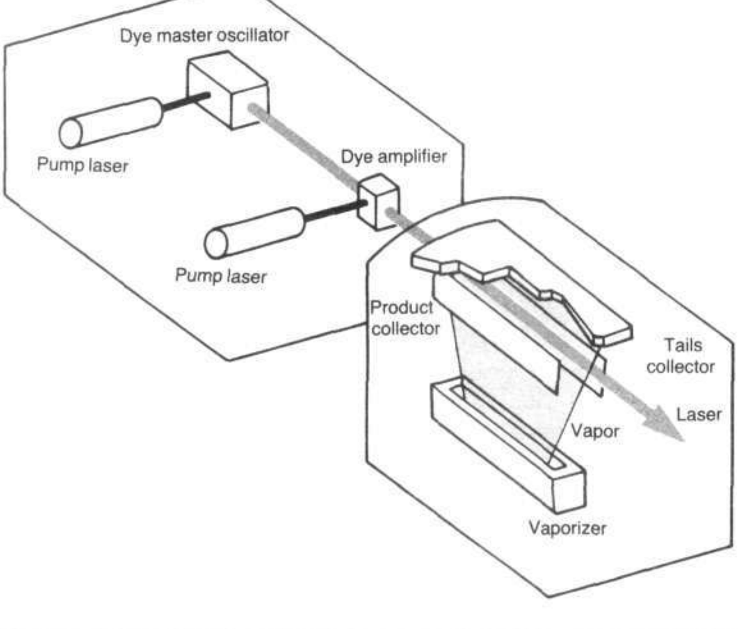


Figure 3
SCHEMATIC OF AVLIS PROCESS
Metallic uranium is melted and vaporized. The vapor is illuminated by visible laser light, which photoionizes the selected isotope. The ions are then electromagnetically extracted.

The plant is modular in both the laser and separator systems. The modularity is suited to optimization of the plant capacity to the market demand: the minimum number of modules needed can be built, and the plant can be expanded later by adding modules. The module size can also be chosen to optimize the deployment and expansion scenario. We have chosen a module of moderate size in order to hasten the development program. Larger modules are somewhat more economical, but take longer to develop.

There is a strong incentive to deploy AVLIS as soon as possible. The dollar benefit gained by replacing gaseous diffusion sooner by a few years will pay for the AVLIS plants. A proposed strategy, then, is to displace gaseous diffusion as soon as possible, exploiting the modular design of AVLIS by starting with a moderate-sized plant and later expanding as needed by adding further AVLIS modules and including technology improvements at that time. The cost of the initial increment could be as low as several hundred million dollars and still be economically competitive.

After initiation of the AVLIS program in 1973, laser and separator systems were developed from early experimental hardware to near-full-scale systems. A kilometer-long underground laser-beam pipeline connects the various laser and separator facilities.

The dye lasers are small units and have been developed to full scale in offline laboratories. They were first tested in the Functionally Integrated Laser Facility and are being installed now in the full-scale Laser Demonstration Facility.

The copper-vapor lasers that pump the dye lasers were also developed offline. They were then tested in the Functionally Integrated Laser Facility, are being lifetested for thousands of hours of operation in the High Power Lifetest Facility, and are being installed in the Laser Demonstration Facility.

Separator components have been tested in offline systems at both Livermore, Calif., and Oak Ridge, Tenn. The first large-scale tests are being completed in the half-scale separator at Livermore. This equipment is now being deployed at full scale in the Separator Demonstration Facility.

While the laser and separator components and systems are being developed independently, integrated enrichment demonstrations are being performed as each new system capability becomes available.

Process Lasers

Lasers for process applications are usually configured in master-oscillator/power-amplifier chains. The master oscillator generates the precise color and pulse shape needed for the application; the amplifiers increase the beam power to that required for the process. Both the oscillators and amplifiers receive their energy from an excitation source or "pump." In the case of our copper vapor lasers, the excitation source is a pulsed electrical power supply. The dye lasers are pumped by the copper-vapor lasers. Both are configured in oscillator-amplifier chains.

The dye lasers are simply a flow channel through which dye dissolved in alcohol is flowed. The channel is transparent, allowing the green-yellow light from the copper vapor laser to penetrate into the flowing dye and be absorbed. The red-orange process colors are then beamed through the dye, removing the energy deposited by the pump laser. In this way, energy from the powerful copper-vapor laser light is pumped into the precisely color-tuned, high-quality red-orange process laser beam.

In general, the dye can absorb and reemit light over a broad range of colors, say, all the shades of red and orange from a single dye. Thus the dye can be tuned to any color over its color band or bandwidth. The precise color selection is made in the oscillator by means of optical elements such as prisms, gratings, and etalons. These elements are

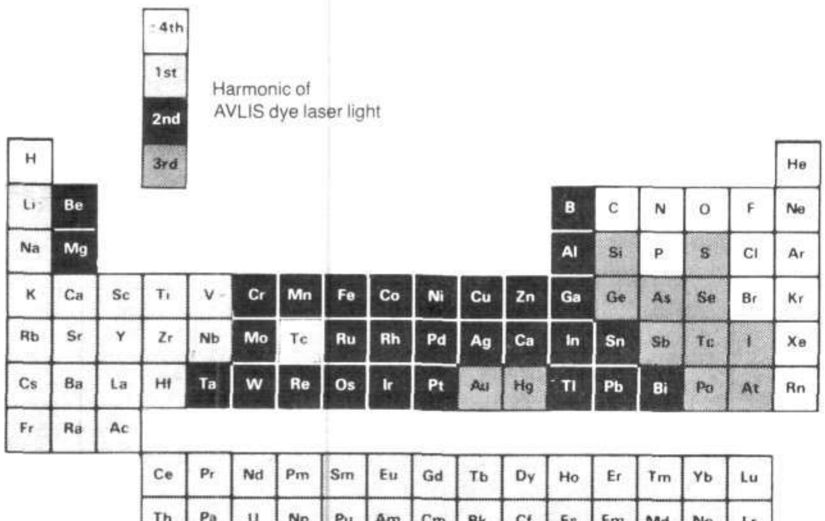


Figure 4
ELEMENTS SEPARABLE USING AVLIS TECHNOLOGY
Most elements and elemental isotopes can be separated using AVLIS. The lightly shaded elements are accessible using the current system. By converting the dye laser beam to its harmonics (for example, 2nd, 3rd, and 4th), other elements are accessible as indicated.

actively controlled to allow real-time adjustment to the desired color.

Once generated, the process beam passes through successive dye amplifier stages, to increase its power. The amplifiers have no color selection devices in them and will amplify any color within the dye bandwidth. As a result, any process color can be chosen by simply retuning the oscillator. The three colors needed to photoionize uranium are all red-orange.

Copper-Vapor Lasers

Copper-vapor lasers provide the power to excite the process dye lasers. The copper lasers pump the dye oscillators, preamplifiers, and high-power amplifiers to achieve a high conversion efficiency from copper-vapor laser light to tunable dye-laser light. The copper-vapor lasers are configured in parallel oscillator-amplifier chains, which are combined to achieve high power.

Copper lasers produce fixed-frequency green-yellow light. These devices operate in a manner somewhat similar to fluorescent lights. An electric discharge is set up along the length of a long cylindrical tube. The discharge energizes the copper-vapor atoms in the tube, which in turn emit the green-yellow laser light. These devices operate in a manner similar to fluorescent lights. An electric discharge is set up along the length of a long cylindrical tube. The discharge energizes the copper-vapor atoms in the tube, which in turn emit the green-yellow laser light. These lasers operate as repetitively pulsed discharge tubes and currently produce average power levels up to several hundred watts per laser unit.

When the AVLIS program started at Livermore in 1973, copper laser technology was very new. The first laser that we built was rated at 1.5 watts, and the first plant design assumed devices rated at only 15 watts. However, the characteristics of dye lasers pumped by copper lasers were recognized at that time to be suitable for large, economical plant systems. Although various alternative laser systems were also pursued for several years, copper laser technology and system integration advanced rapidly and were chosen for the AVLIS system in 1979. By 1983, the laser unit was rated and demonstrated at 200 watts, a record that was doubled again by 1984. An additional factor-of-2 improvement in unit power rating is anticipated. As the unit rating of the copper lasers has increased, the cost of the laser system has decreased in both capital and operating costs.

The copper lasers are packaged into individual, self-contained boxes operated by a microprocessor. Only low-voltage power and cooling water are centrally distributed. Laser packages are essentially plugged in at stations along the optical support structure. The modular characteristics of this laser system allow a redundancy that prevents total shutdown in case of failure in any one unit. Furthermore, any unit can be easily removed and replaced by a substitute

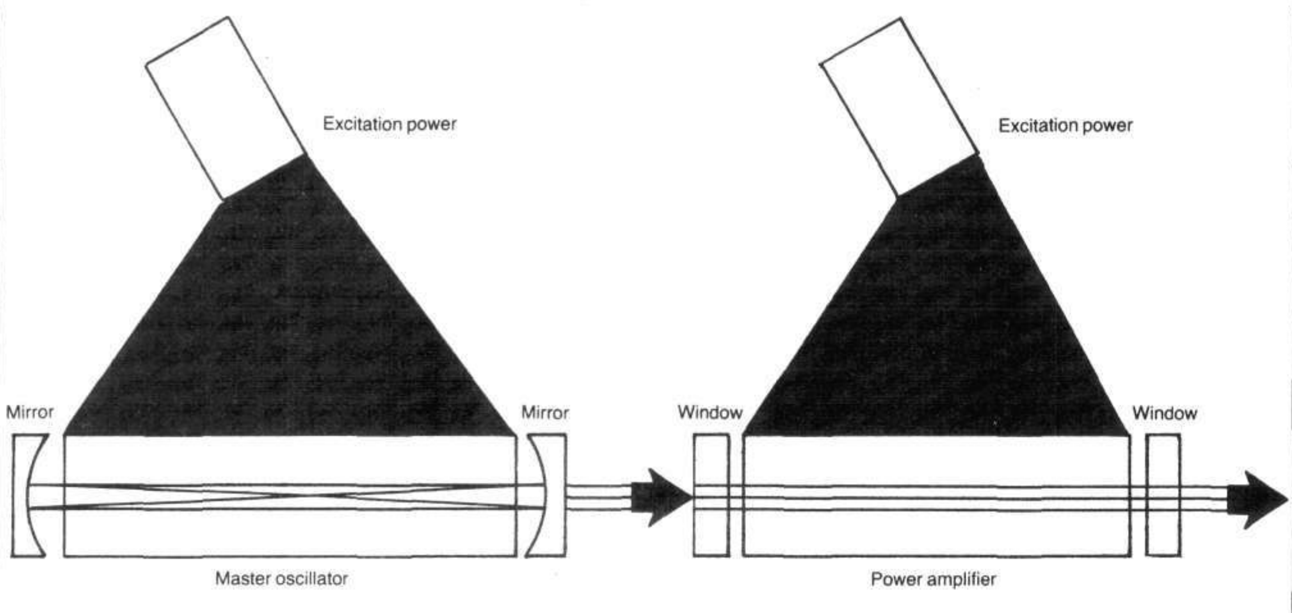


Figure 5
LASER AMPLIFIER SYSTEM

Atoms inside two laser cavities are excited by an external power source, resulting in emission of laser light from the medium in the cavity. Light inside the laser master oscillator reflects (oscillates) between the mirrors, causing light amplification. Some of the light escapes to the right through a partially reflecting mirror, where it enters another laser cavity for amplifications. In the AVLIS system, dye laser oscillators and amplifiers are pumped by copper-vapor lasers, which provide excitation power. The copper-vapor oscillators and amplifiers are pumped by electrical power supplies.

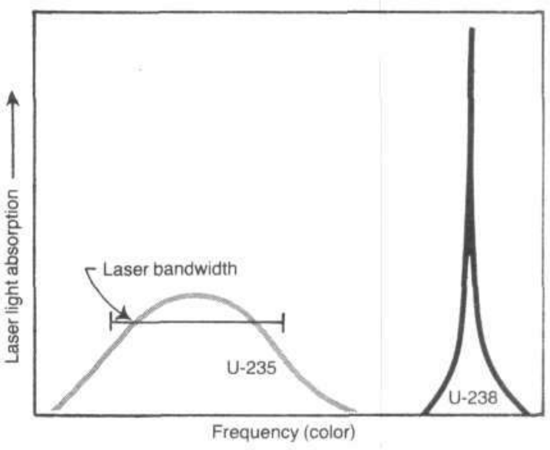
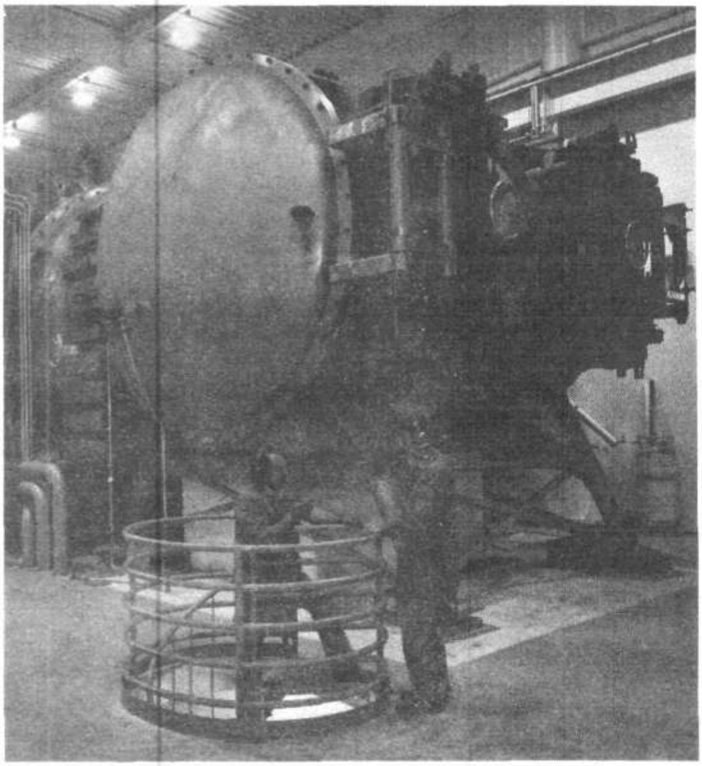


Figure 6
LIGHT ABSORPTION SPECTRA FOR URANIUM ISOTOPES

By properly tuning a laser system, one isotope (U-235) can be selected for photoionization and extraction, to the exclusion of the other (U-238). The figure shows the laser bandwidth for both isotopes.



James E. Stoots/LLNL

The 300-ton Separator Demonstration Facility shown here was constructed by some 120 lab and contract workers between January 1984 and April 1985 at a cost of $24.5 million. The facility will have the capability to enrich uranium in three separator pods at one time, compared with the Mars separator, which has only one separator pod.

About 80 percent of the project's budget involved contracts with U.S. industry, including six main contractors: The Boston-based High Vacuum Equipment Corp., which constructed the $3 million vacuum pumping system; Maxwell Lab Inc. of San Diego, which built the $3 million high voltage power conditioning system; Chicago Bridge and Iron, which built the $2.6 million process vessel; the Idaho Falls-based Industrial Corporation Inc., which built the $1.6 million water cooling system; EMC Corp. of Baltimore, which manufactured the $1.5 million control system; and the Fremont-based S & Q Corp., which built the $1 million ventilation system.

unit for routine maintenance or repairs, or to expand or improve the laser system.

The Uranium Separator

The principal elements of the separator are the vaporizer that melts and evaporates the uranium metal and the extractor/collector cells in which the uranium isotopes are selectively photoionized by the laser light and then electromagnetically separated. Vaporizers and extractor/collectors have been tested in progressively larger separator systems, including the ½-scale Separator Development Facility at Lawrence Livermore National Laboratory, the Materials Handling Development Module (¾-scale) at Oak Ridge, and the Separator Demonstration Facility (full scale) under construction at Livermore.

The objective of the separator development program has been to achieve an economical separator module within the broad constraints of the basic process. The principal goals have been to maximize energy efficiency for vaporization and maximize durability of components in a liquid uranium environment. The efficiency has been achieved and separator systems have now been run for more than 100 hours, approaching the plant run cycle time.

The next steps are the completion and operation of the Separator Demonstration Facility, which is now planned to enrich uranium at plant conditions in early 1987.

In the current design, the full enrichment from 0.7 percent U-235 to 3.2 percent U-235 is achieved in a single pass through the separator. Thus, the material is processed only once. For each 6 kilograms of unenriched uranium fed into the module, 1 kilogram of enriched product is produced. This process efficiency is the result of the fundamental selectivity of AVLIS, which is 1,000,000 times greater than for conventional separation processes. In fact, the Separator Demonstration Facility, when fully activated, will be capable of enrichment at the rate of about 1 million separative work units per year (fuel for 100 billion kilowatt-hours per year).

The AVLIS Full-Scale Demonstration Facility will provide the first complete plant-scale laser/separator system, which will serve as the prototype of the primary modular units central to subsequent AVLIS plants.

With a sustained effort, the system could be brought to full power in 1986. Full production cycle operations could be achieved in 1987, thus allowing conclusive validation of the capitalization and operational economics of AVLIS.

The Full-Scale Facility is segregated into separate systems: the Laser Demonstration Facility and the Separator

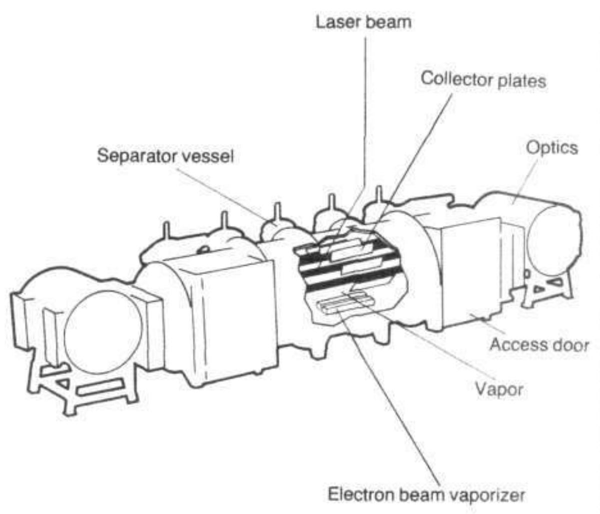


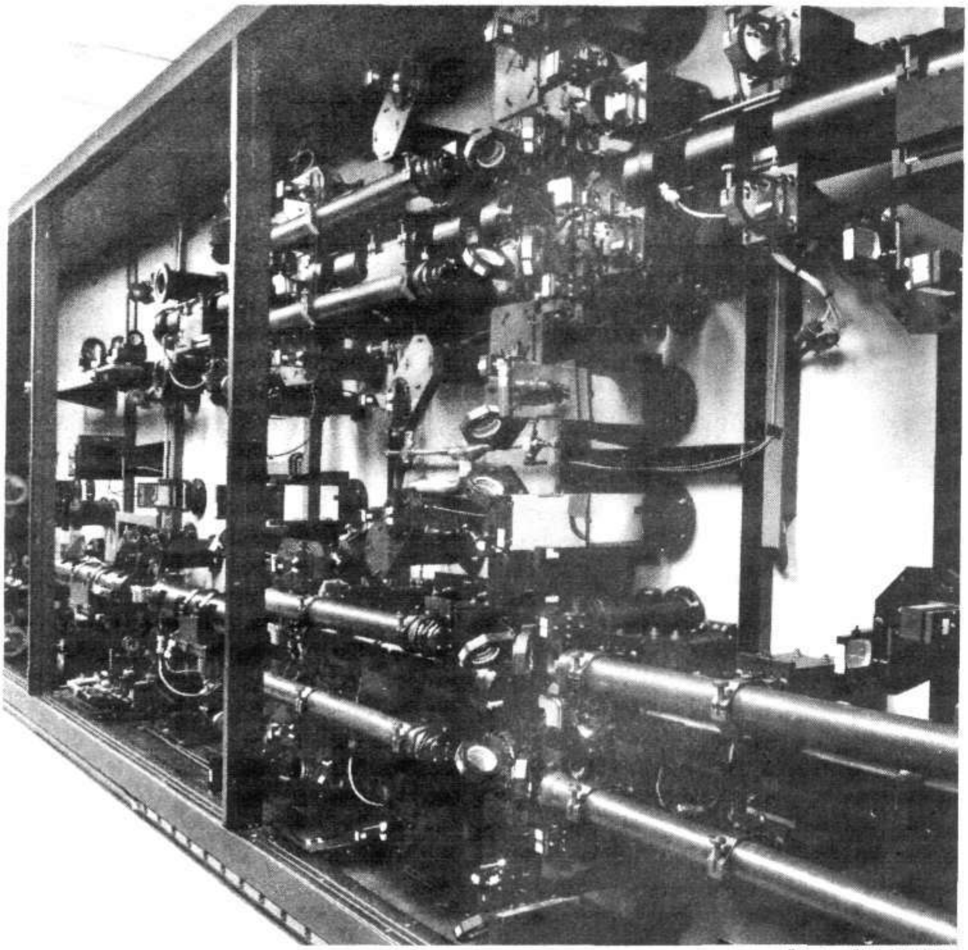
Figure 7
SEPARATOR DEMONSTRATION MODULE
Shown schematically are the primary internal parts of the separator module in the Lawrence Livermore Full-Scale Demonstration Facility.

Demonstration Facility. The laser system will contain all required components and subsystems at full plant scale. It will be implemented in phases, with operations starting in 1985. Laser beams will be transported to the separator systems by means of underground beam pipes like those currently in operation at Livermore.

The Separator Demonstration Facility will be a full-plant separator module complete with all support and auxiliary subsystems, with a potential production rate equivalent to more than a thousand of the largest centrifuge machines in the world. Both the laser and separator systems will be supported by maintenance, refurbishment, and equipment inventories capable of demonstrating long-duration continuous runs and rapid equipment turnaround. Operations procedures and personnel training techniques will be developed in these facilities.

The near-term objective of the Full-Scale Demonstration Facility is to firmly establish AVLIS capital and operating costs. The long-term objective is to develop more economical equipment and procedures through value engineering and technology improvements.

In summary, AVLIS technology presents an exciting breakthrough in the first successful application of laser technology to a major industrial process for material refining. AVLIS represents a real opportunity to provide relatively low-cost enriched uranium and to extend laser technology to a wide variety of other important applications.



Stephen Skolnick/LLNL

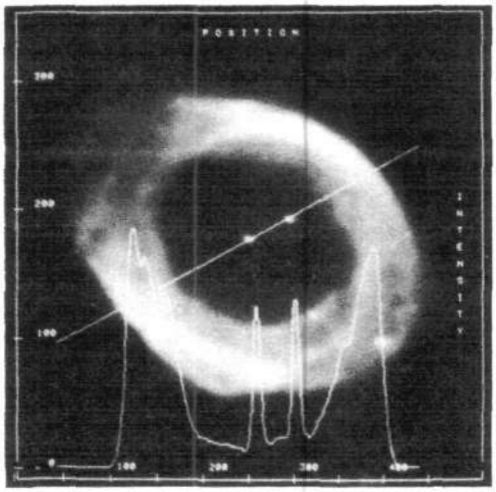
This dye laser corridor has about 2,000 optics that convey the laser light used in the AVLIS uranium enrichment process. Each wall in the dye laser corridor has two dye laser chains that amplify the light to high power for its later use to separate uranium. Inside the enclosures, special air filtering systems reduce the number of particles with diameters larger than 1 micron to less than 1,000 particles per cubic foot—about 1,000 times cleaner than a room with standard air conditioning.

Astronomers' High-Speed Imager for Faint Objects Has SDI Applications

An unusually sensitive light detector that can detect single photons has been developed by astronomers at the National Astronomical Observatory in Mexico and the Space Science Laboratory in Berkeley, Calif. Called Mepsicron, or Microchannel Electron Position Sensor with Time Resolution, it combines high resolution, high speed, and simplicity of design.

Although developed for single photon detection in astronomy, the detector has also been attached to a scanning transmission electron microscope for crystal diffraction studies. Other possible uses include medical and biological imaging where low X-ray dosages are critical. The detector will also undoubtedly find a place in the Strategic Defense Initiative, since new technologies will be required for imaging faint objects through the atmosphere.

Mepsicron joins the family of electronic imagers that are the product of sophisticated space science research. Probably the most familiar electronic images are the pictures transmitted by the Voyager craft of the cloud belts of Jupiter and the rings of Saturn. These pictures were taken with a charge-coupled device and transmitted back to Earth in digital form. They could not have been taken by standard photography, for several reasons.



Source: *The Invisible Universe*, George B. Field and Eric J. Chaisson (Boston: Birkhäuser, 1985), p. 19.

Figure 1
CHARGE-COUPLED DEVICE IMAGE OF RING NEBULA
The graph over this photo of the Ring Nebula was recorded with a charge-coupled device. Since the image is stored digitally, astronomers can extract a large amount of information easily. A cursor moved diagonally across the image to measure the relative brightness of each point along this line. Results were plotted on a graph superimposed on the image itself.

First, photographs cannot record large ranges in light levels. If you want to see the bright inner core of a galaxy, for example, you must take a fast exposure that sacrifices the faint outer features of the galaxy. Second, photographs cannot be easily stored and processed in computers. And finally, how would you get the photographs back to Earth for viewing?

The Charge-Coupled Device

Electronic imagers solved these problems by recording images digitally. The charge-coupled device works by receiving light directly onto an array of silicon chips. These chips produce an electron when a photon of light strikes them. The electrons are accumulated on the separate chips until they are counted and cleared from the chips one at a time.

Each of these chips provides the information for one pixel (picture element) in the completed picture. Thus the picture can be stored as a sequence of numbers, which represents the number of photons hitting each chip (see box, next page).

The satellite transmits these number sequences by radio back to a computer on Earth for reconstruction of the picture. Both bright and faint objects are recorded in this way. While on film

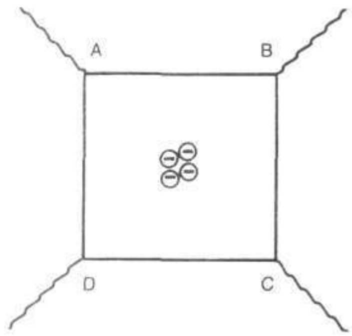


Figure 2
MEPSICRON'S COLLECTOR
The crucial innovation in Mepsicron is its new collector, which replaces the charge-coupled device and permits uninterrupted collection. Electrons place a charge on the metal sheet (anode). The charge is measured by detectors at each of its four corners (A, B, C, D). By measuring the strength of the charge simultaneously at each of the four detectors, the site of the electron impact can be calculated.

The vertical coordinate is given by $(B + C)/(A + B + C + D)$, *the horizontal coordinate by* $(A + B)/(A + B + C + D)$.

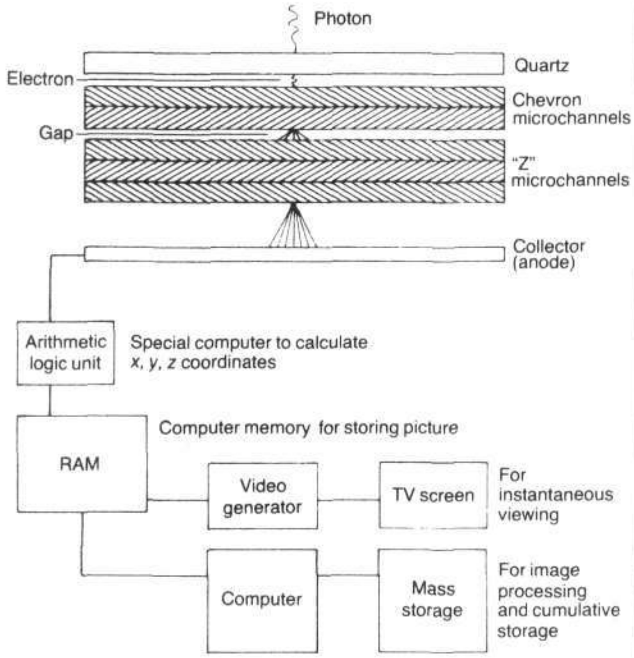
the maximum range between the brightest and dimmest objects is a factor of 100 times, in the charge-coupled device the dynamic range is a factor of 10,000.

Mepsicron's Advantages

The Mepsicron is an important advance over charge-coupled device technology, where the photon-counting mechanism is in the detector itself. This limits the time resolution of charge-coupled device images by the process of counting electrons; while the counting is going on, the instrument is not "seeing." The Mepsicron moves counting away from the detector and onto a computer. The result is the formation of an image in much less time—a particularly important feature where real-time imaging is required.

Instead of using solid-state chips as

How Mepsicron Works



By combining fairly common "off-the-shelf" technologies, Mepsicron provides a way to record images of both bright and faint objects in the sky simultaneously, without either overexposure or underexposure.

In this exquisitely sensitive light detector, the incoming light is first concentrated and focused by a standard telescope. The focused light then passes into a photomultiplier device of the kind also used for charge-coupled devices. This device works by converting a single incoming photon into a cascade of electrons, which are counted at the anode (positively charged) side of the instrument.

In the photomuitiplier, a photon first passes through a quartz photocathode which, through the photoelectric effect, emits one electron into a microchannel. The electron eventually hits the microchannel wall, made of material that emits two electrons for each electron impact. These two electrons later hit the channel wall again, liberating a total of four electrons, and so forth. The efficiency of the process is increased by bending the channels into a chevron or "V" path, so that at the hairpin turn, electrons will be sure to be emitted.

After passing through the chevron channel, the electrons emerge into a gap where they spread out slightly. The enlarged cloud then enters an array of Z-shaped microchannels. The enlarging of the electron cloud ensures that more of these tubes are involved, producing a higher amplification.

100 Million Times Brighter

At the receiving (anode) end of the channels a total of 10^8 electrons are received for every photon originally entering the quartz element. The entire instrument contains hundreds of these microchannels densely packed together. At the exit of the channels, an image is formed up to 100 million times brighter than the original.

The image-intensifier just described is in widespread use today. Usually it is connected to a charge-coupled device that collects the electrons and converts them back to an optical image on a video screen. The charge-coupled device is actually an array of sensors. A number of times each second the sensor array releases the photons it has collected and a computer converts these numbers into a coordinate grid where the two surface dimensions represent location and the depth dimension represents intensity.

The charge-coupled device has the limitation that it takes time to use. The process of counting each chip in the array interrupts the collection of incoming electrons repeatedly. Also, because the fineness of the grid is more limited than the fineness of the microchannels feeding it, the problem of image burnout persists.

New Collector Is Key

The real genius of the Mexican device is in its new collector that replaces the charge-coupled device. It is simply a sheet of metal—the anode of the instrument. Incoming electrons place a charge on the sheet measured by detectors at each of its four corners. By measuring the strength of the charge simultaneously at each of the four detectors, the site of the electron impact can be calculated (Figure 2).

To prevent bright spot burnout, the detectors read the coordinates of the electron impacts 7,000 times a second.

The impulse measurements are fed into an arithmetic logic unit which converts them into *x,y,z* coordinates for storage in a computer. This digital image can be added to indefinitely. Areas of differing brightness will maintain their true contrast. At the end of the observing run—or at any time during the run—the image may be converted into a video display, or simply stored on tape for later analysis.

the counting device, Mepsicron uses a position-sensitive resistive anode. In this type of light detector, a photon of light first hits a quartz sheet that releases an electron through the photoelectric effect. An electric field then guides the electron downward through a series of photomultiplier tubes. When the electron hits the wall of the first layer of tubes, it releases another five or six electrons.

Each of these in turn releases more electrons, until a cloud of up to 10^8 electrons emerges from the bottom tube. Here they hit a positively charged anode plate. The total charge is measured at the four corners of the plate. The charge is amplified and its x,y coordinates are calculated by an arithmetic logic unit.

The coordinates and the amount of charge are then sent to a video generator for immediate display or to a computer for further image processing and storage.

The Mepsicron offers higher spatial and time resolution in low-light conditions than the charge-coupled device. In combination with a scanning transmission electron microscope, the detector obtained very high resolution diffraction patterns. For instance, icosahedral particles of noble metals showed diffraction spots never before observed. And computer-processed images of layered materials permitted modeling of difficult diffraction patterns.

In medicine, the act of X-raying sometimes damages the tissue. Similarly, when experimental medicines are irradiated they are sometimes destroyed. The Mepsicron offers a way to obtain a useful image, full of information, with a reduced flux of potentially harmful radiation.

Beam Defense Applications

One important area in the beam defense program that needs further development is the detection of faint objects despite the obscuring effect of layers of atmosphere. Detection and tracking are necessary before a beam weapon can bring down a missile or other flying object. In the case of either passive imaging or active locating devices like laser radar, faint objects—for example, rockets after engine burnout and tactical nuclear artillery

Continued on page 51

Soviet Life

Soviet scientists at key laser research labs will receive the U.S.S.R. State Prize for their work on particle beam accelerators—work that is crucial for Soviet beam defense deployment. Pictured here are Siberian scientists from the Institute of Nuclear Physics in Novosibirsk.

Soviets Boast About Particle Beam Advances

Soviet scientists working on intense ion and neutral beam systems at the Kurchatov Institute in Moscow, the Novosibirsk Nuclear Insitute in Siberia, and the Institute of Physics in Kiev are going to receive "the U.S.S.R. State Prize," announced E.P. Velikhov, vice president of the Soviet Academy of Sciences and one of the world's most proficient beam weapon scientists.

Writing in the Aug. 12 issue of *Pravda*, the Soviet party paper, Velikhov does not overtly mention the military applications of these beam systems, but he notes the superiority and priority of Soviet research in areas which, indeed, are well known in the West as being crucial for antimissile beam weapons. His article is titled "The Professions of Atomic Beams."

Particle Beam Weapons

Intense, high-energy particle beams offer one of the most efficient means of intercepting ballistic-missile-launched nuclear weapons in space and the upper atmosphere. The reason is that high-energy particle beams, consisting of ions or neutralized fast ions, can be "tuned" to penetrate into the interior of warheads where they destroy the delicate electronic controls of the offensive missile and warhead.

The result is that the particle beam can neutralize offensive missiles at energy costs millions of times lower than those of laser beams and physical-intercept systems—or any other means—and at any phase of their trajectory.

As Lt.-Gen. James Abrahamson, director of the U.S. Strategic Defense Initiative, has discussed in recent months, major progress with both charged particle and neutral particle beams has been demonstrated and U.S. experimental prototypes are in operation. What has not been reported, however, is the fact that these U.S. developments are almost entirely based on pioneering Soviet research.

Velikhov's *Pravda* article emphasizes this reality and reveals new Soviet accomplishments in the field, with particularly important weapon applications, to emphasize the point. He writes: "The source of negative ions, created by using the plasma-volume method and working in a continuous regime, is more economical than the analogous system used abroad. That is, the model which several foreign laboratories focused on when creating their own designs for negative ion sources was that of the plasma surface source."

According to leading beam experts at Los Alamos National Laboratory and the Rand Corporation, the U.S. particle beam weapon program has, indeed, concentrated on plasma surface—as opposed to the more "economical" plasma volume—sources for ions because until recently it was believed that this was the only way to achieve a well-focused beam during acceleration of the ions extracted from the plasma.

Plasma volume sources have been used in the United States for neutral particle beam heaters on magnetic fusion experiments. In this case, the poorly focused beam is acceptable, since the target at which the beam is being directed is only a few feet away.

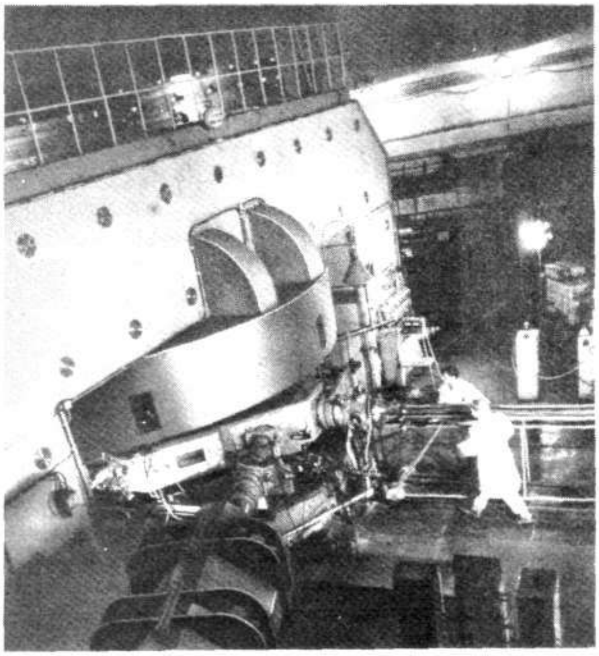
However, as the Los Alamos and Rand experts pointed out, U.S. researchers have just recently concluded that it is possible to utilize the more effective plasma volume source and still maintain a well-focused beam during acceleration, and research along this line has just begun. The point is quite significant, since the use of plasma volume sources will permit an increase in beam currents in the same

New Concepts for Particle-Beam Accelerators

As Velikhov notes in his *Pravda* article, the general public has long been acquainted with the practical applications of electron beam accelerators, such as television, X-ray machines, and electron beam welders. Ion beams are less well known, though they too were first realized more than a half-century ago.

Both electron and ion beam accelerators have attained extremely high energies at which the charged particles are traveling at near the speed of light. But these high-energy accelerators have been limited to very low beam currents, and, therefore, low beam power.

New types of accelerators have had to be developed in order to achieve high-current, high-energy particle beams. In the case of ions, which, because of their much greater mass, promise to have a much greater punch than electrons, Soviet beam scientists have pioneered the most important concepts.



High-energy particle beams are an efficient method for intercepting ICBMS. Here, the Soviet U-300 accelerator.

Source: G.N. Flerov, "The Search for and Synthesis of Transuranium Elements," Proceedings of the Fourth International Conference on the Peaceful Uses of Atomic Energy," (Vienna: IAEA, 1972), p. 471

All accelerators utilize an electric field to accelerate electrically charged particles. This electric field can be either oscillating or continuous, and it can be combined with oscillating or continuous magnetic fields. The chief problem is to damp motions of the ion perpendicular to the direction of acceleration. These "transverse" motions cause the ion beam to become defocused and hit the wall of the accelerating chamber.

The difficulty with high current ion beam accelerators is that the possible modes for coupling accelerating energy into unwanted transverse beam motions are greatly increased by the nonlinear interaction of the beam particles that appear at higher beam currents. But these nonlinear effects become beneficial once the ion beam has been accelerated to near the speed of light. (At this point these nonlinear interactions produce a sort of beam self-focusing phenomenon.) Therefore, it is during the startup and first phase of beam acceleration that the greatest difficulties are encountered.

This resolves down to two distinct areas, ion sources and the first accelerator stage.

Soviet Research Leadership

The Soviet Union has led the way in both areas in terms of the parameters needed for beam weapons. While the United States pursued positive ion sources, needed for neutral beam heaters on near-term magnetic fusion experiments, the Soviet program pursued negative ion sources that are applicable to either long-term fusion reactor requirements or near-term neutral particle beam weapons.

In both magnetic fusion and space-based beam weapons, ions are first extracted from a plasma source and accelerated to high energies. They are then passed through a gas cell in which they become neutral atoms once again without a loss of energy or direction. For higher energy and current beams, negative ions can be gas-cell neutralized more efficiently than positive ions.

In terms of accelerators, the leading technology for high current beams being concentrated on in the West is that of the Radio Frequency Quadrupole (RFQ). This concept was pioneered by Soviet scientists. Despite the great success with the RFQ in the West, the Soviets apparently are concentrating on another concept, the alternating phase accelerator, which is yet to be seriously pursued in the West.

accelerator by as much as a factor of 10, and a similar increase in beam power.

Therefore, Velikhov's mention of plasma volume versus plasma surface sources is quite revealing. We have a situation where both the United States and the Soviet Union have utilized plasma volume sources in magnetic fusion experiments, but the successful U.S. Los Alamos White Horse neutral particle beam weapon program has concentrated on utilizing *surface* plasma sources. Soviet scientists, Velikhov says, have succeeded in utilizing plasma *volume* sources in beam systems, while "foreign laboratories" have been limited to the less efficient plasma surface sources.

Given the testimony of U.S. experts, it is clear that Velikhov is flaunting the apparent superiority of Soviet particle beam weapon work—as well as its priority in their research program. The sad truth is that in terms of pioneering concepts, most U.S. particle beam research is based on concepts derived from Soviet work.

—Charles B. Stevens

High-Speed Imager

Continued from page 49
shells—must be picked out of the atmosphere.

The imaging requirement is to collect and rapidly analyze a relatively few photons. High-speed imaging computers will have to separate signal from noise in split seconds in order for defensive weapons to be deployed.

This latter requirement for high-speed image processing, points to the greatest strength of Mepsicron. The time resolution of this detector is limited only by the time required to recalibrate the charge-measuring device to zero. With improvements in this feature and in high-speed image-processing arithmetic logic units, the Mepsicron will play a vital role in Strategic Defense Initiative requirements for instantaneous imaging.

—Jim Everett

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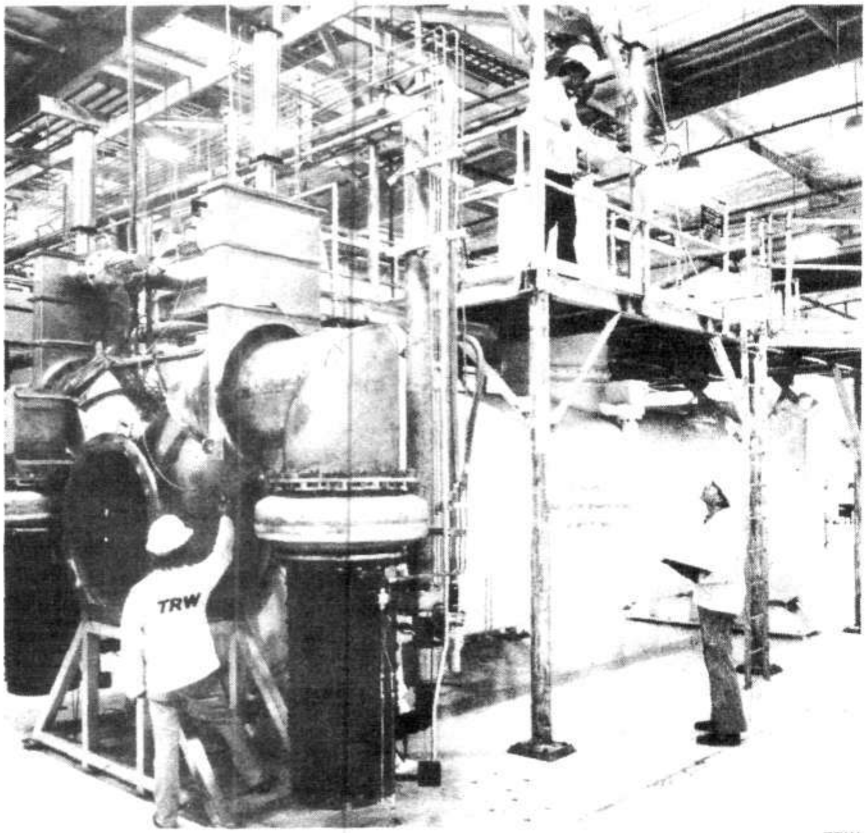


TRW

TRW's Plasma Separation Process prototype facility, shown here, was installed in 1981. It operates at ¼ scale for uranium production and full scale for most other applications.

TRW's New 'Beta Battery' Could Power Defense Satellites

A new way to power long-lived defense satellites in space, making use of the beta decay process, is being developed by the TRW at its Redondo Beach facility in California. The device, originally designed for isotope separation of fission fuel, is called PSP for plasma separation process.

Although the PSP lost out in competition with Lawrence Livermore National Laboratory's Atomic Laser Isotope System for the Department of Energy contract to proceed to a commercial prototype, the device has proven to be versatile in achieving separation in a wide range of elements. Already the quarter-scale PSP industrial prototype at TRW has been used to separate small quantities of radioisotopes used as diagnostics in inertial fusion experiments, and now TRW is exploring the production of long-lived nuclear batteries for powering satellites. These same batteries could also have important Earth-bound applications, such as powering pacemakers and other biomedical devices.

Present Systems Inadequate

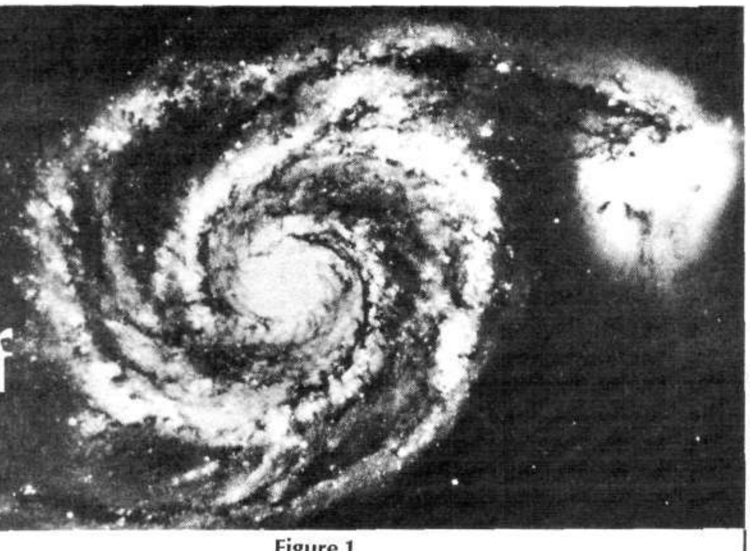
At present, there are two ways to power long-lived satellites in space: solar cells or nuclear-powered thermal electric batteries known as SNAPS (for Space Nuclear Auxiliary Power Systems). However, both methods fail to meet the special requirements for space-based defense satellites.

Because solar cells necessitate large collectors, observation of the satellite is quite simple. Similarly, the SNAPS produce significant amounts of thermal energy. Also, they are not uniform

Continued on page 63

The Young Scientist

How to Make a Star: The Promise of Laser Fusion



Kitt Peak National Observatory

Figure 1
A NATURAL FUSION 'POWER PLANT'
The Sun and the stars are natural thermonuclear fusion "power plants" that have been generating energy for nearly 20 billion years and will continue to do so for billions of years to come. If we can burn deuterium and tritium in miniature stars on Earth, there is enough fusion fuel available in the oceans to provide abundant energy for tens of millions of years.

New stars are still being formed in this spiral galaxy, the "Whirlpool," in the constellation Canes Venatici.

- Take a hollow, spherical plastic capsule about a quarter inch in diameter (the size of a small pea).
- Fill it with 5 milligrams (about 10-millionths of a pound) of a mixture of the hydrogen isotopes deuterium and tritium.*
- Take a laser that for a small fraction (10 billionths) of a second can generate 300 trillion watts of power—the equivalent of 3 *million million* 100-watt light bulbs.
- Carefully focus all this power onto the surface of the capsule.

The capsule and its deuterium-tritium fuel will be compressed to a density more than 20 times that of solid lead (200 to 400 grams per cubic centimeter) and heated to nearly 100 million degrees—more than six times hotter than the center of the Sun. These conditions are exactly the ones required to initiate thermonuclear fusion, and they exist naturally in only one place in the universe—in stars (Figure 1).

And there you have it for a fraction of a second: your own miniature star. During its brief lifetime, it will produce energy the way the stars and the Sun do, by nuclear fusion. The star created by this recipe will produce more than 200 times more energy than we used to ignite it.

Why make a miniature star? Beyond the excitement of actually reproducing and studying in the laboratory the conditions that exist inside stars, making such miniature stars will have important payoffs in two areas.

First, in the near term, because the fusion of hydrogen isotopes is also the energy source for advanced thermonuclear weapons, we will be able to answer basic physics questions that are important to this country's thermonuclear weapons programs.

Second, this laser-driven miniature star holds the promise of providing unlimited energy for mankind once we develop power plants that can turn fusion energy into electricity.

Building a 'Star' Plant on Earth

How can we use this recipe to make a star give us an unlimited amount of energy?

In a man-made fusion power plant,

LLNL

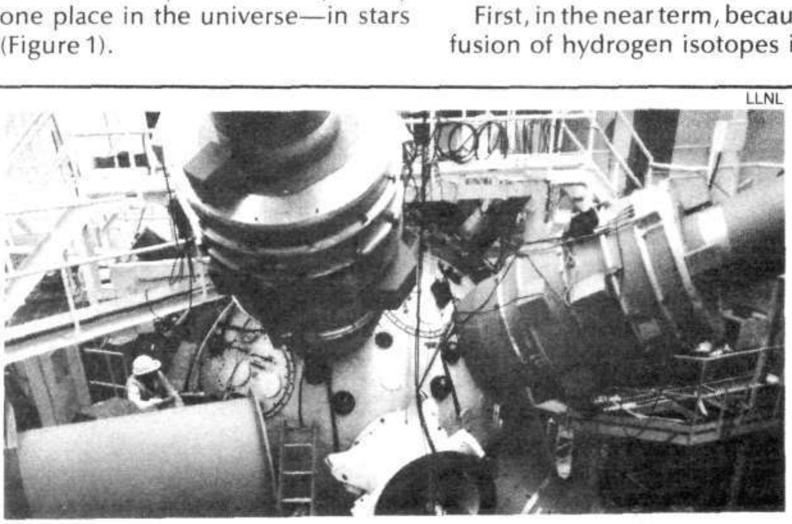
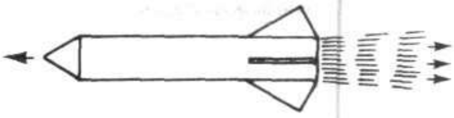
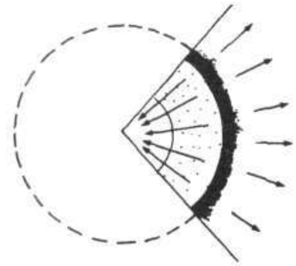


Figure 2
A MAN-MADE STAR MACHINE
This is the target chamber of the world's most powerful laser, Nova, at Lawrence Livermore National Laboratory in California. To produce fusion reactions, its 10 powerful laser beams converge simultaneously onto a small fuel capsule placed in the center of the 16-foot chamber. A commercial-size power plant would have a target chamber almost twice this size.

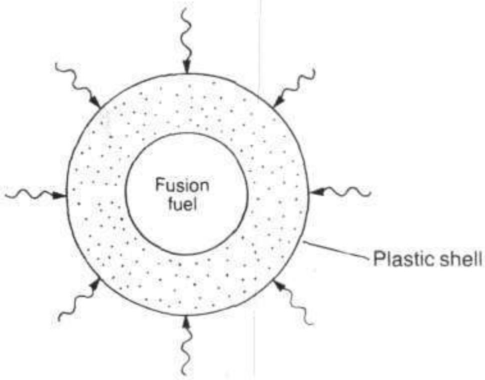
Figure 3
THE FUEL CAPSULE IN ACTION
Each part of the fusion-capsule shell behaves like a rocket, driven inward by the outward blowoff of the superhot material in the surface of the shell. The figure shows this process in four steps.



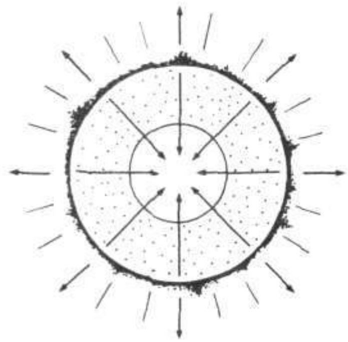
A rocket is pushed forward as rocket exhaust is pushed backward.



The capsule shell is pushed inward as the superhot shell material is pushed outward.



Step 1
Powerful laser beams rapidly heat the surface of the shell containing the fusion fuel to tens of millions of degrees Celsius, and the superhot material expands explosively.



Step 2
The rocket-like blowoff of the shell material produces a pressure of millions of atmospheres, which rapidly compresses the remainder of the shell and the fuel inside it.

Step 3
The fuel at the center of the capsule begins to burn (fuse) when it reaches a temperature of 50 to 100 million degrees Celsius and a density more than 20 times that of lead.

Step 4
The fusion "burn" propagates outward through the fuel, producing several hundred times more energy than was delivered by the laser beams that ignited the reaction.

in contrast to nature's star, we would inject one of the small fuel capsules into the center of a large chamber (about 30 feet in diameter), focus the laser beams onto it, and make our tiny star (Figure 2). We would repeat this process between two and five times a second, depending upon how much power we wanted to generate.

The energy released from the fusion of the approximately 0.005 grams of deuterium-tritium in our small plastic capsule is equivalent to the energy contained in about 4 gallons of oil. This energy would be carried away by very energetic neutrons traveling at nearly one-fifth the speed of light.

Hundreds of trillions of watts of laser power are focused on the small capsule in our recipe. When this much power is concentrated onto the fuel capsule and absorbed by it, the outer layers of the surface will heat up to nearly 100 million degrees and literally "boil off" the surface.

This happens much in the same way that steam boils off from the surface of a kettle of boiling water. At such high temperatures, however, the "steam" will not consist of ordinary neutral atoms. Most of the electrons surrounding the nuclei of the boiled-off atoms will be torn from their orbits, leaving positively charged atoms called *ions*. The resulting high-temperature mixture of negatively charged electrons and positively charged ions is called a *plasma*.

This plasma pushes off from the surface of the pellet and expands outward at speeds exceeding 200 miles per second—that's 1,000 times faster than a supersonic jet. Very much as the expulsion of hot exhaust gases by a rocket engine produces a forward, accelerating thrust on the rocket, the outward acceleration of the plasma leads to a tremendous inward reaction force at every point on the surface of the capsule (Figure 3).

For the very short time that the plasma expands, the thrust on the pellet surface is roughly 100 times the thrust of the Space Shuttle launcher! Under such a tremendous force, the plastic shell and the deuterium-tritium fuel inside are violently crushed inwards.

After the laser pulse stops, the implosion of the shell continues for a while before it slows to a stop, and contains (confines) the fuel for a short time before the fuel expands outward again. By this time, the fuel in the center has been compressed to a density more than 20 times that of lead (200 to 400 grams per cubic centimeter) and heated to a temperature of 50 to 100 million degrees.

How the Fuel Makes Energy

Nuclear fusion is the source of energy in the Sun and the stars. In a typical fusion reaction, the nuclei of two light atoms fuse together to form a heavier atom, releasing energy in the process.

One of the most energetic and easiest-to-produce fusion reactions occurs between the isotopes of hydrogen, called deuterium and tritium (Figure 4). At 50 to 100 million degrees, deuterium and tritium atoms all lose their electrons, leaving bare, positively charged deuterium and tritium nuclei.

At these temperatures, the nuclei are moving so fast (about 300 miles per second) that they can overcome the repulsive electrostatic forces that normally keep them apart. When a deuterium nucleus collides with a tritium nucleus under these conditions, they fuse together, producing a helium nucleus and a free neutron.

The combined mass of the neutron and the helium nucleus is less than that of the original deuterium and tritium nuclei (Figure 5). This mass loss is crucial to the production of energy in the fusion reaction, and it explains why the stars shine. The mass lost in the fusion of deuterium and tritium appears as *kinetic energy*, most of it carried away by the neutron. The neutron is moving very fast—nearly one-fifth the speed of light.

Inertia, the resistance of matter to changes in its motion, holds our miniature star together for a very short time—about a tenth of a billionth of a second. During this time, most of the deuterium and tritium nuclei fuse, and the resulting helium nuclei and neutrons fly apart because of the energy release.

If we have done everything right, the fusion process or "burn" will release more than 200 times as much energy as was needed to create the laser pulse that compressed and heated the capsule and ignited the

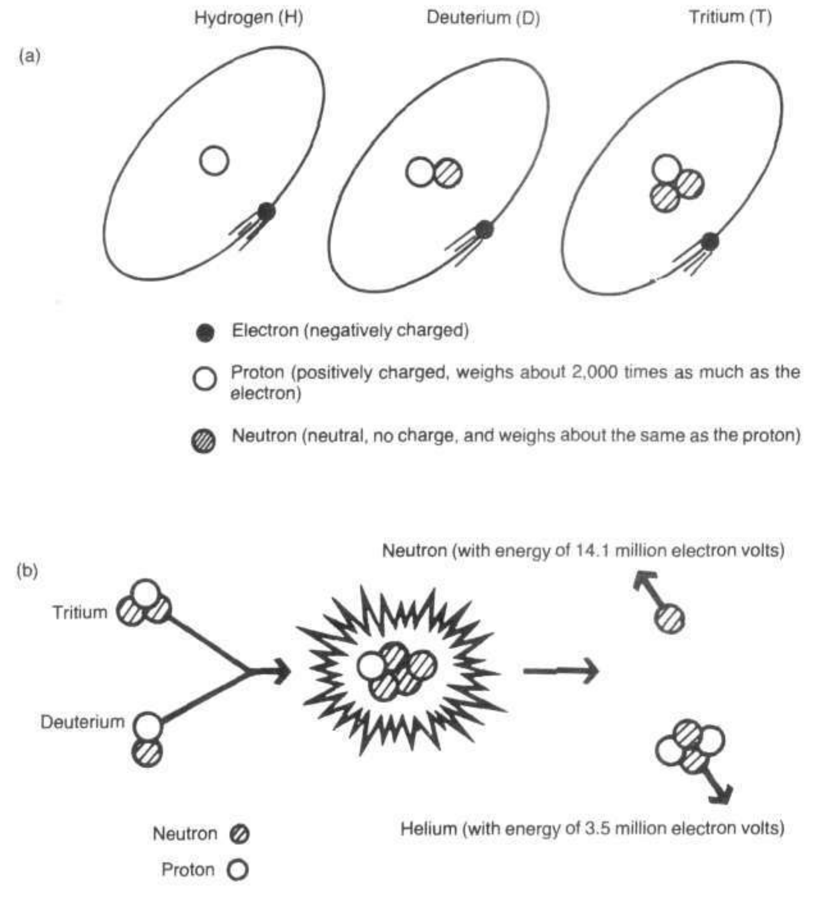


Figure 4
MAKING A STAR IN THE LABORATORY
(a) The ingredients

Each isotope of hydrogen has a single proton in its nucleus, which has a single electron in orbit around it. The hydrogen nucleus contains only one proton; the deuterium nucleus has one additional neutron, and tritium has two additional neutrons. Therefore, deuterium weighs twice as much as hydrogen, and tritium weighs three times as much.

Deuterium, also known as heavy water, is abundant in ordinary water: 2 out of about every 6,500 water molecules are deuterium, rather than ordinary hydrogen. The tritium nucleus can be made in the laboratory by bombarding the lithium with neutrons. Lithium is abundant in seawater.

(b) The fusion process

In this typical fusion reaction, the deuterium and tritium collide and recombine to form a helium nucleus and one neutron, releasing energy in the process. Most of the energy is carried in the neutron. There is a net energy gain because the end-product nuclei weigh less than the nuclei of the input fuel.

fusion "flame." The fact that only inertia keeps our star together gives this process its name—*inertial confinement fusion*. Because a laser is used to ignite the fusion reactions, the process is also called *laser fusion*.

A stream of these "stars" could fuel a power plant. From a single fusion fuel capsule we get about 4 gallons of fuel oil equivalent energy. All by itself, the energy from a single fusion capsule is not much for an electrical power plant of moderate size, which produces 500 million watts of electricity and burns about 10 gallons of fuel oil per second.

But if we could use a laser to compress and heat a whole succession of capsules, and if we could capture the energy carried away by the fusion neutrons and turn it into heat, we could run an electrical power plant.

In a fusion power plant, we would turn the kinetic energy of the neutrons released in the fusion process into electrical power. To do this, we would "capture" or stop the neutrons in a "blanket" of flowing liquid metal or solid granules, where the neutron energy would be turned into heat. This heat would be used to heat water and make steam, which would then be used to spin a turbine and produce electricity in the conventional manner (Figure 6).

The "blanket," whatever it was made of, would contain at least a fraction of lithium. Then the nuclear reactions between the neutrons and the lithium would produce the tritium needed for fuel.

Two to three fusion-energy pulses per second would produce as much power as a medium-sized electric power plant, but very little fusion fuel would be needed—about 90 pounds of deuterium and 900 pounds of lithium for an entire year (Figure 7). By extracting the very small fraction of the ocean that is deuterium and lithium, we could meet the world's energy needs for millions to billions of years—easily as long as the stars and our Sun itself will last (Figure 8).

A Safe and Clean Energy Source

The fusion process will not only give us a virtually unlimited source of energy, but one that is both clean and safe.

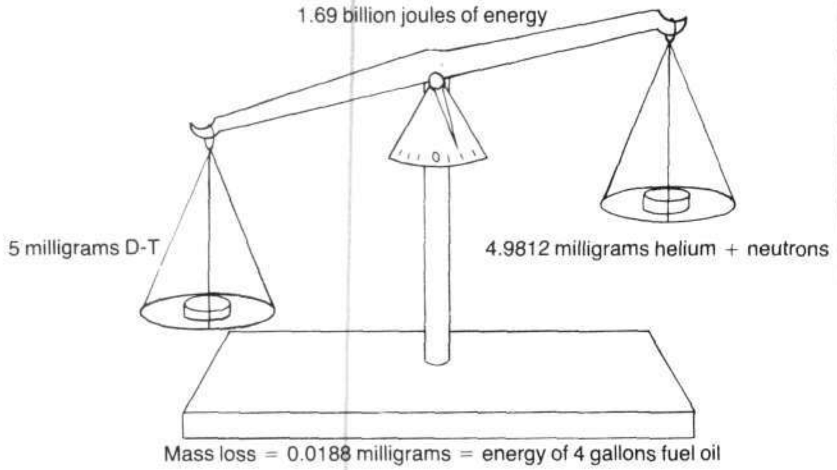


Figure 5
HOW THE FUSION REACTION CREATES ENERGY

The plastic capsule in our star recipe contains 5 milligrams of D-T fuel (equal numbers of deuterium and tritium atoms), less than the weight of a water drop the size of the letter "o" in this sentence. If we could convert all of that D-T into helium and neutrons, there would be a mass loss of 0.0188 milligrams, corresponding to an energy production of 1.69 billion joules—the energy in about 12 gallons of fuel oil.

For the small stars we produce, we can convert or burn up only about one-third of the available fuel. Thus for each small star produced, we will have available the energy equivalent of about 4 gallons of fuel oil.

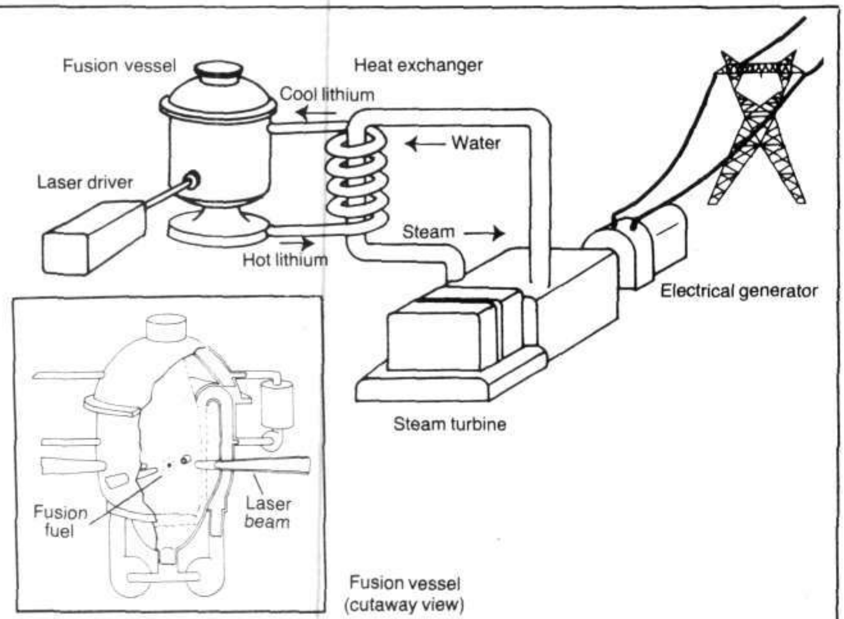


Figure 6
PRODUCING ELECTRICITY

In this artist's drawing of a laser fusion power plant, a laser implodes two to five new fuel capsules every second in the center of the fusion vessel. The energy of the fusion neutrons turns to heat in a flowing lithium "blanket." The heat boils water in a heat exchanger to generate electricity in a conventional steam turbine. Nuclear reactions between some of the neutrons and the lithium produce fresh tritium, from which more fuel capsules can be made.

Let's look at the process compared to other forms of energy. First, fusion energy emits no hazardous materials of any kind, unlike fossil fuel power plants, which emit sulfur and carbon dioxide. Second, fusion, a more advanced form of energy, has certain advantages over nuclear fission.

For example, in contrast to nuclear fission, fusion *cannot* take place spontaneously. Making a miniature star is an extraordinarily difficult task. Laser fusion requires very precise and complex compression and heating of the fuel pellet before fusion can occur. When we have done everything right, the fusion reaction produces more energy than it takes to ignite it, of course, but because the fusion "flame" is so difficult to light, there is no possibility of a runaway reaction or accidental meltdown.

Each capsule contains only so much fuel, and even if all the capsules for a day's operation were assembled in one place, a chain reaction would still be impossible. The few neutrons from each imploded capsule that are not stopped in the cooling blanket cannot initiate a new fusion reaction from a new capsule. Anything done wrong will make the fusion "flame" go out, leaving behind only the rapidly cooling blanket material used to capture the fusion energy.

The products of the fusion reaction are energetic neutrons and nonradioactive helium. Most of the neutrons are captured in the "blanket," generating heat and producing more tritium fuel. A few neutrons can pass through the blanket and can activate the structural material of the vessel that contains the fuel capsule. However, by proper selection of materials, this will be a very limited and easily handled activity.

After operating the plant for a typical 30-year lifetime, the vessel that contains the target chamber where the fusion reaction occurs would have to be stored for about 50 years. This would allow the vessel, literally, to cool down and lose all its radioactivity. After this period, the target chamber materials could be disposed of or processed and reused.

Why Don't We Have Fusion Plants?

An obvious question to ask is, since fusion would give us virtually unlimited energy, why aren't there any working fusion plants today?

One reason is that it is so difficult to produce the conditions needed to light the fusion flame. Another reason is that only in the last decade have we developed the scientific understanding, the computing power, and the laser technology needed to design and carry out the experiments that will tell us how to make fusion power work.

So, the full recipe described here has not yet been put together. We have made some small stars in the national laboratories and we have produced fusion using capsules even smaller than the pea-sized one called for in the recipe. But so far, we have not produced more energy than was used to initiate the fusion reactions.

Let's consider again what we need to create fusion: First, we have to heat the deuterium-tritium fuel to 50 to 100 million degrees. Second, we have to keep enough of this fuel together for a long enough time so that most of the deuterium and tritium nuclei fuse with one another.

This second requirement, is known as the confinement *Lawson condition*. It is expressed scientifically by saying that the number of deuterium and tritium nuclei (n) per cubic centimeter times the number of seconds (τ) they are kept together (called the *confinement time*) must equal at least 100 trillion. To write this as a formula, $n\tau > 10^{14}$ cubic cen-

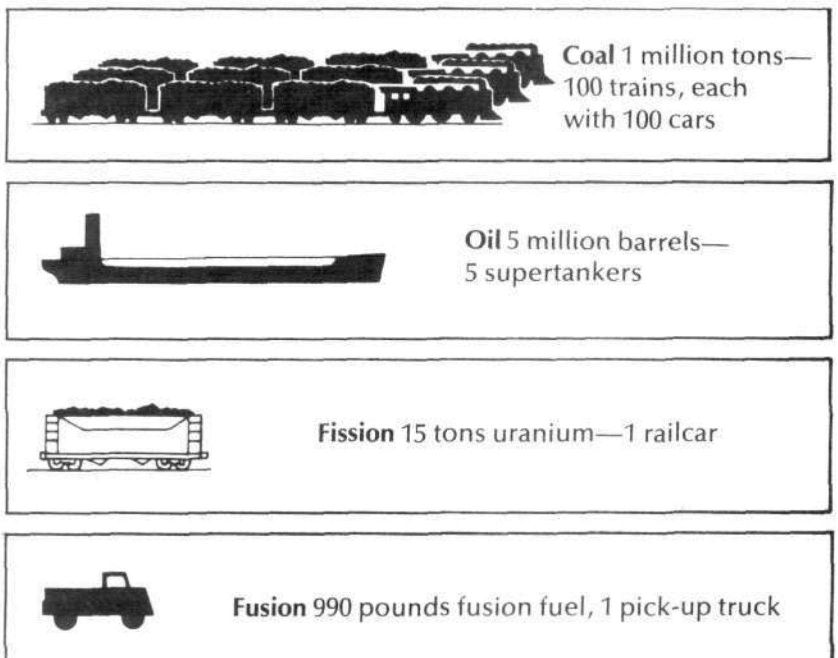


Figure 7
HOW FUELS COMPARE IN WEIGHT
To produce the same amount of power, a typical (500-megawatt) power plant would have to use the amounts of fuel shown here. A fusion power plant would use just one small truckload of fuel per year.

timeters/second. (10^{14} is 10 with 14 zeros, or 100 trillion.)

In the stars, where gravity compresses and heats the hydrogen fusion fuel and also contains it, the necessary confinement conditions have been easily met for millions to billions of years. On Earth, these conditions so far have been met only by using the incredible energy released by a conventional nuclear explosive (a fission or atomic bomb) to compress and burn fusion fuel in the hydrogen bomb, which is more properly called a *thermonuclear bomb*.

Where the Fusion Experiments Stand

For power production, there are two different approaches being taken to reach the goals of high fuel temperature and a high product of fuel density and confinement time—inertial confinement and magnetic confinement (Figure 9). In both approaches, it has been relatively easy to obtain the required temperature; the tough part is getting $n\tau$ high enough to meet the Lawson condition.

In inertial confinement, because of the inherent inefficiency of any "rocket-like" propulsion-driven implosion, the confinement conditions have to be about 10 times the Lawson condition. These conditions will be met with a very high fuel density (200 to 400 grams per cubic centimeter) and a very short confinement time—the tenth of a billion of a second provided by the inertia of the compressed fuel. So far, in laboratory fusion experiments, we have managed to compress the deuterium-tritium fuel to about 30 grams per cubic centimeter. So we are about a factor of 10 short of the required $n\tau$ process.

In magnetic confinement, the hot deuterium-tritium plasma is confined by a force field of huge magnetic "bottles" in various devices called tokamaks, mirror machines, spheromaks, and reversed field pinches. Such devices have confined plasmas of very low density for a fraction of a second, but they have not yet met the Lawson condition.

In inertial confinement, we use high-power lasers to heat and confine the fusion fuel. At the Lawrence

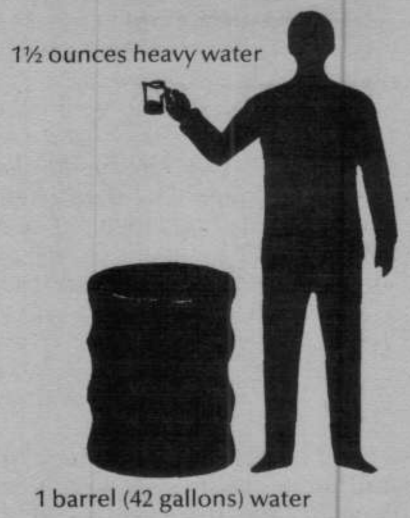


Figure 8
AVAILABILITY OF HEAVY WATER
One barrel of water contains about 1½ ounces of heavy water, from which the deuterium can be easily extracted. Adding an equal amount of tritium would give about ½ ounce of D-T, whose fusion energy would supply enough electricity for a family of four for about 35 years.

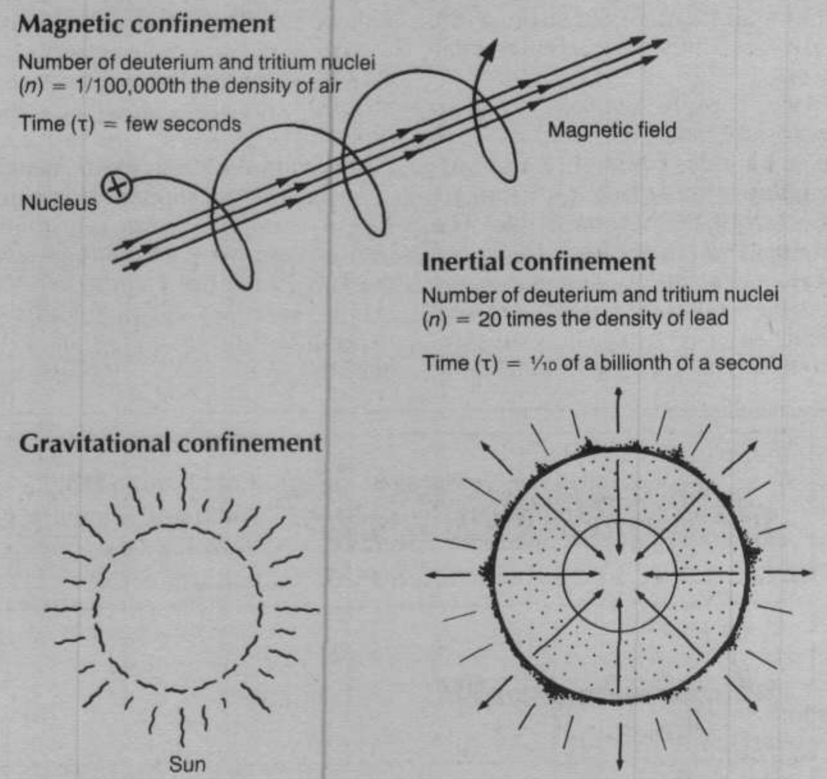


Figure 9
MAGNETIC AND INERTIAL CONFINEMENT FUSION
In a star, the gravitational forces arising from the star's immense mass heat and confine the fusion plasma. Magnetic fields in the laboratory can be arranged in such a way that the forces they exert on moving, charged particles keep a low-density plasma confined.

In inertial confinement, the inertia of fusion fuel imploded by a laser beam keeps the superdense compressed plasma confined long enough for fusion reactions to take place.

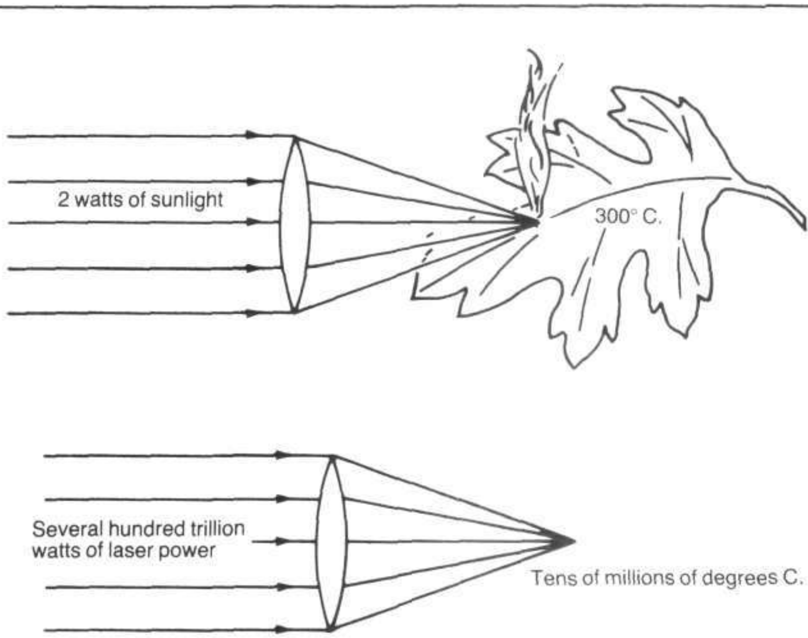


Figure 10
LASER INTENSITY

Sunlight has an intensity of about 0.1 watt per square centimeter. A magnifying glass 2 inches in diameter can focus sunlight to a spot about 2 millimeters in diameter, giving an intensity of about 100 watts per square centimeter and heating the spot to about 300 degrees Celsius. The Nova laser at Lawrence Livermore National Laboratory puts out several hundred trillion watts. This light can be focused to a spot 0.5 millimeter in diameter, heating the spot to tens of millions degrees Celsius.

Livermore National Laboratory in California, the recently completed Nova laser puts out 100 trillion watts. By focusing this power onto tiny targets, Nova can easily produce the intensities of 100- to 1,000-trillion watts per square centimeters required to generate the enormous pressure (50 million to 100 million times atmospheric pressure) and temperatures required to implode the fusion fuel capsule.

How can lasers focus 100 to 1,000 trillion watts of laser light per square centimeter onto the capsule? You can get some idea of this if you think about how you can use an ordinary magnifying glass to focus sunlight on a leaf and make it catch fire. Sunlight has an intensity of about 0.1 watt per square centimeter. If you use a magnifying glass about 2 inches in diameter, you would focus about 2 watts of sunlight onto a spot 1 to 2 millimeters in diameter (Figure 10).

So the intensity of light on the leaf will be about 100 watts per square centimeter, a thousand times the intensity of sunlight. This is enough to heat that small spot to about 300 degrees Celsius and make the leaf burn.

The Nova laser puts out not a few watts but 100 trillion watts. Because it is just one wavelength or frequency, and because Nova has focusing lenses of very high quality, Nova can therefore easily focus that light onto fuel capsules no bigger than a grain of salt. Thus Nova can produce intensities of 100 to 1,000 trillion watts per square centimeter. This is easily enough to heat the capsule up to 50 to 100 million degrees. As the superhot, high-velocity plastic "stream" rushes away from the target surface, it generates the pressures needed.

The lab will conduct two key types of experiment with Nova. In one type, they expect to reach fusion fuel temperatures of the required 50 to 100 million degrees. In the other type, they expect to reach the high densities needed to meet the confinement condition.

To achieve net gain—that is, to get more energy from the fusion capsule than it takes to compress and ignite it—these high temperatures and densities have to be reached at the same time. The Nova laser will not have enough energy to do this, but the experiments with Nova will tell scientists how much laser energy will in fact be needed to run a laser fusion power plant.

Laser fusion and magnetic confinement fusion have made rapid progress in recent years. One of the things now holding back that progress is lack of funds.

Think about the Apollo space program when the United States spent nearly $80 billion (in today's dollars) over 10 years to put a man on the Moon. Only a nation as rich in human and material resources as the United States could have accomplished such a feat. Not only was the race to the Moon an immense scientific and engineering challenge, but the spinoffs of benefit to mankind are nearly beyond counting.

In contrast, the United States has spent less than 2 percent as much pursuing laser fusion as it did on the Moon program, and less than 10 percent as much on all fusion programs combined. If we were to treat the challenge of tapping the unlimited resources of fusion power as seriously as we treated the race to the Moon, we could have working laser-fusion power plants by early in the 21st century. Such a national policy would profoundly change the future of mankind, by providing a truly unlimited energy source—fusion—that would know no geographical or political boundaries.

This article was written by a laser fusion scientist at a national laboratory.

Notes

* Deuterium is a hydrogen atom with one extra neutron in the nucleus. It is abundantly available from water; 2 out of every 6,500 water molecules are deuterium water molecules. Tritium is a man-made hydrogen isotope with two extra neutrons in the nucleus. It is made by bombarding lithium with neutrons.

NSIPS

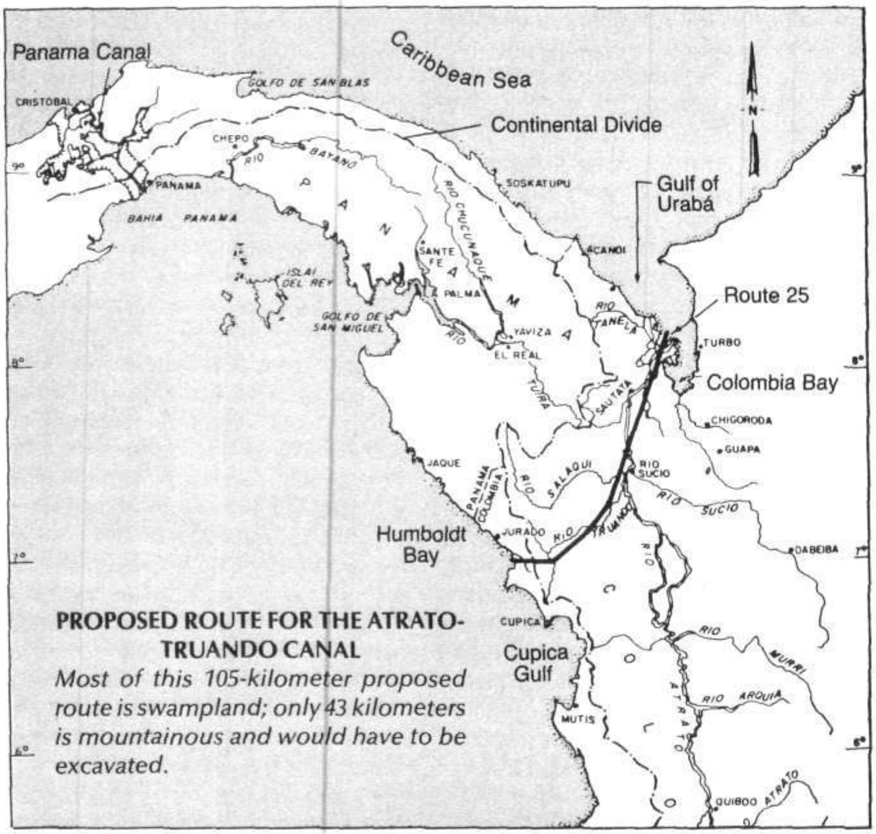
Ramtanu Maitra (left) at the podium at the Colombia conference. With him, from left, are Colombian Labor Minister Jorge Carrillo; Colombian congressman Daniel Palacios Martinez; Guillermo Silva, president of the Colombian Society of Economists, Cundinamarca section; Hans Bateman, representing the Colombian Institute of Engineers; and Major (ret.) Rafael Convers, a civil engineer.

A 'NASA Project' for Colombia: The Atrato-Truandó Canal!

"The Atrato-Truandó Interoceanic Canal must be our NASA, our project of interplanetary travel, our colonization of the Moon." That is how one conference participant characterized the importance of the biggest infrastructural project ever undertaken by Colombia—building the first Atlantic-to-Pacific sea-level canal. The proposed Atrato-Truandó Interoceanic Canal, whose construction the Colombian National Congress officially mandated in December 1984, will open up enormous potential for the economic development of Ibero-America, as well as of the entire Pacific Ocean basin.

Organizing for the multi-billion-dollar project was launched at a conference in Bogota, Colombia, Aug. 8-9, sponsored by the Fusion Energy Association of Colombia, the Colombian Geographical Society, and the Colombian Economists' Society of the Bogota-Cundinamarca region. Eighty international experts and government and industry representatives attended the two-day conference.

A message of greetings and support was sent to participants by Colombian



PROPOSED ROUTE FOR THE ATRATO-TRUANDO CANAL

Most of this 105-kilometer proposed route is swampland; only 43 kilometers is mountainous and would have to be excavated.

President Belisario Betancur, an enthusiastic supporter of the canal project who has seen prospects of funding for it eliminated by International Monetary Fund pressure. As several conference participants later stressed, the canal's construction will not rely on financing from international money-center banks or from supranational agencies like the International Monetary Fund and the World Bank.

A Monumental Task

Major (ret.) Rafael Convers Pinzón, a civil engineer, outlined the scope of the project, stressing that the wealth of the region alone—wood, coal, oil, and the value of the land—could finance the canal. Forestry engineer Jorge Castro confirmed that the forest products of the canal area are estimated at $2 billion. The cost of the canal is calculated at about $5 billion.

The canal will be 166 kilometers long, 35 meters deep, 500 meters wide at its base, and 600 meters wide at water level. Its route starts at the Gulf of Urabá, on the Caribbean (Atlantic) side, to Humboldt Bay on the Pacific, following the valleys of the Atrato and Truandó Rivers (see map). Of the total canal length, 26 kilometers are appropriate for excavation with peaceful nuclear explosions (PNEs)—the most cost-effective method.

Other speakers included Guillermo Silva of the Economists' Society and Jorge Carrillo Rochas, labor minister in the Betancur government.

How to get the job done was the subject of a presentation by Ramtanu Maitra, a nuclear engineer who is the editor-in-chief of *Fusion Asia*. Maitra, who is based in New Delhi, explained how a Fusion Energy Foundation organizing campaign in Thailand had succeeded in obtaining the support of both the population and important sectors of the government for a similar Great Project, the construction of a canal through the Isthmus of Kra.

The organizing drive there was successful, he said, particularly because regional participation was encouraged from other countries that stand to gain from the program. This in turn provided a powerful means to overcome regional political antagonisms. The same is true for the case of an Atlantic-to-Pacific canal in Panama or Colombia.

In Colombia, one of the major ar-

The Lessons of Thailand's Kra Canal Project

Ramtanu Maitra's presentation at the Atrato-Truandó Interoceanic Canal conference is excerpted here.

You may be wondering why I have come all the way from Asia to talk about the Kra Canal, when this conference is about the Atrato-Truandó Canal. To clarify this question, look at a Pacific-centered map that shows the trade flow through the Indian Ocean into the Pacific Ocean. With a bit of effort, trade among Asia, Africa, Australia, and the Americas can be made more prolific. In other words, the entire area can function as one family.

We are restricted from functioning in this way because of the very few, inadequate waterways. . . . We have run into this problem because we have not built up basic infrastructure for a long time, and this is taking a massive toll on the world economy. We built the Suez Canal in the 1860s, and the little Panama Canal in 1914. There is no doubt that these canals helped us over the years, but now we find them inadequate and a definite bottleneck to the increasing trade flow.

Why am I referring to the Panama Canal as the "little canal"? We are building more cost-efficient 300,000-dwt (dead weight ton) ships that cannot go through the canal, since the Panama Canal is small, even for 60,000-dwt ships.

Look how this little canal is affecting the world economy. In order to allow ships to pass through the Panama Canal, we have come up with a specification called the Panamax, which simply means the maximum size of ship that can pass through this canal. We are deliberately building inefficient carriers. So, for example, it becomes cheaper to lay oil pipeline across the land connecting the two oceans, than to carry oil in those small ships. The constraints on the canal also mean that ships of 200,000 dwt or more, carrying iron ore from Carajas, Brazil to Japan, have to go below Africa. This has lengthened ships' travel time and fuel consumption astronomically.

Unless we are able to implement great projects, such as the Kra and Atrato-Truandó canals, we will run down the world's economy and depopulate the planet. This is already happening in Africa. The lack of infrastructure causes stagnation in productivity and in the economic process as a whole. Lack of adequate waterways and port facilities is bleeding every nation's economy, through increased delivery and handling costs. We are generating wealth and then squandering it on delivery and handling costs. . . .

A 200-Year-Old Project

The Kra Canal project has a long history. It was conceived about 200 years ago by the younger brother of King Rama I of Thailand. DeLesseps, who built the Suez Canal, had done a geological feasibility study and was interested in getting the canal built. However the colonial interests in the region were too powerful at that time, and building such large infrastructure projects was politically extremely difficult. . . .

In October 1983, following meetings with influential Thai individuals, the Fusion Energy Foundation held a conference, in collaboration with the Thai Ministry of Communication. FEF board member Lyndon LaRouche spoke at that conference and Thai Minister of Communication Samak Sundaravej inaugurated it. We laid out a plan for how to build the canal and discussed its importance in facilitating trade connecting the Indian Ocean economically with the Pacific region.

In 1984, we held another two-day conference in Bangguments of groups opposed to the canal, is that the rights of the Indians living in the region will be violated. An Indian from the Ganapaga tribe, associated with the Catayumal Indian Foundation, forcefully countered this argument:

"We Indians are not against the construction of the canal. We live in that region, but we are not going to close ourselves off, to stop the contruction of the canal. . . . The anthropologists and Communists have wanted to brainwash us into opposing the development of the nation, the welfare of the nation. What we want is that our rights be respected, that we be given new lands, and that we be given direct participation in the project."

—*Timothy Rush*

Javier Almario

A Fusion Energy Foundation exhibit in Bogota displays a model of the proposed Atrato-Truandó Canal.

kok, stressing this time the industrializing potential of Thailand that can materialize through the building of the Kra Canal. The subject of regional participation was also discussed, and members of the Association of the South East Asian Nation (ASEAN) countries, along with representatives from Japan and India, attended.

Benefits of the Canal

Let's look at the Kra Canal project itself. What most people usually think of is the increased trade that the canal will bring into the region. However, the trade part is only the tip of the iceberg. Because of the mileage and fuel saved in shortening the trade route, the canal will pay for itself in 15 to 20 years, counting only revenue earned from tolls charged to passing ships. But once the canal is built, and even while it is under construction, many other interesting things will begin to happen.

Thailand has significant reserves of tin and rubber and a surplus in food production; the canal zone will be the base for developing a food-processing industry and a rubber-processing industry: In spite of the extensive use of synthetic rubber today, the demand for natural rubber will grow, since at least 15 percent of natural rubber is needed to be mixed with synthetics for the production of synthetic rubber. . . .

Once the canal is built, it is only a matter of years before Thailand changes from being an agrarian nation to an industrial nation. Its agriculture will be more mechanized, more productive. The canal zone would make way for the development of ship-repairing and shipbuilding industries. This will bring in the development of a machine-tool industry, which most developing nations lack. . . .

Recently the FEF representative in Bangkok, Pakdee Tanapura, testified before the Thai Parliament on the Kra Canal. A 60-member commission has been set up in the Parliament to look after the project.

Last May, a Japanese delegation led by Takeo Nakajima, chairman of the Mitsubishi Research Institute, came to visit the proposed Kra Canal site, along with representatives from Kajima, Sumitomo, Long Term Credit Bank, and others. Upon returning, they informed the Japanese government that they have formed a consortium of 20 firms to look after the Kra Canal project. The firms include Nippon Steel, Mitsubishi Heavy Industries, and Bank of Tokyo—among others.

I told you this little story to give you the concept of how such infrastructural project building is to be pushed. It must cut across the political barriers and form a hardcore nationalist alliance to look after the interests of Colombia, the region, and the world. It is important that such a process be started now, so that the canal-building can start as soon as possible.

Financing the Construction

I would like to touch upon the issue of financing the project. The cost, if peaceful nuclear explosions are used for blasting the last 25 miles of the mountainous region, would come to about $5 billion. This is not a large sum of money, considering that it would be spent over eight years. . . .

One thing that you must do, particularly in light of the capability that Brazil and Argentina have in the region, is to push for the formation of an Ibero-American Common Market. This is quite feasible, because the entire region would benefit from the canal. Every nation's transportation costs would be reduced. That is enough of an incentive.

Letters

Continued from page 5

In a comparable problem, a similar regrettable situation appears to exist: (4) If administrators and staff of an organization find inference of causality from correlation to be scientifically acceptable, such as in the correlation of insulin usage with diabetes mellitus, there is also a problem of incompetence in science and in the use of statistics; (5) if the personnel are aware that inferrring causality from correlation is bogus "science," but adhere to it for personal security or political reasons, or both, then there is a problem of deception; and (6) if public funds are employed in support of such deception, and if personnel are required to accept this fallacy as true, in order to remain employed, then there would appear to be a problem of fraud. Related questions of misuse of public funds and of obstruction of justice might also be raised. Such problems, if authentic, tend to lead to broader questions of mismanagement and corruption.

Such questions should be raised in congressional investigations. However, there is an important problem regarding members of the House and Senate regarding the addressing of rigorous and often complex scientific questions. Since few members of the House and Senate are professional scientists, there is a risk of scientific malpractice occurring without the congressmen being aware that anything improper or dishonest has been occurring.

National and international affairs involve highly technological matters that pertain to economic and national securities. Scientific malpractice relating to health effects of low-level ionizing radiation cannot be tolerated in military and national security areas in which knowledge of health effects of radiation is essential. Nor can scientific malpractice be permitted in policy determinations regarding nuclear power plants.

Antiradiation propagandists and ideologues have been wielding excessive power in the obstruction and delaying of operations of nuclear power plants in the United States.[9,13,15,17] The nature of certain aspects of the problem has been described in the record of a U.S. District Court lawsuit and decision.[17]

It's Later Than You Think

The situation is serious. The saying "It is later than you think" comes to mind. The United States has not been competing well in certain areas of the international marketplace, considering the continued expansion of the national debt, and considering the balance problems. The importing of considerable foreign oil is one aspect of the problem. Is it unreasonable to consider the prospect that acceptable and even desirable electric-powered small automobiles (for short trips) are likely to be introduced in the forseeable future?

If they are, they would no doubt have their high-tech batteries recharged by plugging into the home electric power outlets designed for such use. Large scale introduction of such vehicles would, of course, apply increased demand for electric power.

Considering the continuing instability of the Middle East, can we be certain that oil embargoes will not occur again? It is dismal, of course, to have to contemplate "what we should have done" in the event of an emergency.

It is essential, obviously, that scientific malpractices be eliminated if possible, or at least minimized. Rejections of at least three fallacies, wherever they occur, are essential. These are: (a) the fallacy of extrapolation, (b) the fallacy of inferring causality from correlation, and (c) the fallacy of equating "judgment" or personal opinion with fact. Since these problems have continued for some time, it seems doubtful that necessary action will be taken without either congressional action or executive edict.

As a note of interest, Martell[18,19] has reported on "radioactive" cigarette smoke. He claims that radionuclides are important in the etiology of lung cancer among smokers.

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The Author Replies

The estimates of radiation hazards given in my article are those of the National Academy of Sciences Commitee on the Biological Effects of Ionizing Radiation (BEIR) and the International Commitee of Radiological Protection.

The issue raised is an interesting one, but I consider questioning these estimates as beyond the scope of my paper.

Bernard L. Cohen
Department of Physics
University of Pittsburgh

'Beta Battery'

Continued from page 51

in their energy output over even a few years of operation.

Unlike other satellites, space-based defense satellites will be placed in extremely high orbits where they can be more easily hidden from enemy detection. Also, they must be small, cold objects in order to avoid being seen by infrared, radar, or optical sensors. Finally, these satellites have to be capable of lying dormant for many years and yet being instantly activated when necessary. A small computer, operating throughout the satellite's lifetime, must be able to receive the activation signal and turn on the satellite and its major power supplies.

How the PSP Works

The TRW battery is powered by nuclear disintegrations—beta decay—where the nucleus of an atom emits a high-energy electron that can then be converted efficiently and directly to an electric current. The PSP system would be used to produce significant quantities of the desired radioisotope to power the battery.

The PSP device is a magnetic bottle into which the material to be separated into isotopes is introduced in the form of a plasma. Oscillations of the bottle's magnetic field are combined with radio waves injected into the plasma to energize just one of the isotopes in the plasma. (The PSP can be easily modified to separate the isotopes of different chemical elements by changing the frequency of the radio wave input.)

The energized isotope then travels along the magnetic field lines of the bottle in a helical path. The energized isotope's helical path will have a much greater radius than that of an unenergized isotope. This difference is then used to sieve one isotope from another by simply placing a screen in the path of both isotopes: The isotope with the smaller helical path radius will pass through; the other isotope will not.

One isotope candidate for the beta battery is nickel-63 which has a 92-year half-life; that is, half of any given quantity of nickel-63 undergoes beta decay over a period of 92 years. This is sufficiently long enough for a battery based on nickel-63 to have a 50-year lifetime and yet have a relatively uniform energy output.

Nickel-63 beta decay generates a 67,000-volt electron. One method of efficiently converting this high-voltage electron into a low-voltage current is by utilizing solid-state electron multipliers, which work as follows: Layers of semiconductor are maintained at different voltages. As the high-voltage beta electron passes through each of these layers it will generate several additional electrons and in the process give up some of its energy. In photomultipliers, which work in a similar manner, one input photon of light can generate at the end of the cascade billions of photons.

In the case of solid-state electron multipliers, the net result is to efficiently convert the high-voltage beta electron into a low-voltage, large electric current, which would then be used to operate a long-lived computer and switching system.

This same beta battery could replace the more primitive batteries used in pacemakers—which currently have to be replaced every few years.

—*Charles B. Stevens*

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Protein-Rich Grains

Continued from page 17

potatoes, yams, and cassava.

Cassava is a starchy root that grows under very poor conditions, but unfortunately has no nutritional value except in providing calories. Cassava is widely grown in impoverished developing countries, where agriculture is very primitive.

The Baton Rouge group has inserted a small section of deoxyribonucleic acid (DNA)—the chemical genetic material is made of—into potato leaf tissue. This piece of DNA includes the gene for protein storage found naturally in corn but modified to make it a complete protein, plus a "promoter" gene, which tells the plant to produce this stored protein in the tuberous root only. This small section of DNA is inserted into the potato leaf tissue by infecting the tissue with a agrobacterium that has been genetically modified to include this DNA segment.

This is the same family of agrobacterium that infects the root tissue of legumes, like soybeans, and makes these infected root nodules fix free nitrogen from the air. The infected potato leaf tissue is then regenerated by cell culture techniques to produce a whole potato plant, which can then be propagated by the "eyes"—the potato callus area that produces green potato plant sprouts when potatoes are left too long in warm, moist storage areas. Since white potatoes, sweet potatoes, yams, and cassava are all very closely related genetically, the same technique is used for each crop. This group expects to have high-protein, complete-protein potatoes, sweet potatoes, yams, and cassava in a year or so.

The Long-Term Impact

Beyond the emergency value of these grains and root crops in keeping alive countless humans who would otherwise die of kwashiorkor and related medical problems, these protein-enrichment technologies will have a major long-term impact on global agricultural production and livestock.

Farmers in the United States are already growing primarily high-lysine, rather than regular corn. This high-lysine corn is fed to cattle and pigs to spur their growth. When fed this superior protein-quality grain, livestock produce more growth hormone and therefore reach slaughter size much more quickly. Younger animals require much less feed to put on the same slaughter weight than older animals. Therefore, the farmer achieves a healthier, slaughter-size animal not just more quickly, but with a tremendous savings in grain and economy of production, and he achieves this without employing any chemical additives.

—Carol Shaffer Cleary

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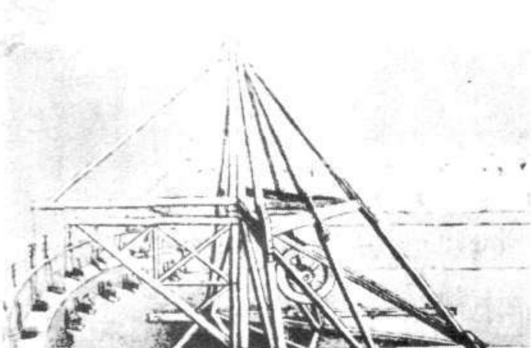

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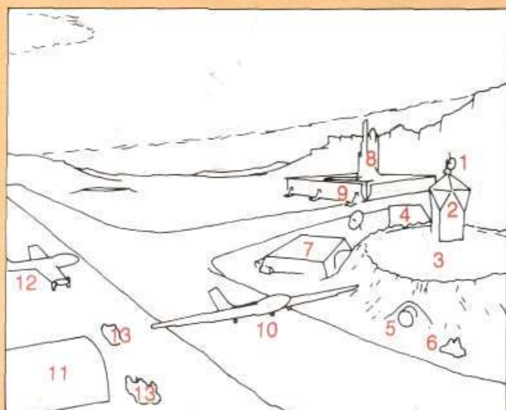
Moving Man Into the Cosmos

Man has long dreamed of making our nearest planetary neighbor habitable. As the cover story by Marsha Freeman makes clear, colonizing Mars is a question of political will. Since the 1940s, space scientists have discussed detailed plans for how to get there and what to do there. Today we can draw on this knowledge to develop the technologies to get the job done in the next few years.



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