Here is the Preface and Prologue to the book *Fire From Ice: Searching for the Truth Behind the Cold Fusion Furor* by Eugene F. Mallove, a reprint of 1991 Edition, 338 pp., Paperback. It is availble from Infinite Energy Press, P.O. box 2816, Concord, NH 03302-2816, www.infinite-energy.com

Preface

> It is really quite amazing by what margins competent but conservative scientists and engineers can miss the mark, when they start with the preconceived idea that what they are investigating is impossible. When this happens, the most well-informed men become blinded by their prejudices and are unable to see what lies directly ahead of them.
>
> Arthur C. Clarke, *Profiles of the Future,* 1963

> The discovery of fission has an uncommonly complicated history; many errors beset it.... Above all, it seems to me that the human mind sees only what it expects.
>
> Emilio G. Segre
> "The Discovery of Nuclear Fission," December 1988

> The energy produced by the breaking down of the atom is a very poor kind of thing. Anyone who expects a source of power from the transformations of these atoms is talking moonshine.
>
> Physicist Ernest Rutherford, about 1930

SKEPTICS HAVE WRITTEN A HUNDRED OBITUARIES for cold fusion, the unprecedented "miracle or mistake" that burst out of Utah into the public arena on March 23, 1989, but despite many unanswered questions about what "cold fusion" is or is not, evidence for the phenomenon (or phenomena) is now much too compelling to dismiss. Some would call the scientific clues only provocative. I choose to say *compelling.*

With an electric power supply hooked up to palladium and platinum electrodes dipped in a jar of heavy water spiked with a special lithium salt, chemists Martin Fleischmann and B. Stanley Pons were thought to have unleashed one of the wildest goose chases in the history of science. Now there is a significant possibility that they have discovered a quite revolutionary phenomenon that—along with hot fusion— could conceivably turn the world's oceans into bottomless fuel tanks.

Cold fusion is very likely to be real after all, although which aspects of it are valid remains in question. Despite many roadblocks that arose against confirming it as a new physical phenomenon, it is now here to stay. For a time, negative experiments and widespread skepticism seemed to have put cold fusion permanently on ice. Incredulity still runs deep. But cold fusion research is now very much alive in laboratories far and wide. It moves forward through those scientists with intense curiosity and courage to pursue these studies in the face of mountains of ridicule.

It is now reasonably clear that fusion reactions that liberate energy—near but very peculiar relatives of nuclear processes that are the lifeblood of the stars—can occur at room temperature. There is *no chance* whatever that cold fusion is *a mistake. There is the exceedingly remote possibility that "cold fusion" is a collection of many mistakes made in nuclear measurements of many different kinds, in heat measurements of great variety, and in all manner of control experiments. But to believe that hundreds of scientists around the world have made scores of systematic mistakes about the nuclear and nuclear-seeming anomalies that they have reported is to stretch credulity to the breaking point—to distort the meaning of scientific evidence to absurd limits. Cold fusion is not "pathological science" as many have charged, but for critics to continue to describe it as such or to ignore it completely is pathological.*

Current evidence suggests that *nuclear* processes are actually at work in what at first seemed to be merely table-top *chemical* experiments. This is absolutely shocking, and the root of widespread disbelief in cold fusion among scientists. There has been no more iron-clad principle separating chemistry from physics than that chemical behavior *never* leads to nuclear transformations. The tiny atomic nucleus has been inviolate to assault, but now it has been breached by the puffy electron cloud world of chemistry. You see, if the tiny, dense nucleus of an atom were blown up to the size of a golf ball, at that scale its attending fuzzy little electrons would orbit a mile away. Chemistry has only to do with how these distant electrons interact to make connections and disconnections among atoms. Atomic nuclei never become directly involved in chemical reactions and nuclei had not been known to react with one another except in extreme high-energy conditions.

Though the occurrence of cold fusion phenomena at present is erratic, it might some day be tamed and made regular and useful. Many experimenters are finding specific conditions, not reported initially by Drs. Fleischmann and Pons (perhaps not even known to them at the time), that prompt the effects. Furthermore, cold fusion phenomena are now seen in very dissimilar but related physical systems: pressurized gas cells, electrochemical cells with molten metal salts, and metal chips and films alloyed with fusion fuel.

To an extent, the phenomena remain not repeatable *at will*—but repeatable, to be sure, in a *statistical* sense, and sometimes now with very high confidence. (The same has been true in the early development of certain solid-state electronic devices.) There is now convincing evidence for the observation of significant heat *in excess of energy fed in,* bursts of neutrons, radioactive tritium at concentrations elevated above natural background (despite fears of preexisting contamination, there is ample evidence that the tritium is generated by nuclear reactions), possible abundance shifts in some chemical isotopes, and much more. And in a *piece de resistance* of cold fusion research, in October 1990 scientists in several laboratories confirmed the nuclear *creation* of high-energy nuclei—probably those of tritium atoms—that fly out from titanium chips infused with the well-known fusion fuel, deuterium.

The measurements of power in the form of heat coming from some cold fusion cells is extraordinarily impressive—tens, to over a thousand, times the energy that could emerge from any conceivable chemical reaction. If the numbers from some experiments are to be believed, they add up to tens and even hundreds of kilowatt-hours coming from each cubic centimeter of cold fusion cell electrode material (about the volume of a stack of two pennies)! You know what a kilowatt-hour of electricity is when you pay for ten 100-watt bulbs turned on for one hour. More vividly, a kilowatt-hour is the energy of motion in a 4,000-pound car traveling 140 miles per hour.

Furthermore and most important, there is now a theoretical basis to begin to understand these apparent cold fusion phenomena. The heat-generating nuclear process must be very exotic, indeed, somehow being able to distribute released nuclear energy over a large array of atoms rather than emitting it as discrete high-energy particles.

Soon after the startling announcement at two universities in Utah in March 1989, the idea for this book was born. This might have been a very different work—a chronicle of the birth of a new age of cheap, clean, and limitless power. Though that era may still arrive through some form of controlled fusion—including the very real prospect of *controlled cold fusion,* the story turned out to be far more interesting, in both its scientific aspects as well as in the *process* of science that triumphed in identifying cold fusion as something literally new under the sun.

We have, instead, the saga of the tumultuous birth of a new physical phenomenon—more exactly, a class of scientific phenomena—an origin beset by bouts of optimism, pessimism, and every emotion in between for both proponents of the new wonder and those who vehemently deny its possibility—respected and well-intentioned scientists all. There occurred a veritable scientific roller-coaster ride that has held the scientific world in sway for almost two years. Now that many more facts are available and the furor has quieted down, the story can be told in its delicious and delirious detail. This is an account of the unfolding of a new phenomenon—the scientific process observed.

Through a sometimes tortured, contentious process the truth ultimately triumphs in science. Thus is scientific research done in the real world, not by idealized textbook prescriptions. Science is not conducted by poll nor by appeal to authority, nor always shackled to an imperfect and occasionally obstructive peer review process. Science proceeds through dogged experimental and theoretical effort.

At the beginning of the cold fusion saga, it was my good fortune to be working at the Massachusetts Institute of Technology. I was trained as an engineer, both in aerospace and environmental engineering at MIT and at Harvard, but after having done engineering for some 15 years, writing about science and technology became first an avocation and later a job.

As the chief science writer at the MIT News Office during the period when the cold fusion controversy arose, I found myself at a crossroads of scientific inquiry and intrigue. I heard from all sides in the scientific turmoil that broke loose and had the opportunity to witness firsthand how scientific news was being made. I, too, swang from skepticism to belief, back to skepticism, many times. At the outset, cold fusion seemed both too preposterous to believe and too important to ignore. The urge to chronicle this fascinating chapter in scientific history became irresistible. I have tried to be as faithful as possible in chronicling the complex events in the cold fusion saga and in illuminating difficult experiments and theory. *The opinions and perspective on the cold fusion controversy are entirely my own, however, and are absolutely not intended to represent any official or unofficial university position.*

We will explore the scientific intrigue and infighting that occurred in the cold fusion revolution, which provided much human drama. There were fights to publish and to forestall publication, issues of priority of discovery, funding matters, misinformation and disinformation, rumors that became "fact," questions of academic standing, and even allegations of scientific deceit. The hard lessons in science learned in the quest for cold fusion will depend on the ultimate resolution of the scientific questions, but whatever the outcome, some are already clear:

*Spectacular resistance to paradigm shifts in science are alive and well. Plasma fusion physicists were extremely reluctant to consider new fusion mechanisms even though they knew very well that the environments of electrochemical cells and palladium metal atomic lattices were remarkably different from the high-temperature gaseous systems to which they were accustomed.

*The majority does not rule in science. It is a gross mistake to draw conclusions about the validity of reported findings by polling the membership of this or the other scientific organization or panel.

*It is dangerous and often deceptive to make analogies between one scientific controversy and another. Comparing the cold fusion episode with several notable blind alleys in science—the "polywater" episode of the 1960s-70s, or the early 20th-century "N-rays"—is counterproductive and wrong. I acknowledge, however, that it may also be hazardous to compare the cold fusion debate to heated episodes in science that *did* result in a well-established discovery.

*Irving Langmoir's rules for identifying so-called "pathological science" are best retired to the junk heap for prejudice and name calling.

*Ockham's Razor is too easily forgotten. In science, the simplest unifying theory or connection is often most appropriate. Better to have a single explanation to bridge a host of apparently related phenomena, than to concoct baroque excuses for why multiple independent experiments may *all* be systematically incorrect. Any possible nuclear effect, even a tiny suspected one, such as low levels of neutron particle emissions seemingly unconnected with heat production, should have been a tip-off that other puzzling and erratic effects in similar physical systems might also have something to do with nuclear phenomena.

*Use extreme caution in dismissing experimental results just because theory suggests they are "impossible." Theory must guide science, but it should not be allowed to be in the driver's seat—especially when exploring the frontier.

*The fear that possible scientific error would be ridiculed, or worse, interpreted as fraud, is stultifying. A witch hunt against cold fusion affected researchers: Some who wanted to work in the field did not get involved for fear of scorn; others hid positive results from colleagues, anticipating career problems; and some laboratory managers refused to allow technical papers to be published on positive results obtained in their organizations. Most incredible, some scientists publicly decried cold fusion, while privately supporting its research.

*The peer review process by which articles make their way into journals is not infallible. While peer review is meant to act as a filter against spurious results and sloppy science, mismanaged or unchecked it can be a tyrannical obstacle to progress as well. It is unwise to be persuaded by the editorial position and selection of technical articles that appear in a single well-respected publication.

*Vested scientific interests are not easily persuaded to share their resources. Too small a total funding pie, in this case limited federal expenditures for energy research, led naturally to rivalry and antiscientific tendencies that would have moderated with a policy of broader research support. The hot fusion fraternity, like any scientific community with its back to the wall, may find it difficult to draw impartial conclusions about a perceived threat to its dominance.

Above all, I wanted to distinguish between the real, initial scientific shortcomings of Drs. Fleischmann and Pons' work (including their initial incomplete disclosure of relevant experimental protocols) and their fully justified bewilderment in the face of a phenomenon for which they had no satisfactory explanation (other than a firm belief that the evidence pointed to it being nuclear). This required raising numerous questions about the *process* of science and communicating scientific developments to the public.

This may shock the uninitiated or misinformed, but when the science finally works its way to more firm conclusions, it is my view that Fleischmann and Pons, Brigham Young University's Steven E. Jones with his reports of neutrons, and other early cold fusion pioneers may be regarded in the history of science as heroes—very human, imperfect ones. Fleischmann and Pons' most serious failing, which ultimately sandbagged the whole subsequent scientific process, was to suggest initially that their experiment was very easy to reproduce, and that scaling it up to practical, power-producing devices would not be especially difficult. In some sense the Fleischmann-Pons experiment *was* relatively easy to reproduce, but it proved *far* from simple to interpret or to augment. Ironically, Steven Jones is to be faulted for consistently *denying* that electrochemical cells could be producing excess heat from nuclear reactions—an opinion arising from his stubborn disbelief and desire to protect the priority of *his* discovery, not from the results of his own experiments or deep analysis of the thermal measurements made by others.

Yet all three protagonists took their incomplete preliminary findings to the scientific community and kicked it into unprecedented and rapid global action. A U.S. Department of Energy report estimated that initially between $30 and $40 million dollars were spent worldwide on cold fusion research. That estimate is now woefully low, as the pace of research quickens. A recent compilation of reports of only *positive* evidence for cold fusion, which have come from more than 80 research groups in a dozen nations and at five U.S. national laboratories, gives some idea of the scope and seriousness of the activity (see pages 246-248 in Chapter 15).

The cold fusion story cannot be understood without grasping the parallel effort to develop controlled *hot* fusion, one of the most noble and difficult technological quests ever undertaken, now in its fifth decade. Without rehashing the extraordinary history of hot fusion research—a fascinating saga in its own right—included is sufficient background to put cold fusion in proper perspective.

An essential caveat: After reviewing mounting evidence from cold fusion experiments, I am persuaded that it provides a *compelling* indication that a new kind of nuclear process is at work. I would say that the evidence is *overwhelmingly* compelling that cold fusion is a real, new nuclear process capable of significant excess power generation. The evidence for significant power generation, however, cannot be said to be *conclusive.* The word conclusive in science denotes an intimate melding of experimental observation and theoretical explanation. In the case of cold fusion, this cannot be said to have occurred. There is yet no *proved* nuclear explanation for the excess heat. That excess heat *exists* is amply proved.

Teasing a new phenomenon from nature is not easy. Simply review the history of the discovery of fission in the 1930s—the phenomenon was staring physicists in the face, yet fission was slow to be recognized. Or recall superconductivity, which a Dutch physicist stumbled across in 1911, but for which no good theory existed until the 1950s. High-temperature superconductivity, which exploded into the world of physics in 1986-87, is still incompletely understood. Or recall the "cat's whisker" or crystal radio of the 1920s, which wasn't understood until the transistor was invented three decades later. But for ignorance and skepticism, we might have had transistor radios in the 1920s! Or take the totally unexpected phenomenon of lasing, both at optical frequencies (lasers) and at microwave frequencies (masers), and more recently at X-ray wavelengths. Radio waves themselves, predicted in the 1860s and discovered in the 1880s, were another totally unexpected manifestation of matter and energy. Why not "cold fusion?" Nature has marvelous tricks up her sleeves, and it is the delight of the scientist to discover them. Let us see how the power of the stars is coming down to Earth.

Bow, New Hampshire

Acknowledgments

IF AN IDEA HAS A THOUSAND PARENTS, a book may have at least a few hundred. *Fire from Ice* would not have been without the dedicated work of the hundreds of researchers who probed and who continue to investigate cold fusion phenomena, and without the efforts of thousands who strive to tame hot fusion. Proponent and skeptical views alike were the two streams that blended and fused in this work.

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1. Prologue: Desperately Seeking Fusion

Water, water, everywhere,
Nor any drop to drink.

Samuel Taylor Coleridge, *The Rime of the Ancient Mariner*

Anything that is theoretically possible will be achieved in practice, no matter what the technical difficulties, if it is desired greatly enough.

Arthur C. Clarke, *Profiles of the Future,* 1963

*A Genie Shrugs

THE SNOW-COVERED WASATCH MOUNTAINS, so beautiful and unreal in late March, glistened against the intense blue of the skies above Salt Lake City. Spring skiers sported within those hills, unaware of news that was soon to come from the city below and oblivious to an approaching intruder above, in deep space.

For those—superstitious or not—who like to connect life on this world with celestial events, an auspicious or portentous happening: At about 8 hours Universal Time on March 22, 1989, multimillion ton asteroid 1989FC whizzed by Earth and its Moon, coming within 430,000 miles of our world. It made the closest known pass by a body of such mass since Hermes in 1937—the year before the discovery of nuclear fission.

As the asteroid continued on its path traveling many miles per second, the world turned not even once on its axis. The next day, Thursday, March 23, 1989, brought a glimmer of hope from a city that had grown up near the barren flatlands of the Great Salt Lake in Utah. At 1:OO P.M. in Salt Lake City, chemists Martin Fleischmann and B. Stanley Pons burned their names into the history of the quest for fusion power. Essentially unknown to the hot fusion community, they claimed to have achieved what seemed to be impossible: power-producing fusion reactions at room temperature.

Hours later, a gargantuan tanker left the port of Valdez, Alaska, en route with oil for an energy hungry world. At four minutes past midnight, March 24, the Exxon Valdez ran aground and spilled 11 million gallons of crude oil into the pristine waters of Prince William Sound. The disaster symbolized the ultimate futility of our dangerous dependence on the planet's subterranean fossil fuels.

The massive oil spill drew deserved national attention and outcry, but it did not eclipse the extraordinary news from Utah about "cold fusion"—a concept that seemed to drop from the sky like an alien intruder straight into the public psyche. At the press conference held at the University of Utah, B. Stanley Pons, professor of chemistry and chairman of the Department of Chemistry at the University of

Utah, and colleague Martin Fleischmann, professor of electrochemistry at the University of Southampton, England, proclaimed that they had discovered an amazingly simple method to create power-producing nuclear reactions—possibly fusion—not at hundreds of millions of degrees in imitation of the stars, but at room temperature!

The Genie of fusion shrugged in his ancient vessel that year and amazed the world. The spring of 1989 will long be remembered as a time of unexpected shaking, when extraordinary claims by groups of researchers in Utah and subsequently around the world led scientists to reexamine a decades-long pursuit: the quest to tame nuclear fusion. The struggle has been to bring this power of the stars down to Earth, much as fabled Prometheus snatched fire from the gods. The interest of the scientific community and the public at large was temporarily galvanized by the idea that a new kind of fusion process, immediately dubbed *cold fusion,* might soon lead to a way to get the fusion Genie to stop shrugging and come completely out of his bottle.

Startling events occasionally make us step back to get a better view of our pursuits and to examine cherished assumptions. This often leads to rededication, to unforeseen possibilities, and to new directions. The shaking of complacency now and then in a positive way is healthy, no more so than in the fields of science and technology where intense concentration on an established course sometimes promotes a possibly too narrow focus.

We now know that confirmation or rejection of the remarkable cold fusion claims of 1989 were not to come easily and that unusual doubt and confusion (inevitably termed "fusion confusion") beset a baffled, bemused, and even outraged scientific community. Estimates are that, for a time, more than one million dollars per day—in person-hours and equipment—was expended worldwide to confirm or disprove the claims that nuclear fusion reactions can occur in apparatus no more complex than a laboratory electrochemical cell, or in pieces of metal infused under pressure with a heavy version of hydrogen, the isotope deuterium.

At a bare minimum, it now appears very likely that a wholly unexpected scientific phenomenon has been discovered. If it really is a new mode of fusion, it occurs, quite surprisingly, at room temperature. Moreover, the phenomenon appears to be capable of net power generation, but whether what seems to be an erratic, difficult-to-reproduce process can be tamed for practical applications remains an open and extremely intriguing question.

While the jury is still out on the significance of these developments, there can be little doubt that the larger effort to tame fusion for human needs has received an unexpected and perhaps much needed boost. The public imagination and interest in fusion power has stirred in a way that has never before happened in the relatively unknown quest. The nations of the world have spent billions of dollars to control thermonuclear (hot) fusion in gaslike plasmas whose temperatures sometimes reach several 100 million degrees centigrade, but the average citizen has heard little about the dramatic progress in recent years in this exceedingly difficult scientific and technological effort.

The new developments on the frontiers of fusion research come at a critical juncture in the U.S. and international efforts to control this potentially limitless and extremely benign source of energy. A large and complex laboratory machine, the Joint European Torus (the so-called JET tokamak in England) has just now reached, in effect, the long-sought energy *breakeven* point in "conventional" high-temperature fusion experiments: achieving about as much energy output as input. A few more years and self-sustaining, so-called *ignited,* fusion experiments are destined to produce significant net power, but in a form still not suitable for practical and extended power generation. For hot fusion, the goal of reaching engineering and commercial feasibility lies two or more decades ahead.

To fully understand the implications of cold fusion, it is essential to put fusion power in the widest possible context, and to tell how it may eventually dramatically affect human affairs. The fossil fuel era is nearing an end. No matter what conservation steps are taken, the world's reserves of coal, oil, and natural gas are clearly running down. They will be severely depleted within a single century and will have vanished completely within a few hundred years, if we keep using them intensively. Moreover, the local and global environmental consequences of running full-tilt at power generation with fossil fuels may perhaps be as ominous, if not *more* frightening, than simply running out of power. Whether or not there will be significant global warming as a result of carbon dioxide and other "greenhouse" gas emissions is not the issue. To continue dumping the other noxious end products of combustion into the environment is simply *stupid* given existing and emerging alternatives.

Fusion power offers the prospect of energy abundance over times comparable to geological ages, in contrast to the microscopic blip in human history of reliance on fossil fuel.

If we expect our descendants to live virtually indefinitely on this planet—until perhaps our Sun, our fusion reactor in the sky, "dies" some five billion years hence—we had better plan now to possess a source of inexhaustible power. What will that be? Possibly a source of solar power captured by vast solar cell arrays in space and beamed back to Earth's surface as microwaves, solar power collected by large arrays deployed in desolate areas, or a new kind of nuclear fission power perhaps, a modification of present nuclear reactor technology that may allay even passionately antinuclear fears? This kind of passively safe nuclear reactor, which can be shown to release no radioactivity to the environment even when its coolant is lost, has already been built and is practical.* (*Professor Lawrence M. Lidsky, MIT: "Safe Nuclear Power," *The New Republic* December 28, 1987: 2~23; "Nuclear Power: Levels of Safety," *Radiation Research, Vol.* 113, 1988: 217-226.) A new generation of safer fission power plants merely awaits the economic and political wherewithal.

Despite public fears about present-day fission power reactors, they have by *far* the best track records in safety of virtually all means of generating electricity (remember, even hydroelectric dams break and kill), and with their high-level radioactive wastes safely disposed in subterranean chambers—as must begin to be done in the coming decades—fission reactors are infinitely more benign to the environment than fossil fuel power. But while fission power may take us very far into the future—some hundreds or several thousands of years, depending on how fuel sources hold up—even fission has a demonstrably limited future. Fusion is an energy resource that is *virtually infinite.*

***Fusion Is Forever**

We inhabit a water planet. Though relatively speaking it is less than eggshell-thin, a layer of water covers more than 70 percent of the world's surface. If we could use a tiny fraction of the millions of cubic kilometers of water for fuel to produce power for an energy-hungry globe, it would be infinitely better than achieving the alchemist's goal of turning base metals into gold. One way or another, the vision of harnessing the world's oceans to that end will come true. In researchers the world over, the dream of wrenching fire from ice is alive: fusion power, the fire of stars, taken from icy water.

The clever Prometheus of Greek legend merely stole fire from Zeus, the chief deity, and returned it to humankind. More audacious, fusion scientists have been struggling for four decades—roughly since the birth of the idea of fusion bombs—to steal the fire of stars from ordinary water. Because water is so cold (on a relative scale being but a few hundred degrees above the absolute zero of temperature) taming fusion aims almost literally at teasing fire from ice.

Enough fusion fuel exists on Earth to keep billions of people going effectively forever. It is frozen fire that has existed since the birth of time. When realized, the vision of controlled fusion power will allow us to release energy from deuterium, a special form of hydrogen ("heavy" hydrogen) that exists in a small but potent amount in every drop of water in nature. About one hydrogen atom in every 6,700 on Earth is a hydrogen isotope, deuterium (often written, D). That is, deuterium is hydrogen because it has one proton in its tiny, dense nucleus, but deuterium also has a neutron accompanying the usual single proton, making it about twice as heavy as H—ordinary hydrogen (a neutron is only very slightly heavier than a proton). Every water molecule, H_2O, contains one oxygen atom and two hydrogen atoms.

When you look out a window on a rainy day, you are watching fusion fuel falling from the sky. The tiny amount of deuterium in every gallon of ordinary water, about 1/250th of an ounce—not nearly enough to fill a baby's spoon if it were liquid -- contains potential fusion energy equivalent to the chemical combustion of 300 gallons of gasoline. A comparison of fusion, fission, and fossil fuel required for a typical power plant is in order: A typical electric power plant of 1,000 megawatt (MWW) capacity—meaning one thousand million watts—requires about twenty thousand railcars of coal *per year*—a procession carrying some two million tons and stretching about 400 kilometers! The oil energy equivalent of this is some ten million barrels of crude oil—seven supertankers worth. The nuclear fission fuel equivalent of this horrendous pile of coal or lake of oil comprises a mere 150 tons of raw uranium oxide— a volume easily carried by about eight tractor trailers. But a single pickup truck could carry the 0.6 ton of heavy water (D_2O) necessary to fuel an equivalent 1,000 MW fusion power plant for one year!

There is obviously more than enough fusion fuel to go around, but before we can use it, we have a lot to learn.

***The Fusion Universe**

Look up in the sky on a dark night and you will see thousands of bright fusion reactors—the stars. The Sun is the fusion reactor that keeps us alive. If plants were to die for lack of fusion-produced starlight, the animal kingdom would soon follow into oblivion. We can say with confidence that every life-form on Earth—energized as it is by sunlight— is an embodiment of fusion power.

We owe this to the violent collision of the nuclei of hydrogen atoms at the cores of stars where temperatures are reckoned in tens of millions of degrees. These collisions of hydrogen nuclei, simple single protons stripped of their ordinarily attending electrons, promote fusion reactions—the buildup of heavier nuclei from lighter ones. This results in a stupendous release of energy and an "ash" or reaction end product, the nuclei of the next heaviest element, helium—the kind of atom that buzzes within a child's balloon.

A star's fusion reactions produce the necessary temperature and gaseous pressure to counter the tendency of the star to collapse from its own self-gravitation, that is, from under its own weight. But gravity keeps the fusion fuel in a star cooking and contained. For decades, hot fusion researchers on Earth have tried to mimic the Sun by using intense magnetic fields to contain fusion reactions in gaslike *plasmas* at scores of millions of degrees, and more recently by aiming intense laser beams at solid fusion fuel pellets to turn them briefly into glowing plasmas— in effect, miniature stars.

Plasmas are omnipresent in the universe. The visible universe is more than 99 percent plasma: the hot interiors of stars themselves; glowing reaches of material between the stars about to give birth to other stars or luminous from the intense radiation of stars of advanced age; lightning itself; the minute sparks jumping off one's finger after walking on a rug on a cold, dry day; the eerie, glowing auroral displays (Northern Lights); and plasmas within glowing fluorescent light bulbs or neon lights. The word plasma was coined in the 1920s by American physicist Irving Langmuir, who made a metaphoric comparison between the multicomponent blood plasma that carries red blood cells and the species of charged particles in the hot plasmas with which he was working.

Plasmas are gases in which temperatures are so high that negatively charged electrons have been stripped off of atomic nuclei to one degree or another and are swimming within a "soup" of positively charged particles. The overall charge of a plasma is typically zero, but it is a good conductor of electricity, because, like a metal, lots of electrons may roam freely.

Plasmas exhibit some of the most complex, dynamical behavior in nature, because their charged components respond to the forces from electrical and magnetic fields and these motions, in turn, set up their own fields. Not solids, liquids, or gases, high-temperature plasmas constitute a veritable fourth state of matter, the most common one in the cosmos. Rocky planets and moons with their ice, liquid oceans, and gaseous atmospheres are the exception rather than the rule in the plasma universe.

When the universe was born some 15 billion years ago in the titanic Big Bang explosion at the beginning of space and time, by the end of the first three minutes a high-temperature maelstrom of quarks (the fundamental constituents of protons and neutrons) and other subnuclear particles had cooked up a mixture of about 75 percent hydrogen nuclei (protons) and 25 percent helium nuclei (each with two protons and two neutrons), plus some other trace elements.* (*Percentages by mass not number of atoms.) Yes, the visible universe consists mostly of fusion fuel and helium ash. Perhaps even more fantastic: All the heavier elements that go into building our planet and our bodies, such atoms as carbon, oxygen, nitrogen, iron, silicon, not to mention more exotic ones such as palladium, platinum, or uranium, were once inside distant stars that exploded billions of years ago. That fusion is central to the scheme of the universe is a striking cosmic fact.

No matter that the kinds of fusion reactions within the Sun and other stars are of a different variety than we might expect to use in a human-engineered reactor. It will probably be much too difficult to fuse protons at high temperature, so hot fusion scientists have sought to fuse together deuterium nuclei and one even heavier hydrogen nucleus *tritium* (containing one proton and *two* neutrons) in various combinations.

The absolute zero of temperature is mighty cold: about—460•F (Fahrenheit) or —270•C (Celsius). In most substances, atoms jiggle barely at all near that frigid temperature. At higher temperatures, atoms and molecules move around faster, bumping into one another, their average speed depending on the temperature. Temperature, in fact, is a measure of the average velocity and energy of moving atoms or molecules. Indeed, temperature seems to be central to the occurrence of fusion reactions in nature. This is true because the relative velocity between atoms or their nuclei is one means by which the nuclear ingredients of fusion reactions can be made to overcome the extreme electrical repulsion forces between positive charges that normally keep them apart. That is why it is so difficult to fuse the bare protons of two ordinary hydrogen nuclei.

> It is by far more convenient to use the Kelvin (K) scale of temperature, rather than Fahrenheit (•F) or Celsius (•C). There are no "below zero" temperatures on the Kelvin scale, because temperature is reckoned from 0 K, absolute zero, where minimal atomic or molecular motion is occurring. When we are talking about millions of degrees, as is often done in fusion research, the Kelvin temperature is virtually identical to the Celsius

temperature, since a Kelvin and a Celsius degree are of the same size (measure of temperature rise) and the zero temperature for Celsius (0•C, the freezing point of water under normal conditions) begins only 273•C above absolute zero—a small number compared to millions of degrees. (Unlike for •C temperatures, it is customary not to indicate a degree sign "•" before the K.)

***Star or Planet?**

It is not *strictly* true that without the fusion reactions of the Sun, the temperature of our planet would approach that of deep space—about 3 K. When the rocky Earth and the other planets formed some 4.5 billion years ago from a cloud of primordial debris that was enriched with the heavier elements of exploded stars, radioactive atoms were mixed into the recipe for the planets. The nuclei of these atoms are so unstable that they disintegrate and emit radiation spontaneously, radiation that can slowly but surely heat the body of a planet. The heat flow coming from the interior of Earth is thousands of times less than the power of radiation from the Sun that strikes the planet.* (*Still, it is interesting that upward through a square of continental surface about 130 feet on edge passes enough heat to power a 100 watt electric light bulb (if the heat were convertible to electricity with 100% efficiency). No one has ever tried to harness this weak flow of energy from radioactivity, except in those rare places where geological formations— hot springs, geysers, and the like—bring greater heat flow to the surface.)

Now these nuclear processes that contribute to heating Earth's interior are, of course, not fusion reactions. They are simple radioactive decays of one heavy element such as thorium or uranium into lighter elements—ultimately to such stable forms as the element lead. For the most part, these nuclear processes are not even *fissions,* in which atomic nuclei split into two roughly equal fragments, although a small amount of natural fissioning does occur. The recent interest in cold fusion, however, has prompted wild speculation that low levels of natural *fusion* reactions may be occurring deep within the Earth.

So basic a question as, "What is the difference between a star and a planet?", has to do with whether copious fusion reactions either are occurring or ever did happen within an astronomical body. Tiny Earth, Mercury, Venus, Mars, and Pluto are obviously planets. They certainly aren't massive enough to have any abundant "conventional" fusion reactions going on within their cores, nor do they have hydrogen fusion fuel in their central regions. But what about the Solar System's gas giants, Jupiter, Saturn, Uranus, and Neptune? Could these planets more properly be termed *failed* or *borderline* stars?

Certainly Jupiter and its sister giant planets may make at least a remote claim to being stars. Astronomers have measured the electromagnetic radiation coming from Jupiter—both visible light and infrared radiation—and find that more energy is coming out than is going in. Some have speculated that this excess radiation is coming from weak fusion reactions going on within Jupiter. If this were true, we would have hot fusion reactions in stars and cold fusion reactions in planets—from fire to ice, as it were.

However, to be a true star that generates significant energy of its own, astronomers believe that an aggregation of hydrogen and helium, self-contracting from the force of gravity, must have a mass of about 80 times that of Jupiter. This is still much less matter than exists in our own Sun. Jupiter, with 300 times the mass of Earth, has but one-thousandth the mass of the Sun, so to be a star, a body should be no less massive than about 8 percent of the Sun. There has been much interest in the search for these low mass stars that have been dubbed brown dwarfs, because of their presumed very low surface temperatures. In recent years, evidence (albeit not yet conclusive) has accumulated that brown dwarfs with relatively weak fusion reactions in their cores exist, both as companions orbiting other suns and perhaps as independent objects coasting freely through space.

It is important to realize that despite the multimillion degree temperature and high density of the Sun's core, it is still far too cool for the kinds of fusion reactions that scientists have been trying to produce in laboratory hot fusion reactors. (Newspaper articles often say that hot fusion scientists are trying to "tame the power of the stars," unfortunately giving the misleading impression that they are planning to use those very same fusion reactions. They are not.) The temperatures that scientists are seeking are 100 million K and beyond. What is more, energy production in the solar core is actually very weak—only a few watts per ton of "starstuff." The bodily heat output of a resting human being, coming from chemical reactions of course, is by far more impressive! The solar core's great size and mass explain how the total output of the Sun can be so stupendous—4×10^{26} watts. The energy released in *one second* by the Sun could keep our civilization going at its present rate of energy consumption for more than a million years; collecting that power radiated in every direction by the Sun would be another matter.

***What Is Fusion?**

The idea behind fusion is really very simple. Two light-weight* *(*Mass is* the more general and accepted terminology that physicists use, because, technically, *weight* depends on location (an object weighs less on the Moon than on the Earth), whereas the quantity known as *mass* does not.) nuclei come together and stick to one another or *fuse,* forming a nucleus of greater weight than either of the two reactant nuclei. In creating the new nucleus, this fusion process may also include the ejection of one or more subnuclear particles such as a positive electrically charged proton or a chargeless neutron, or other kinds of particles. But the key phenomenon in fusion—its *defining characteristic*—is the formation of a more massive nucleus and the release of energy in a number of forms, whether in the velocity of particles such as neutrons or protons, in penetrating powerful radiations called *gamma rays* (like X rays, only much more energetic), or in other mechanisms that some have hypothesized for cold fusion. The resulting mass of the newly fused nucleus is less than the combined mass of the nuclei that formed it—a tiny amount of mass disappears during fusion and is converted to energy.

The energy release in fusion comes from the conversion of matter to energy by an amount given by Albert Einstein's formula from his 1905 theory of special relativity, $E=mc^2$; that is, the energy release is equal to the mass that is converted multiplied by the speed of light squared. (Light speed must be in units consistent with the mass, such as meters-per-second if mass is in kilograms; then E would come out as *watt-seconds, a unit like kilowatt-hours* that you notice in despair each month on your electric utility bill.)

What form of matter is disappearing in a fusion reaction is far less obvious, but disappearing it surely is. To cite one astonishing example: Every second some four-million metric tons of mass disappear within the Sun's fusion reactor, being converted to energy that eventually emerges at the star's surface! Yet so massive is the Sun that this destruction of mass can occur for billions of years and still less than one ten thousandth of its original mass will have vanished. We too easily forget, but this is what is so remarkable about any kind of nuclear power: The conversion of a minute fraction of the mass of fuel can liberate staggering amounts of energy, all because of $E=mc^2$.

The energy requirement *per proton or neutron* to bind an atomic nucleus together for a long time *generally* becomes *less* in the case of larger nuclei (up to the mass of about iron, which typically has 26 protons and 30 neutrons). This is the so-called *binding energy* of a nucleus. When two light nuclei fuse to form a more massive nucleus, adding up the masses of the resulting nucleus and any particles such as neutrons that may fly off in the process, gives a total final mass that is *less than that of the original two nuclei added together.* This mass deficit or loss is what has been converted to the energy of particles and radiations that emerge from the fusion reaction. Fusion reactions, just like fission reactions, *must* involve the loss of mass and its conversion to various forms of energy such as heat and radiation.* (*For our purposes, it really isn't important to understand exactly why *less* energy per constituent *nucleon*—neutron or proton—should be required to hold this more massive nucleus together by what are called *nuclearSorces.* Understand, however, that there is a natural tendency for positively electrically charged protons to repel one another, and it is only the presence of charg,eless neutrons along with the attractive nuclear forces that "glue" a nucleus together.)

There are many, many kinds of fusion reactions that can occur among light elements, but the following one, for example, is of concern in the engineering of hot fusion reactors because it illustrates how deuterium can be used as fuel (the → means simply goes to or becomes):

$$D + D \rightarrow {}^{3}He \text{ [at 0.82 MeV energy]} + n \text{ [at 2.45 MeV energy]} \qquad (1)$$

Deuterium plus Deuterium (Goes to) Helium-3 plus a neutron

We will have more to say about such reactions in discussing the different technologies that scientists have considered to tame fusion, but it is instructive to understand how to interpret these simple symbolic equations. Don't let them scare you—they are really quite easy and you certainly *don't have to memorize them!* Reaction (1) suggests that two *deuterons* (deuterium nuclei, designated D, just as ordinary hydrogen has its own symbol, H) can combine to form the nucleus of helium-3 (designated ^{3}He) plus a neutron (n). By definition, the element helium has two protons in its nucleus (the number of protons always defines what the element is), and the added neutron gives a total nucleon count (protons plus neutrons) of three, hence the superscript 3. Helium-3, extremely rare in nature (though prevalent on the surface of the Moon, having been transported there by the solar wind), is a variant or an isotope of the ordinary kind of helium, helium-4 or ^{4}He, which has two protons and two neutrons in its nucleus.

For the nuclear "bookkeeping" in such equations to be correct, the number of individual particles or nucleons (protons or neutrons) on the left side of the equation must equal the number of nucleons on the right side. (Example: Together the two deuterons on the left in reaction (1) comprise four nucleons; on the right, ^{3}He plus the neutron, n, comprise 3 + 1 or four nucleons. Thus, the equation balances.) The numbers in brackets near each reaction product tell how much energy of motion *(kinetic energy)* is vested in that particle or nucleus after the reaction occurs and energy is liberated. This is the energy that typically may be used in some kind of conversion process toward useful power generation. The numbers represent how many *"MeV"* or *"millions of electron volts"* of energy are in the motion of that particle or nucleus.

An *electron volt is* a very tiny amount of energy. Millions of electron volts are still a small amount of energy (one MeV is about the energy needed to lift up a speck of dust weighing a millionth of a gram a distance of about one-millionth of a meter), but when many reactions are occurring simultaneously among trillions of like particles, the energy adds up! One electron volt is the energy that a tiny electron (with only l/1836th the mass of a proton) picks up when it is accelerated by one volt—about the voltage difference between the two ends of a flashlight battery. Ordinary *chemical* reactions between individual atoms have energies on the order of a few electron volts (a few eV's), but *millions* of electron volts (MeV's) are characteristic of the energy output of the several nuclear reactants in fusion processes. This explains why fusion reactions involving nuclei are typically millions of times more potent than chemical reactions, which *by definition* only involve the interactions of the tenuous clouds of flitting electrons that surround individual nuclei.

Several other reactions are of major interest to fusion pioneers:

$$D + D \rightarrow T \text{ [at 1.01 MeV energy]} + p \text{ [at 3.02 MeV energy]} \qquad (2)$$

Deuterium plus Deuterium (Goes to) Tritium plus a proton

$$D + D \rightarrow {}^{4}He + y \text{ [at 23.8 MeV energy]} \quad (3)$$

Deuterium plus Deuterium (Goes to) Helium-4 plus a gamma ray

$$D + T \rightarrow {}^{4}He \text{ [at 3.5 MeV energy]} + n \text{ [at 14.1 MeV energy]} \quad (4)$$

Deuterium plus Tritium (Goes to) Helium-4 plus a neutron

In reaction (2), two deuterium nuclei react and form a *tritium* nucleus (a *triton),* another isotope of hydrogen (two neutrons plus the basic proton that identifies tritium as an isotopic form of hydrogen), plus a surplus proton. In reaction (3), two deuterium nuclei react to form a nucleus of helium-4 plus a high-energy gamma ray. In reaction (4), a deuterium nucleus reacts with the nucleus of the hydrogen isotope tritium. The reaction produces ordinary helium-4 plus a surplus neutron.

The first three reactions occur when pure deuterium fuel is brought to extremely high temperature. The first two of these three reactions, or branches as they are fondly called, are by far the dominant ones that occur with pure deuterium fuel. These two occur with about equal probability. So "burning" deuterium in a fusion reaction gives about an equal number of end products from these two reaction branches: about as much helium-three (${}^{3}He$) as tritium and about as many protons as neutrons. Much more rarely (with a probability of only about one out of ten-million for every two D's that come together) the third branch occurs, producing ordinary child's balloon helium-4 and a powerful and penetrating gamma ray.

Because in high temperature plasma fusion the so-called branching ratio between reactions (1) and (2) is about one-to-one and because reaction (3) occurs only rarely, this became a major bone of contention in the cold fusion controversy. Hot fusion physicists who were already extremely skeptical of "fusion by chemistry" were loath to abandon so solidly established a finding as the hot fusion branching ratios and took this point as a fundamental article of disbelief. It is perfectly true that in no cold fusion experiment have the traditional branching ratios been found, much less was there any evidence of consistency between these reported reaction end products and the amount of heat being measured.

Even though these are the three reactions with which hot fusion scientists primarily concern themselves in present experiments, for various technical reasons it would be difficult and needlessly expensive to build a hot fusion reactor using pure deuterium fuel, so the practical working reactors that they hope to build would use the more powerful and easy to produce reaction (4) between deuterium and tritium (D + T). The potent neutron coming off the reaction is the key to hot fusion power, because its energy could be absorbed in a surrounding blanket of molten lithium (Li) metal, which would, in turn, heat water to produce steam to run an electricity-producing turbogenerator (Chapter 2).

The fast neutron would also turn some of the lithium atoms into tritium, which could then be extracted and fed back to the reaction chamber and used as fuel. In a sense the tritium part of the fuel would be *self-regenerating* through the conversion of lithium. Tritium is one of the less hazardous radioactive isotopes, in part because it decays so fast—half of it disappearing in only 12.5 years, half of the remaining atoms in 12.5 more years, and so on till it virtually vanishes.* (*Tritium doesn't have any extremely powerful penetrating radiation coming from it when it decays, just a single electron—called a beta particle in this kind of decay. The beta particle is easily stopped by a single sheet of paper! To make this electron, one of the neutrons in the tritium nucleus changes to a proton, leaving a helium nucleus behind, specifically helium-3 or 3He. (An even more evanescent particle with no electric charge, called a neutrino, also comes out of this tritium decay, but the fleeting neutrino is one of the least interacting particles in nature. Neutrinos are a hazard to no one **except those** wracking their brains trying to find better ways to detect them.) But this also means that tritium occurs in almost imperceptibly tiny amounts in nature and must be produced bootstrap-fashion in a working fusion reactor that used D + T. But so be it—this can be accomplished.

You may have heard that the radioactive gas, tritium, is also useful in making part of the fusion fuel for hydrogen bombs. Tritium is hydrogen—simply an isotope of hydrogen. (That's why we call thermonuclear weapons hydrogen bombs or H-bombs, though to be accurate we should really call them "T-bombs" or "D-T bombs," because they use deuterium too.) We make tritium now with fast neutrons that emerge from certain fission reactors (in Savannah, Georgia, and elsewhere). Unfortunately, these have lately been in the news because their waste products have been so poorly attended in the weapons program. This has led to serious environmental problems that we must now correct— problems not having to do with tritium itself. Since March 23, 1989, tritium has also made news in the cold fusion controversy, because researchers have claimed to have observed it in numerous cold fusion experiments. If this tritium is really being *generated* and is not the result of contamination, then cold fusion is proved.

Thousands of scientists and engineers around the world have been working for decades to harness the power of these hot fusion reactions. They heat plasmas to hundreds of millions of degrees in elaborate machines designed to produce fusion. To confine the plasma, they typically work with torus-shaped (donut-shaped) vessels called *tokamaks* pervaded by high-intensity magnetic fields, or they assault sometimes frozen pellets of fusion fuel with intense laser beams from many directions at once. The hot fusioneers have reached the threshold of the Genie's inner sanctum and are knocking on his door. Are they seeking fusion desperately enough to break down the final barrier? Will civilization give them the keys—namely, money and time? Or, has a backdoor labeled cold fusion opened far enough to enable them and a new generation of fusion scientists to step in?