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FUSION PHYSICS AND PHILOSOPHY

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1. INTRODUCTION

The advancement of science and technology normally occurs through evolutionary research and development. These activities and their fruits, knowledge and capabilities, might be very interesting and useful, but they normally do not challenge our overall view of the world. When something revolutionary comes to light, the potential paradigm shift, then we are forced to examine both our knowledge and our beliefs, which are intertwined. The topic called "cold fusion" caused reexamination of the physics of nuclear reactions and some aspects of the philosophy of science. We will consider these factors after a brief introductory survey of the complex experiments and results reported in the field, and the motivations for continued attention. "Cold fusion" is used here as an accepted label for the arena of interest, and not a statement about whatever processes might be involved. [1]

The situation in 1989 was complex in many respects, and remains so even after a decade has passed. There were numerous and significant difficulties with the early electrochemical experiments involving palladium cathodes and heavy water in relatively simple electrochemical cells. These included instrumental problems, especially sensitivities and proper calibrations, unknown impurities in the materials employed in the experiments, problems with protocols such as control experiments, lack of experimental reproducibility within and between laboratories and numerous mistakes in both performing research and reporting results. The situation became even more complicated in 1990 when heat generation was reported in experiments with nickel cathodes and ordinary water in cells of both similar and very different designs. One set-up had a bed of metal-coated plastic spheres serving as the cathode in a closed-loop flow system. Anomalous results were reported with molten salt electrolytes and with solids as the ionic conductors between the electrodes. Ultrasonic and kinetic loading of deuterium into materials gave heat and unusual effects in some laboratories.

Several experiments apparently produced nuclear particles, notably neutrons, tritons, and alpha particles (helium nuclei), and radiation, including x-rays and gamma rays. The generation of neutrons was reported in high pressure and heated gas-phase experiments as early as 1989. A hybrid electrochemical and gas phase experiment produced helium in 1992. Then another pressurized gas phase experiment with commercial Pd catalysts was said to be yielding helium in 1998. Not all of the reports dealt with the potential fusion of light nuclei. Transmutations of heavy elements were reported first in 1995 when the Pd electrodes in a heavy water electrolyte became radioactive and exhibited gamma ray spectral lines appropriate to neighboring elements of Pd. Later, the coated-sphere experiments and solid-electrolyte experiments lead to reports of the generation of numerous elements across the periodic table, with many of the same elements increasing in concentration within both of the very different experiments. All of these problems, the diverse experiments and the complex results continue to make study of the field of "cold fusion" challenging. We will concentrate on the possible fusion of deuterons in experiments with heavy water electrolytes, a topic of great complexity itself, which has yielded enough strange results to warrant focused attention.

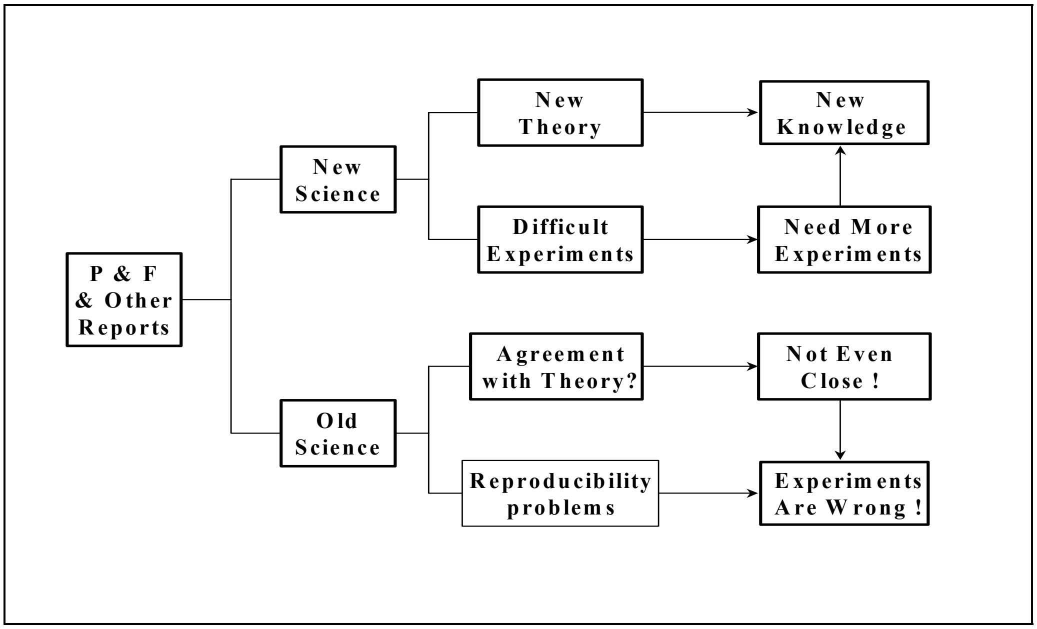


Figure 1. Diagram showing that the ideas of known (old) science lead to indefensible conclusions and acceptance of the possibility of new results can lead to new knowledge.

There are ample motivations for grappling with the diverse problems, and potentially multiple new physical effects in the field. Intellectual curiosity is first among them. The vilification received by many people who did experiments in the field is hard to accept. It was sometimes "justified" because of a perceived waste of public monies, but that view is also difficult to defend if the responsible government program managers approved. In fact, many managers felt they had a responsibility to pursue what might be really new science in areas, energy generation and materials production, of great commercial and national importance. The generation of significant amounts of heat in low-temperature (low energy) experiments that could only be ascribed to nuclear reactions, which ordinarily require high energies for their initiation, was and is not in agreement with accepted nuclear theory. However, this in itself is not excuse for the dismissal of the experiments and their anomalous results. Figure 1 shows that sticking with known nuclear physics leads many to conclude that the experiments had to be wrong. Those people chose to ignore the possibility that effects outside of what is now accepted were observed, and with it the possibility of new knowledge.

Practical reasons for attention to the odd reported results were already mentioned. Even if the energy generated by "cold fusion" did not lead to high temperatures, desalination might be a very important use of the energy. Over 10% of the countries in the world, that is, about 20 nations, are dependent on others for their water. [2] Even nations with enough internal water have severe distribution problems, such as afflict use of the Colorado River in the western United States. It seems likely that regional conflicts similar to the Gulf War about ten years ago, augmented or even borne of water interests, will be increasingly likely in this new century. It is not widely known that almost all of the oil on earth has been located and soon half of it will be used. Declining oil production in the dry Middle East in the second half of this century could make alternative sources of energy very attractive. Ways to make "cold fusion" yield higher temperatures, possibly by pressurized reactors, might follow control, even without full understanding of the odd effects. This would enable many more applications.

A simple graph of reported energy generation, expressed in watts per cubic centimeter of the electrodes in the deuterium-Pd experiments, against the year of the report is striking. As indicated in

Figure 2, it shows that Pons and Fleischmann reported at the Third International Conference on Cold Fusion in 1992, that the excess power in their "heat after death" experiments exceeded the volumetric heat generation within the fuel rods of ordinary nuclear reactors. It can be asked why this did not get truly widespread attention.

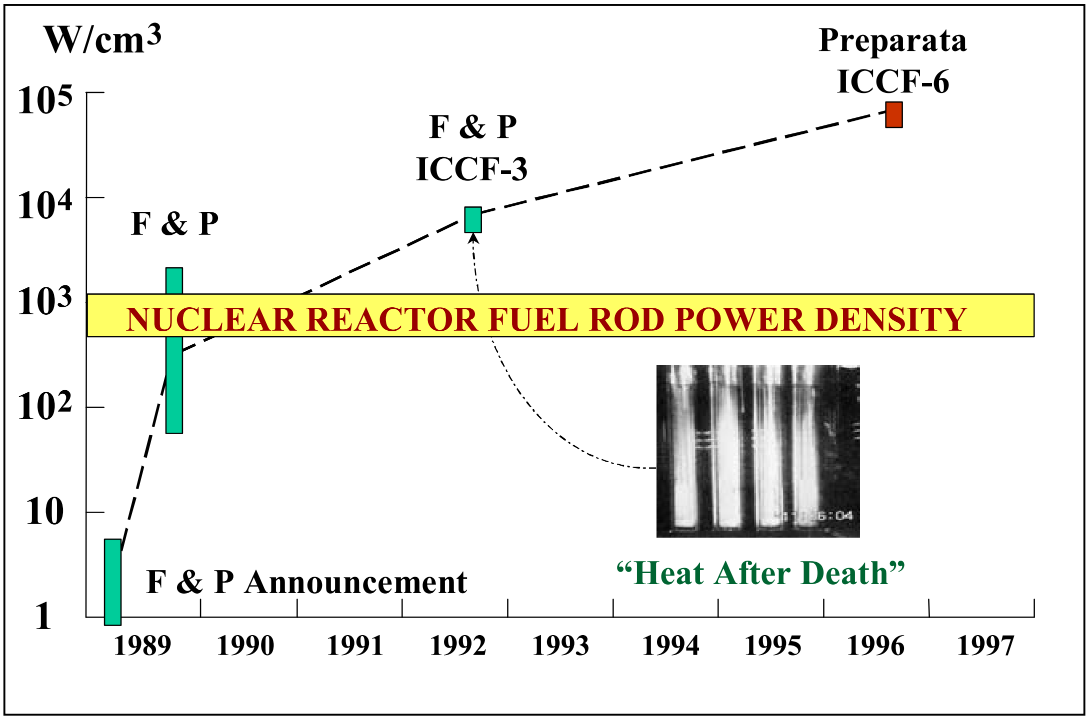


Figure 2. Plot to reported excess power generation rate in electrolytic "cold fusion" cells, ratioed to the volume of the Pd electrodes, as a function of the year of the report.

The energy aspect of this field has another significant aspect. In one of their earliest papers, [3] Fleischmann and Pons made the following statement: "We have to report here that under the conditions of the last experiment, even using D_2O alone, a substantial portion of the cathode fused (melting point 1554ºC), part of it vaporized, and the cell and contents and part of the fume cupboard housing the experiment were destroyed." Hence, a subsequent question to the reality of "cold fusion" is its potential for weapons. The possibility of national security concerns, on top of the scientific and potential commercial ramifications, make "cold fusion" even more interesting.

If nuclear reactions do prove to be the cause of the anomalous heat production reported from "cold fusion" experiments, then changes in elemental or isotopic makeup would be involved. Such alteration of the basic composition of materials might have many practical implications even for the lighter elements. If transmutation of heavy elements were possible, as claimed by some, the possibility of reduction of some of the radioactive waste from nuclear reactors might follow. Even partial relief from the waste problems of fission reactors would have global impact.

The gravity of both the results reported from "cold fusion" and related experiments, and of their commercial and geopolitical implications, drew great early attention. They lead physicists to review their knowledge about nuclear reactions and also caused much strange behavior in different communities. So, now we turn to some of the physics and philosophy associated with the subject. This attention is motivated partly by the view that, whatever the future holds for "cold fusion," it is already established as a “case study” for how science operates. The archiving of detailed material for future study by historians is of interest to many, this writer included.

Dictionaries provide multiple definitions of physics and philosophy. Physics is characterized in modern terms as “the science of matter and energy and the interaction between the two.” [4] This definition implicitly bows to Einstein’s mass-energy relationship, and it is also quite fitting for “cold fusion.” The archaic definition of physics is also germane, namely “the study of the natural or material world and phenomena: natural philosophy.” There are at least a dozen definitions of philosophy. [4] These include “the investigation of causes and laws underlying reality,” which certainly applies to physics. Another meaning of philosophy is especially relevant to “cold fusion,” that is, the “inquiry into the nature of things based on logical reasoning rather than empirical methods.” The furor in 1989 in response to the Pons-Fleischmann announcement was due in part to physicists reasoning on the basis of available knowledge that room temperature nuclear reactions were ignorably improbable. But, the claim of such reactions was based on empirical, laboratory evidence of levels of heat that could not be explained otherwise.

This examination of the physics and philosophy of “cold fusion” will begin in the next section with a review of the physics of deuterium fusion reactions, as known in 1989 and essentially unchanged now. The following section will deal largely with the scientific process and how is was both followed and abandoned by different people active in or concerned about “cold fusion.” What might be done in response to the current situation is discussed in a concluding section. Two appendices deal with areas of uncertainty in science and with a taxonomy for discussing accountability in research.

2. FUSION PHYSICS

In many respects, the twentieth was the century of the physicist. The selection by Time magazine of Albert Einstein as the Man of the Century is symptomatic of the impact of physicists. The transistor, integrated circuit, computer and internet all sprung from solid state physics. The laser and optical fiber communications systems similarly have their roots in physics. The impacts of nuclear physics in the last century were dramatic. It can be argued further that the last was the “nuclear century.” The nature of the nucleus was unknown at the outset. It was determined to be a compact object within atoms only in 1911. Basic nuclear studies, nuclear weapons, nuclear fission power and nuclear medicine appeared within thirty years, roughly from 1930 until 1960. Problems with nuclear waste and pollution followed. Despite such legitimate concerns, the nuclear physicist was widely respected and emboldened to develop fusion power sources during the latter half of the last century. Knowledge of nuclear reaction physics was highly developed, although its details continued to be explored.

It has to be emphasized that many possible reactions between two nuclei can occur. There are about 300 stable isotopes among the almost one hundred elements, and hundreds more unstable (radioactive) isotopes, many with long half-lives. Hence, the number of nuclear reactions that are experimentally feasible exceeds one million. Their possible outcomes are also varied, ranging from literal fusion, in which all of the protons and neutrons in the reacting nuclei end up in one resultant nucleus, to complex disintegration into multiple nuclear products.

For two *atoms* to react, their electron clouds have to overlap, which brings their nuclei to within about 10^{-7} mm of each other. As the atoms approach, they are attracted to each other in many cases. The distance for molecular formation just cited sounds very small, but nuclei have diameters about another 100,000 times smaller than atoms. For two *nuclei* to react, they have to come within about 10^{-12} mm of each other. And, because of the positive charge on all nuclei due to their constituent protons, the like forces on nuclei always repulse each other strongly at close distances. Hence, it is necessary to slam nuclei together in order to overcome their mutual repulsion and make their reactions possible. This can be done using directed beams of nuclei from accelerators, such as Van de Graaff devices or cyclotrons.

Alternatively, nuclei can be given high random velocities in very hot plasmas. Then they will have enough energy to overcome the electrostatic repulsion, called the Coulomb barrier, enabling nuclear reactions like fusion. Thermally-induced reactions figure in most schemes for nuclear fusion power generation.

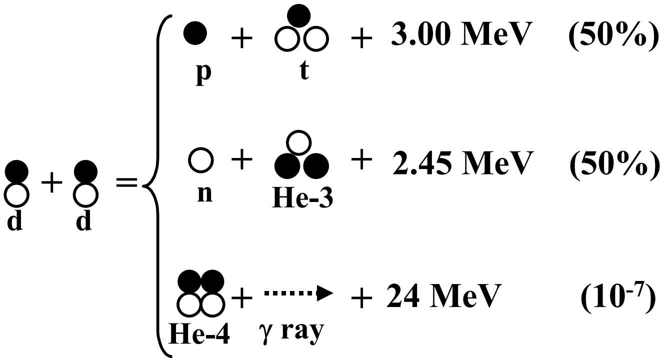


Figure 3. Deuterium fusion paths, with the product particles, the excess energy and the probabilities for each of the three observed reaction paths.

The term fusion is generally germane to reactions between light nuclei, namely hydrogen, helium, lithium, beryllium and boron, including their isotopes. Usually, there are two product nuclei from the two reacting nuclei. The fusion of two deuterons into one helium nucleus, with the excess energy going off as a 24 MeV gamma ray, is an exception. It has a very low probability. The usual outcomes of a deuterium-deuterium reaction, either one proton and a tritium nucleus, or one neutron and a He-3 nucleus, have equal (essentially 50%) probabilities, given that the fusion reaction has occurred.

The probability for a nuclear reaction to occur is often expressed as a cross section, a measure of the apparent size of the reactants. It depends on two primary parameters. The first is termed the impact parameter, essentially the miss distance between the interacting nuclei measured perpendicularly to the path of the incoming nucleus. Because nuclei have radii on the scale of 10^{-12} mm, values of impact parameters larger than such distances cause the nuclei to miss each other, that is, not to react. Deuterium nuclei in molecules and solids are ordinarily at spacings on the scale of 10^{-7} mm, so that they have a vanishingly small probability of reacting. Put simplistically, they do not touch each other. The second important parameter is the energy, or equivalently, the velocity, which has to be sufficient to force the particles close together in the face of the Coulomb repulsion. It also determines the time the nuclei spend in proximity to each other. For a nuclear reaction to happen, the wave functions of the nuclei have to overlap spatially for a time determined by their velocities. Figure 4 is a quantitative presentation of the cross section for two deuterons reacting to yield a proton and triton as a function of their impact energy. [5] At one keV, the reaction probability is over one billion times lower than the peak value. Room temperature imparts thermal energies to atoms on the order of only 1/40 of one electron volt. This graph provides a clear view of why physicists were incredulous at the Pons-Fleischmann report. The reported excess powers of about 1 watt would require about 6 x 10^{12} reactions per second, if each yielded about 1 MeV. If the known outcomes of deuterium fusion, shown in the third figure, were applicable, then deadly levels of radiation would have been emitted as a result of this large number of reactions each second of many hours.

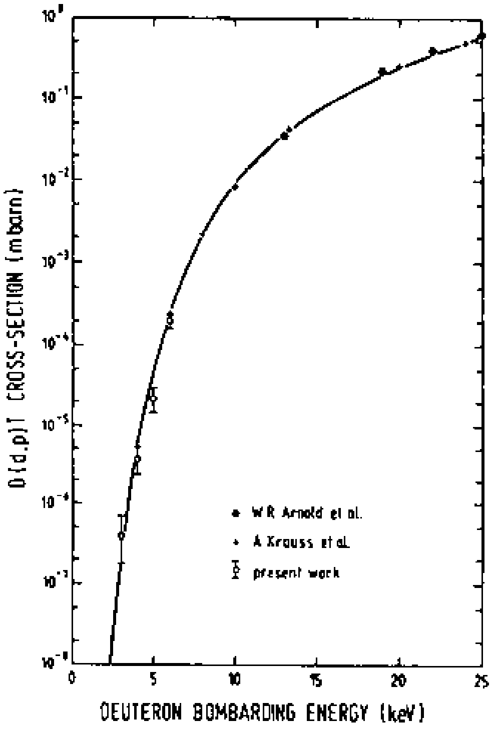


Figure 4. Deuterium fusion cross section, expressed in millibarns (1 barn is 10^{-22} mm^2), as a function of the incident energy, given in kilo-electron-volts. [5]

Another way to view the problem is to consider means to concentrate energy within the lattice. This involves two considerations. The first is the required increase in energy density to go from solid-state energies (about 1 eV per atom) and atomic spacings (about 10^{-7} mm) to nuclear energies (1 MeV or greater) and spatial scales (about 10^{-12} mm). This amounts to an increase in energy density of 10^{21}! The eV-scale energies from a cube 10^{7} atoms (or about 1 mm) on a side would have to be concentrated on one nucleus. The second consideration is the time required for such a concentration of energy. The fastest that this could happen is energy transfer at the speed of light: 1 mm/3 × 10^{11} mm/sec or 3 × 10^{-12} sec. Such a time is very long compared to nuclear reaction times. That is, even if there were a mechanism for the incredible energy densification, the required times are totally incompatible with times in the nuclear domain.

Interactions between solid-state and nuclear domains are well-known in physics. The one closest to “cold fusion” is the Mossbauer effect. [6] It involves the emission of absorption of gamma rays by nuclei in solids, where the entire solid absorbs the associated momentum change and the gamma ray lines are not broadened in the process. Nuclear effects can be seen in the details of optical and x-ray spectra, among other measurements. They fall in the field of “hyperfine interactions,” so named because they are relatively small effects. [7] Several of the mechanisms for solid-nuclear interactions have been reviewed for their applicability of “cold fusion,” but without any successes.

It should be noted that no satisfactory theoretical description, based either on old or new ideas, is available for the various observations in the deuterium Pd system, let alone all the other types of experiments under the general heading of “cold fusion.” Many attempts have been made by skilled theoreticians, but all schemes are at least incomplete and many are wrong. Few, in fact, have been reduced to numerical predictions for comparison with the results of past experiments or for the design of new experiments. Any theory for “cold fusion” has to survive scrutiny not only in comparison to reported anomalous results, but also with regard to other relevant and tested data. There are still viable theoretical ideas worth considering. However, this is not being done now because the entire field is viewed as incorrect, and funding for research is generally not available.

In summary, the nuclear reaction physics known in 1989 was applied to the fusion of two deuterons. It indicated that the reaction rates in Pd metal at ordinary temperatures were far too low to account for the excess power reported by Pons and Fleischmann. An alternative view, based on the prevailing knowledge of the outcomes of deuterium fusion, stated that if somehow such fusion was occurring at rates enough to give watt-level powers, then the associated radiation would be lethal. Theoretical explanations of “cold fusion” and related phenomena are wanting.

3. PHILOSOPHY

This section might be titled “Psychology and Philosophy.” The extraordinary reactions to the announcement of “cold fusion” had several bases. Within physics, motivations ranged from rational examination of the probability of nuclear reactions occurring at low temperatures, as discussed above, to the desire to protect major program funding for fusion energy research, discussed below. Other scientists reacted to the announcement in diverse ways. Some of it was clearly inter-disciplinary arrogance or ignorance. The public responded to the prospect of cheap energy with fewer environmental consequences. The dependency of most industrial economies on oil from abroad was widely recognized, because of the artificial oil shortage in the 1970s, if for no other reason. We will consider in this section some of the time-honored aspects of the philosophy of science, which were brought into the “cold fusion” discussion.

In a very basic sense, scientists have two roles, independent of their fields of study and the tools they use. The first is to learn new information, and the second is to communicate it to others. If there is no learning, there is no science. If the obtained knowledge is not new, whether discovered from the world or “simply” conceived, then there might be scholarly study and communication, notably teaching, but not real science. Research can be taken literally as re-search, that is, repetitive searches for or attempts to learn new truths. It has the development of new knowledge both as its hallmark activity and measure of success. But, without communication, the new knowledge lacks both independent tests and the potential for use by others. This duality, the learning and communicating of “reliable knowledge” [8], is the organizing principle of this section.

Philosophy in general, and the philosophy of science specifically, have been concerned historically with how humans know things. Arguments over whether there is an external reality outside and independent of people, or whether the world is only an internal construct, have filled a voluminous literature. [9] The different ways that individuals filter similar sensory input, and map it onto their internal models, depend on their general experiences and professional training. Arguments over the nature and details of the same experience are common. Consider the courtroom. Views that science is a social [10] or cultural [11] construct are topics of current discussion. There is also a continuing tension between the role of authority, be it in religion or in science, and an objective and rational approach to drawing independent conclusions. The former is at the root of some of what is recently called anti-science. [12] The latter is the essence of the scientific method as presently accepted and practiced. [13]

The ideal in science, what ever the field or approach, is a dispassionate and clear-headed generation and examination of evidence germane to whatever problem is under consideration prior to drawing conclusions. [14,15] It is accepted that mistakes can and will result from this process.

Communication enables thorough study of reported results and conclusions by other scientists, and constitutes the necessary quality control function in science. Presentations, especially publications, also make new information available for commercial and other applications. This is true for both classical print and new electronic media.

The separate steps within the overall scientific process are worth reviewing. Some of them got unusual attention during the first decade of "cold fusion" research. Most of them were mishandled, sometimes very publicly, in one episode or another. Everything starts with a researcher having an idea on his own, or being asked to look into something. The number of individual scientists and research groups that dropped what they were doing and paid attention to the initial reports was certainly extraordinary. This was driven by the magnitude of the potential payoff, both in terms of fame and money, and by the rapidity of modern communications, especially facsimile and electronic mail transmission. Disposable private time, or time in a paid position, is ordinarily used to address the question at hand. A very large amount of uncompensated private time has been spent on "cold fusion," especially by retired scientists, who were still intellectually engaged and had access to needed tools. The alternative, compensation from some private or public source, required either having flexibility within available funding or the ability to acquire new funding, usually through a proposal process. A remarkable amount of time has been spent in fruitless quests for funding to pursue "cold fusion" research.

Whatever the employment situation, the next normal steps in research, involve setting up or acquiring the desired computational or experimental tools, trial calculations or measurements, modifications of the tools, full parametric computations or measurements, data analysis, discussion with close colleagues in most cases and the preparation of oral and written reports. This litany is so familiar in the sciences that it might be asked why it is recited here. The point is that haste, use of unfamiliar tools and procedures, lack of proper support, pressure from others and still other causes lead to problems in each of these phases of research in various studies. There resulted a large number of reports that did not withstand scrutiny, sometimes even for very short periods. Retractions and accusations, on top of the errors, discredited the careful "cold fusion" researchers along with those who made mistakes that would not normally have plagued a field of inquiry. This furor resulted in both scientists and the public having a very poor opinion of the topic and of those who were interested in its challenges.

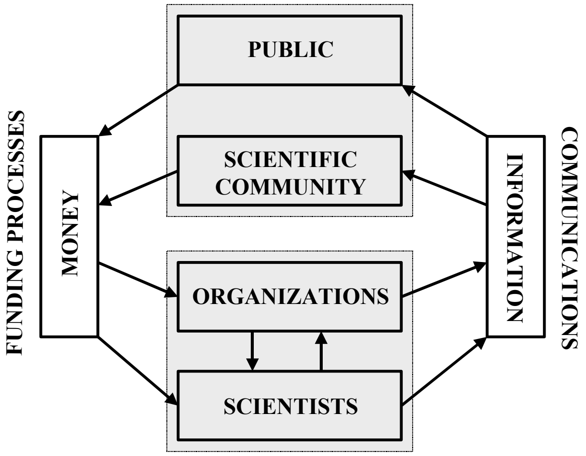


Figure 5. Four of the groups (center) and two of the functions (left and right) germane to the operation of science in general.

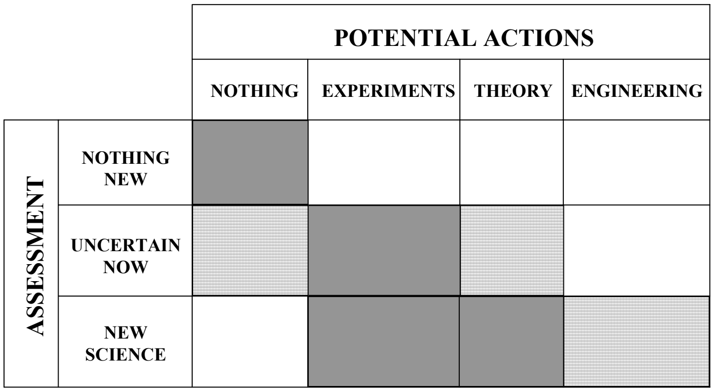
The problems just cited fettered both the “input” or funding side, and the “output” or communication side, of the field of “cold fusion.” The diagram in Figure 5 can be used to discuss these problems. It shows relevant groups of people, from the largest at the top to the individual researcher at the bottom. The shaded areas are meant to indicate that the community of scientists is embedded within the larger group of non-scientists, called the “public” here, and scientists are commonly members of organizations. The disrepute of the field soon and seriously disrupted the flow of public monies. Private funding by members of the “public” remains available in a few cases, but both the perception problems and the difficulty (costs) of the research have often deterred serious funding in recent years. The availability of public, that is, tax monies for research in this arena is usually decided by cooperation between government officials and the scientific community. In many cases, these officials come from and return to the scientific community. Such funding was very seriously impacted by the same problems that limited funding from rich individuals and venture capital groups. Many funding agencies, as well with organizations responsible for public funds were highly and properly concerned with the use of the citizen's taxes. Fear of being seen as wasting public money, or of organizational embarrassment, was not uncommon regarding “cold fusion.”

There were also two serious breakdowns on the communications side of the field. The usual pipeline of information to other scientists, called the scientific literature, suffered from the actions of many editors and referees. Most were responsible and well intentioned. Some were downright arrogant. In a similar fashion, after a time, communications to the public generally were disrupted by the lack of interest by reporters and editors of the press. Print and broadcast media coverage of the field dwindled almost monotonically after the early 1990s. There were certainly notable exceptions to the described situation in both the scientific and public communications arenas. However, there can be little argument that both funding to and communications from researchers still interested in the field have become quite limited.

A final observation regarding the generation and communication of scientific knowledge regards its eventual assimilation into the fabric of overall human knowledge. [16] The lack of activity within and substantial communications from the field of “cold fusion” now has left those who have heard of it, but not followed it, with the impression that the topic is wrong. Probably, most citizens who have heard of the topic believe that it was a large and very public mistake, another case where a segment of the scientific community has erred. If there are really anomalous effects, as reported, the field will later evolve from its current status of being a case study in the sociology of science to being that *and* a case study in the difficulty of unexpected new science. Additional comments on the fields of science that can be termed uncertain are offered in the first appendix.

4. CONCLUSION

A balanced evaluation of the evidence for new effects in the voluminous “cold fusion” literature could be undertaken by people not earlier associated with the field. Such an analysis has been performed recently by Charles Beaudette, an independent writer. [1] If many people did similarly, some would conclude that there is nothing new at all, that is, all the observations are mistakes or lies. Others might be uncertain, enticed but not persuaded by the reports. And, still others might conclude that there is sufficient evidence for the reported new effects, even though they certainly are not currently understood, and may not be so for many years.



		POTENTIAL ACTIONS			
		NOTHING	EXPERIMENTS	THEORY	ENGINEERING
ASSESSMENT	NOTHING NEW	■			
	UNCERTAIN NOW	▨	■	▨	
	NEW SCIENCE		■	■	▨

Figure 6. Relationship of the conclusions of an assessment of the field of "cold fusion" and logical related actions.

These three groups can next be asked what they would like to see done in light of their evaluations. Those who think everything in the field is either errors or fraud would logically conclude that no further investigations should be undertaken. Some in the uncertain group might prefer this course of inaction, which is close to the current actual situation, in fact. Others could desire additional experimental work. Attempts to repeat earlier positive reports of anomalous results, new types of experiments and supporting research in relevant materials and surface sciences might be desired. Helium production, hot isostatic pressure experiments and aging of materials would be wonderful candidates for more work in each of these areas. People in this second group might also like to see additional theoretical and computational research, both to explain the past observations and to guide future experiments. After all, if there are really new physical effects, they will eventually be understood both conceptually and quantitatively. Cooperative or coherent mechanisms are thought by many to be a fertile arena for attempts to develop a theory of "cold fusion" mechanism(s). Those in the third group, convinced that there really is something real to investigate, would probably also opt for a program of experimental and theoretical research. However, given their conviction, some of them might also want to have preliminary designs of engineering systems developed, based on the parameters, such as current densities and isotopic loading, and the protocols, notably unsteady conditions, that are already known from several experiments to be important. The output power and energy values and densities that have been reported might also form the basis for preliminary engineering designs. The assessment-actions matrix in Figure 6 summarizes the possible outcomes of reviews of "cold fusion" and the correlated actions that might follow.

The argument here has two thrusts: (a) the mass of information generated in the field of "cold fusion" deserves evaluation and (b) there should follow actions that responsible people deem appropriate after such an examination. If more work is desired, arguments over funding appropriateness and levels are expected. One way to gain some perspective is to examine the levels of funding for fusion research in the U. S. (only) in the past. Figure 7 is a plot of the funding in "then year" dollars, that is, the figures are not adjusted for inflation. It shows that physicists have used over $8B ($16B in current dollars) of public funding a half-century attempt to solve permanently most of the world's need for energy. This writer participated in the adventure by measuring x-ray spectra from the multi-million-degree plasmas produced both by lasers and in Tokamaks. It is interesting that this continuing attempt to produce commercially-viable fusion energy is occurring in the middle of the two centuries in history when mankind is finding and burning most of the oil and gas reserves on earth. Geopolitics, especially in the middle East, will be heavily impacted by the decline in oil availability in the second half of this century, depending on conservation efforts and uses of alternative sources of energy and lubrication. It is interesting that middle East countries have not played a role in "cold fusion" research. Possibly, they, like others, believe that nuclear fission, despite its waste problems, is available any time before high temperature fusion reactors are robustly engineered.

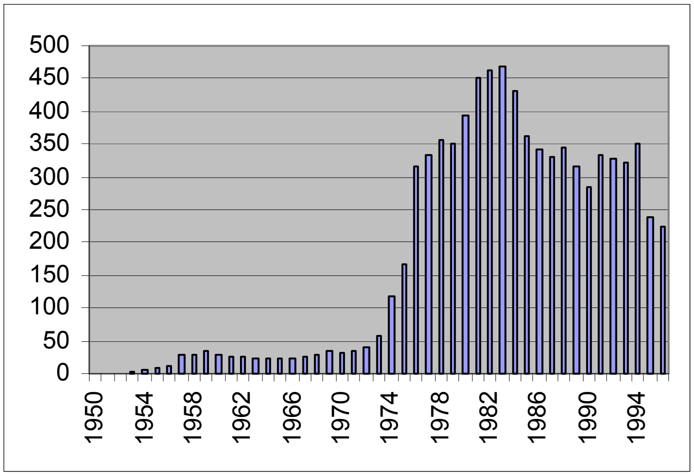


Figure 7. History of the funding of magnetic-confinement and inertial fusion research by the U. S. Department of Energy (millions of dollars vs years).

This article has been critical of the behavior of elements of the scientific and broader communities. Because science, even if pursued privately, becomes a public matter upon open publication, and because criticism is an essential element of the scientific and associated processes, the negative comments above are a normal matter of opinion. However, it should also be noted that many people in all groups concerned with “cold fusion” have deported themselves superbly. Accountability to one's self and others has positive as well as negative outcomes. Additional comments on accountability in science generally, and with regard to “cold fusion” specifically, are found in the second appendix.

ACKNOWLEDGMENTS

Scott Chubb provided me with a welcome opportunity to express some of my conclusions and viewpoints about larger questions surrounding “cold fusion” Graham Hubler provided the paper on deuterium fusion cross sections. The fusion funding data came from Jeff Auchmoody. Their assistance is appreciated greatly.

APPENDIX A: UNCERTAIN SCIENCES

Uncertainty within acknowledged fields of science is commonplace. The precise values of parameters and the reality of newly observed effects are commonly subject to discussion, which is often contentious. When a new effect outside the realm of accepted knowledge is reported, it has the possibility of opening up a new sub-field or even a whole new field of science, depending on one's viewpoint on the taxonomy or organization of the sciences. Many examples can be cited. Transistor action in physics, fullerenes in chemistry and DNA in biology are all famous examples. The point is that, occasionally, something unexpected arises in the sciences, either because it is really new, or because it is outside of the predictions of tested theory. Feuds, some of them famous, can result before matters are settled. [17]

A new observation is successfully explained sometimes by the discoverer in the initial report. Such was the case for the Mossbauer effect. That was new and unexpected, but it was soon understood theoretically by Mossbauer. However, the history of science has several famous examples for which decades passed between an observation and its elucidation, or between development of an idea and its substantiation. Superconductivity refers to the lossless and persistent circulation of electrical current in some materials at low temperatures. It was discovered experimentally in 1911 by Onnes, but not understood until development of the correct quantum mechanical theory by Bardeen, Cooper and Schrieffer in 1957. Plate tectonics is the name given to the slow (few centimeters per year) relative motion of major sections of the earth’s crust. The idea was put forward in 1912 by Wegner, who was a meteorologist. However, the theory was not generally accepted until the 1960s, when earthquake and other data made clear the existence and motion of crustal plates. Einstein postulated stimulated emission in 1925. But, the maser was not demonstrated by Townes until 1954. Other cases could be cited in which many years elapsed between a laboratory discovery and its explanation, or between an idea and its validation. The fact that cold fusion is at present without a satisfactory explanation might merely rank it with other topics in science that await understanding. The current lack of an explanation, and the decade that has passed since the announcement of cold fusion, are not necessary reasons to ignore it. Possibly. it will indeed require a new generation of scientists for interest to reignite.

Fields of science vary widely in both their content and their character. Some topics in science and technology have been dismissed as incorrect. Among them are N-rays, polywater and memories in highly diluted solutions. Other subject are on very solid ground because of their observational or theoretical bases or, best of all, strong agreement between these two facets of inquiry. It is noteworthy that some of the theoretical topics, among them string theory, may not be testable, yet there is no doubt of their scientific character. The boundary between topics in science that are accepted as wrong and those accepted as legitimate fields of study can have one of two characters. Either it is sharp, with no intermediate or uncertain cases, or else it is broad and allows the possibility that some fields in science are not known to be either right or wrong at any time, such as the present. The term “pseudoscience” is commonly applied to such difficult and contentious fields, usually in a derogatory fashion. [18,19] The historical fact that some topics occupied an uncertain status for long periods would argue for the boundary between “bad” and “good” science being broad. Of course, it could be stated that it was broad in the past, but is no longer so because of the advanced state of knowledge and our ability to deal rapidly with new scientific riddles. An argument counter to this deals with time scales. There is commonly a period of time between an experimental observation and its understanding, even for items that are within the boundaries of well-developed fields of science. At what point in time must the observation be deemed to be either incorrect and rejected, or understandable and acceptable? The issue, of course, is the magnitude of the importance of the observation. Is it merely adding a proverbial brick to a familiar edifice of knowledge, or is it the start of a new structure?

It is the opinion of this writer that there are now major topics in science of uncertain character that will be shown in the future to be either incorrect or correct. New ideas and advances in instrumentation will be brought to bear to illuminate topics that are now considered in the "gray" area between right and wrong. There are some items, ball lightening for example, that have relatively good prospects for being real and understood. Others, such as astrology, may be very popular with some people, but are not likely to have an understandable physical causation. Investigation of still other areas might discredit the core concern, but still lead to new knowledge. Even if UFOs have never neared earth from afar, it is still possible that some things could be learned about atmospheric optics, weather, psychology and human interactions, areas of legitimate inquiry, if the reports of UFOs are thoroughly and broadly examined.

	UNCERTAIN SCIENCES					
CHARACTERISTICS						

Figure A1. Template for compilation of the characteristics of uncertain sciences prior to their systematic examination.

A list could be made of dozens of topics that are highly uncertain and contentions now. Included would be such things as dousing for water and the potential effects of thought on the outcome of experiments. This would be a compilation of what are commonly called "pseudo sciences." Another list of the characteristics for each topic can also be drawn up. Included on it would be descriptions of the observers giving odd reports, for example, their training in making and reporting observations, and their physical and mental conditions at the time of the anomalous observations. These two lists could form a matrix that would provide a framework for the systematic consideration of "gray" sciences, as indicated in Figure A1. One could even rank the areas of uncertain science according to their likelihood of being worth study or their practical payoff if they turned out to be real. In the end, if only a few topics did withstand scrutiny and succumb to understanding, it is likely that the process would significantly expand our knowledge. Posibly, one or two new fields or sub-fields of science would result, perhaps with some payoff to people generally. Really new areas in science tend to have the most impact.

Returning to "cold fusion," the argument here is for the topic to be counted as an area of "gray science," that is, of uncertain correctness. A program for the examination of the claims in the field can be envisioned. It would have its roots in the arena of measurement science. For a very wide range of measurements in the physical sciences, there is a graph that relates what is wanted to what can be measured. The shape is generally as shown in figure A2. The measurand can be any quantity on interest, for example, temperature in an electrochemical cell. The observable might be the voltage from a thermocouple. The instrument yields observable noise until the measurand reaches a value such that the observable exceeds the noise. Then the measurement system works well, having a unique relation between the desired measurand and the observable. That is, the obtained value of the observable can be converted into the desired value of the quantity of interest. Eventually, the system can no longer respond to increases in the measurand and the output observable saturates. This relation of measurand and observable is commonly called a "calibration curve." Its determination for any experimental arrangement is often challenging and always open to discussion.

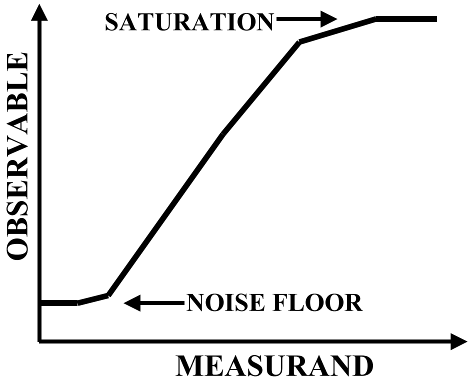


Figure A2. Calibration curve relating what is desired (the measurand) to what can be actually measured (the observable).

It is instructive to consider various measurement systems against this template. A ruler for measuring distance has a linear relation between its divided length and the distance being measured. The minimum reading is determined by the resolution of the eye or the sharpness of the graduations on the ruler. The maximum reading is set by the length of the ruler. Another common case deals with stellar observations. The stars are "out" in the daytime, but not visible because the background due to sun light scattering from the air sets the noise floor above the brightness of the stars. The minimum detectable limits of analytical instrumentation are determined by the noise floor of the systems used, and are the subject of much research and development. Many other examples could be given, since calibration curves are pervasive in experimental and observational sciences.

The primary measurands of interest to "cold fusion" researchers included excess heat, emitted or residual radiation and numbers of nuclei. The observable quantities can vary widely even for each measurand, depending on the instrumentation employed. Voltages dependent on temperature, or counted pulses from detectors, are common. The point is that, when the measurand involved in an experiment has a low value, then the noise floor of the measuring system precludes or limits the desired determination. And, indeed, many measurements in "cold fusion" experiments were marginal. My recommendation is to discard all of these! That is, let those concerned with the reality of the reported effects confine themselves to experimental reports for which there is no argument about the relative size of the observed signal and the noise floor of the instrumentation. Dozens of experiments will survive this screen. Then, examination of how the calibration curve was determined can follow to eliminate, or bound, possible errors. This has been openly and successfully done for many key experiments in the field. The point is that, there is a residual of a few dozen anomalous reports that cannot be dismissed on the basis of current knowledge. Further, it is not likely that all of these diverse experiments and measurements can be explained away. That some of the experiments can withstand scrutiny does not mean that all reports lumped under the "cold fusion" moniker will weather the test of time. The field has attracted many marginal topics and people, but their association does not make all of the reported anomalies wrong. The conclusion might be that there have indeed been sound observations of effects outside of current knowledge. That is, possibly the field of “cold fusion” has already graduated from the uncertain “gray” world even though it is not widely accepted within either the scientific or broader communities.

APPENDIX B: ACCOUNTABILITY

One definition of accountability is the “quality or state of being accountable, liable or responsible.” [4] Implicit in this idea are two things. The first is an expressed thought or action (including inaction). The second is a pair of individuals or groups of people, one performing the behavior and the other judging it, whatever their motivations. In the “cold fusion” episode, as for scientific research in general, there were several relevant classes of people. They include the individual scientist, their research group, the organizations for which they work, other sponsors, editors of diverse communication media, others in their field of science, scientists in general and the public. In order to appreciate the diversity and complexity of accountability in science, it is possible to make a matrix of the pair-wise relationships of performers and judges as in Figure B1.

TO: FROM:	**SELF**	**GROUP**	**ORGANIZ.**	**SPONSORS**	**EDITORS**	**FIELD**	**SCIENCE**	**PUBLIC**
SELF								
GROUP								
ORGANIZATION								
SPONSORS								
EDITORS								
FIELD								
SCIENCE								
PUBLIC								

Figure B1. Matrix for the examination of accountability in an area of science, with who is responsible (on the left) to whom (at the top).

Each of the boxes could be examined for breakdowns of various types, including omissions and commissions; honest, careless and stupid mistakes; and willful deceptions, notably lies and fraud. In fact, an essay could be written about the topics germane to each box. Accountability to one's self is particularly interesting, since the prospects of fame and fortune, and other pressures, drove some “cold fusion” researchers to depart from their normal standards. Instances could be cited where all the other entities in the first column failed the individual researcher. Many with an interest in the subject feel that this is especially so for the larger scientific community, which often did not maintain a dispassionate view and open mind that scientists tout as one of their characteristic behaviors. They feel that it is no less the case for the public's response to people who wanted to pursue studies of “cold fusion.” The breakdown in communications between those in the field and both the scientific and public communities contributed greatly, but does not excuse, the casual (even lazy) and generally uninformed behavior by many other scientists and by society at large.

The normal fallibility of scientists, their ordinary human ability to make mistakes, and bad behavior of various types by many scientists, caused many lapses in the responsibilities of individual scientists to others in the first row above. It began with the ill-starred press announcement by Pons and Fleischmann, something they have long acknowledged as a mistake. Many scientists lacked the courage to stand up for their private viewpoints for fear of ridicule or retribution. Other failures by scientists can be cited.

The roles of research colleagues and the organizations for which they worked are interesting. In some cases virtual or actual religious fervor within a group lead to excess enthusiasm and forestalled rationale approaches to the complex topic of "cold fusion." Many research laboratories lost their stomach for participation in the field, sooner or later, due to fear of loosing face in the scientific or larger communities. The roles and behavior of sponsors, both public and private are among the more interesting aspects of the first decade of the field. Some governmental organizations still discharge their responsibilities to investigate new scientific reports that might be important to the tax-paying public. Individual investors and investment groups provided monies that were important for investigations of many aspects of the field, although such funding, like government support, has declined greatly.

Those involved in the communication of scientific results are represented here by editors because of their pivotal positions. Also included are others involved in the process, notably referees and the managers of journals, and reporters who write for the scientific and general audiences. As with the other pairs represented in each box of the matrix, there is plenty of praise and criticism for the accountability exhibited by those who link the scientific investigator to others. The same is true for those in the more specific fields relevant to "cold fusion" research, notably solid-state and nuclear physicists, electro- and other chemists, material scientists and those skilled in analytical and other measurement sciences.

It must be noted that actual or perceived misbehavior has lead to legal action in some "cold fusion" cases. That is, the accountability of interest here was extended beyond ordinary opinion to the evidentiary realm in courts of law. This has opened in the current field all the problems associated with scientists providing expert testimony in suits whose core is not about science or technology, but rather concerned with product and other liabilities.

Ethics in science is another important and contentious topic related to accountability in science generally and in "cold fusion" particularly. This topic gets much more attention in the life sciences than in the physical sciences, although it is germane to both. The field of "bioethics" [20] and the funded Ethical, Legal, and Social Issues (ELSI) component of the Human Genome Project [21] are indicative. However, recent articles with titles "Conduct, Misconduct and the Structure of Science" [22] and "Science Comes to Terms with the Lessons of Fraud" [23] apply to more than biology and medicine. Figure B2 from an "Ethics in Science" web site [24] nicely makes the point that the behavioral aspects of science are no more black and white than the fields of science themselves, as discussed in Appendix A.

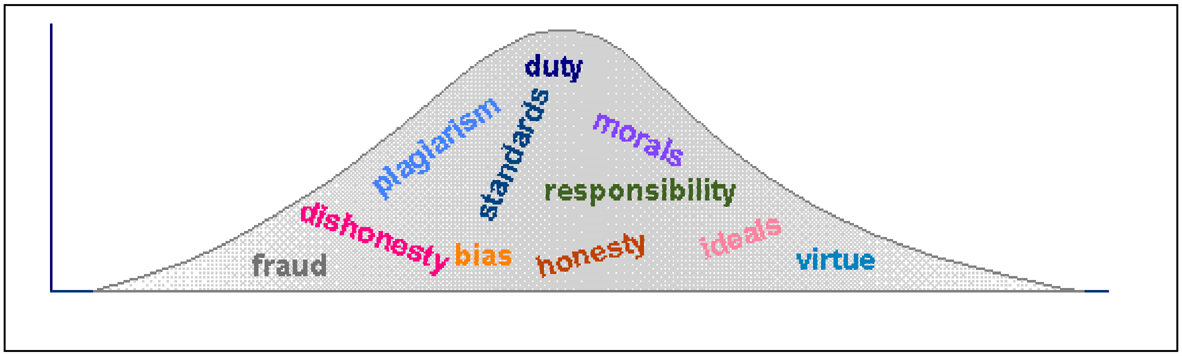


Figure B2. Representation of the continuum of behaviors in science from the reprehensible to the wonderful, most of which behaviors can be found in the "cold fusion" field.

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