Committee I
The Nuclear Option in the Past,
Present and in the Future

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A PROMISE UNFULFILLED

by

Karl P. Cohen
Palo Alto, California

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Karl P. Cohen
928 North California
Palo Alto, California 94303

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The realization 50 years ago of a controlled chain reaction in uranium by Fermi and his associates opened the door to mankind of previously unimaginable energy resources. The magnitude and concentration of this resource may be readily appreciated by noting the fission energy of 200 Mev, 40 million times greater than the chemical energy of ordinary combustion.

This enormous energy source is not, however, an unmixed blessing. It can be used to generate electric power without using oxygen or producing CO_2 or other polluting gases. But the generation of fission power is accompanied by the production of radiation six orders of magnitude larger than any other human activity. It can also be used to trigger weapons of such awesome destructive potential that, after one unfortunate example in 1945, man has dared not use them in subsequent wars. Indeed, in three instances nations with nuclear weapons have accepted defeat rather than employ them.

The Fermi experiment which we commemorate today was financed by the U.S. government as a step towards the production of plutonium for weapons. The possibility that chain reactions of uranium could also be a source of unlimited amounts of energy for peaceful purposes was well understood, but the threat of exclusive possession of atomic weapons by the Third Reich was of far greater immediate importance. Thus from the very beginning of the atomic age (as it was then called) peaceful applications were subordinated to military ones.

And they have remained subordinated. Until 1954, civilian power activities were restricted to government programs under strict security control. The Eisenhower "Atoms for Peace" program which opened the way for civilian power stations was really a calculated concession to non-nuclear nations in return for their renunciation of nuclear weapons. Subsequent administrations--most notably the Carter Administration--sought to reinterpret the terms of the agreement between weapons and non-weapons states by discouraging the development of nuclear power plants and associated technologies. In this way the weapons states have sought to retain their monopoly of weapons without accomplishing the promised transfer of technology which had secured the acquiescence of the non-weapons states.

In numerical terms, the subordination of civilian to military applications is also striking. In 1945, the US had three reactors totaling 900 MWt of reactor thermal power. The world today, omitting naval reactors, has approximately 330 GWe of operating electrical power reactors, or 1000 GWt. This amount is about 5% of the world energy supply, quite consistent with historical energy substitution patterns for the introduction of coal, oil and gas.[1] The expansion factor 1992 vs. 1945 is 1.1 thousand.[2]

The two nuclear weapons used in August, 1945, had a combined explosive power of about forty kilotons. The combined explosive power of the arsenals of the U.S. and the former USSR in the late eighties has been estimated at 17,500 megatons.[3] The expansion factor is 440,000, more than two orders of magnitude greater then the expansion of nuclear electric power. The growth of nuclear weapons has been rank and untrammeled, far beyond any reasonable requirement. The cost of this arms race has been ruinous to both parties. The disposition of the now excess nuclear weapons, and of the factories, research laboratories, and personnel who designed and fabricated them, has emerged as one of the major problems facing the post-cold-war world.

Although mankind appears to have been spared the ultimate catastrophe of a nuclear war between superpowers, the legacy of the first demonstration of a chain reaction, up to now, cannot be regarded with complacency. The balance is not entirely negative: nuclear electricity has undeniable benefits, not the least of which is its potentially unlimited abundance. But the environmental devastation of Chernobyl, and the unresolved issues of handling spent fuel and disposing of nuclear waste products, cast a shadow over the peaceful uses of chain reactions. Further, the close relation between nuclear weapons and power technologies poses the problem of how to use the latter broadly without risking renewed proliferation of the former. It is far from clear that the deserved and welcome collapse of the nuclear weapons establishments will not also result in drastic limitations on the use of nuclear electric power. There are certainly powerful constituencies who are implacably hostile to any and all applications of fission energy.

Thus, the successful demonstration of the fission chain reaction cannot yet be celebrated as a boon to mankind. The painful history of the past half century, and the world chaos, political and economic, which now confronts us, was in part a consequence of it. But we cannot put the genie back in the bottle. It remains for us now to adopt policies which will make future centuries more worthy of mankind's highest aspirations: to remove the threat of imminent destruction, and yet secure the benefits of clean electric power to billions now living in squalor.

To do this we shall be obliged to depart from present policies, however well they may conform to public prejudices. We shall also have to overcome a tendency to assume that any policy which has lasted for a long time, and is the result of painful debate and compromise, must somehow have some virtue.

The Marxist theory of history as a reflection of economics and class struggle has had a profound effect on modern thought. Even those who reject socialism and class struggle are attracted by the idea that history is not merely the sum of more or less accidental human actions, but is the result of deep underlying forces, which it is the historian's mission to discern. The concept adds dignity, as well as a sense of inevitability, to history.

The idea of inevitability confers legitimacy to actions and decisions once made. Now, many decisions after a while become irreversible by the weight of their consequences: as a practical matter they must be accepted. But the idea of inevitability has so permeated our society that we feel impelled to go beyond acceptance of past decisions and feel obliged to defend them as correct. For example, the US decision to bury unreprocessed spent fuel was based on proliferation concerns: it was purely political. Subsequently, it has been justified on economic grounds.

The recent startling reversals of over forty years of history in Eastern Europe and seventy years in the Soviet Union should encourage us to take a less respectful view of past decisions and attitudes. The weapons-dominated development of nuclear energy that the world has followed for so long was not inevitable, nor intrinsic to the perverse nature of chain reaction technology, but due to human decisions which could well have been different.

Many decisions, in particular those of the much overrated Manhattan Project, depended on predispositions and expediency, and contributed significantly to our present predicament. The decisions to bomb Japan in 1945 and "Keep the

Secret" helped alienate the Soviets and start the Cold War.[4] Less well known, the Manhattan Project lost all chance of ending the war in 1944, by dropping, against the advice of Harold Urey, the more advanced centrifuge process in favor of the gaseous diffusion process. [5]

The purpose of the present paper is to review, admittedly with the benefit of hindsight, other critical decisions and events of the last half century affecting civilian reactor power. In so doing, we may at the very least shed some light on the origins of our present difficulties. We may even shed some light on whether, in a world at peace, there is any possibility that the promise of unlimited, cheap and environmentally friendly energy from nuclear fission can be fulfilled.

The discussion will cover seven areas, each of which will have a separate Section. The Sections are: The Need for Nuclear Power, Disposing of Nuclear Weapon Stockpiles, Spent Fuel, Nuclear Waste Management, Nuclear Proliferation and Civilian Power, Reactor Safety, and Nuclear Power Economics. The background of the author has been almost entirely American, and the discussion and examples will therefore reflect that experience. The author recognizes this is a parochial point of view, especially for an International Conference, but counts on it being balanced by contributions from other countries.

1. THE NEED FOR NUCLEAR POWER

Before considering this issue, we must investigate the global need for electricity. In the U.S., per capita electricity use is 11,000 kilowatt hours per year. European industrial nations use about half as much. The world average is 2000 kwh/yr.[6] In the U.S., this has led to the belief that more efficient use of existing electric power can obviate the need for more power plants. While this proposition has some validity for the U.S.[7], simple arithmetic shows us that the potential for increase in electricity use by the four billion--soon to be eight billion--in third world countries, whose per capita use is about 1000 kwh/yr, is far greater than for reductions by the 250 million in the U.S.

Concern for the CO_2 (and other gas) content of the atmosphere suggests that it would be prudent to limit the number of fossil-fueled power plants (and vehicles) to roughly the present numbers. While the need for additional electrical power is most acute in developing countries, concerns about technical expertise and/or political stability suggest a strategy of replacing fossil plants in developed countries with power plants that do not emit CO_2, (inter alia nuclear plants) to permit fossil plants to be used in developing countries.[8]

This is obviously a short-term strategy. It is not credible that 4/5 of the human race will permanently accept lower electricity application than the remaining fifth.

The next hundred or 150 years will see a continuing growth in the demand for electricity. Whether this will be supplied by fission power will depend on resolution of the problem of nuclear weapon proliferation, and on the relative economics of alternate non-polluting power sources.

At this point it is worth noting that the present predominant nuclear fuel cycle--once-through enriched uranium--will rapidly exhaust our uranium resources. In 1990 the Western world nuclear power cohort of 272 GWe required 42,500 MT of uranium.[9] A world nuclear capacity of 1 TWe, roughly 40% of present world electric power capacity, (and 10% of the capacity in the middle of the next century) would require about 150,000 MTU/yr. Conventional estimates of the uranium resources which might be recovered at forward costs of less than $130/kgU are about 5 million tons.[10] IIASA speculates that after more complete world exploration, this number might be about 25 million tons.[11] Depending on the value used, the lifetime of the present fuel cycle at 1 TWe calculates to be 33 or 167 years. Either number tells us that recovering the plutonium from spent fuel will be necessary rather soon unless we are prepared to see fission energy phased out as a major contributor to electric generation in the next century.

2. DISPOSING OF NUCLEAR WEAPON STOCKPILES

The two alternatives are permanent monitored storage under international auspices, and consumption of the nuclear materials in reactors. The former leaves the materials as a permanent menace, subject to seizure and eventual re-use. The second produces useful power and eliminates the materials.

Highly enriched uranium can easily be diluted with natural uranium and used in existing, conventional light water power reactors. Plutonium can likewise be mixed with natural uranium and used as fuel in the same reactors. Both systems, however, produce more plutonium--albeit of a different grade--in the process.

At this point we must address some semantic problems. There are two kinds of plutonium: weapons grade plutonium and reactor grade. Plutonium produced specially for weapons by short bouts of irradiation has low ratios of $Pu^{240}$to Pu^{239} (about 6.5%). This is called weapons grade Pu. Power reactors, for economic reasons, irradiate their fuel as long as possible, typically producing Pu with relatively high Pu^{240}/Pu^{239} ratio (over 40%). This is reactor grade Pu. Pu^{240} has a spontaneous fission rate which leads to a high neutron background: its presence could lead to preinitiation and consequent low yields in nuclear weapons. The U.S. nuclear weapons program uses weapons grade Pu (or 90+% U^{235}) exclusively. As recently as two or three years ago, the DOE proposed to build a billion dollar laser separation facility to produce weapons grade Pu from reactor grade.

The Carter Administration was obsessed with the idea (since proved erroneous by Saddam Hussein) that the most likely route for proliferation of nuclear weapons outside the charmed circle of the acknowledged weapons states was the diversion of (reactor grade) plutonium from the civilian power reactor fuel cycle. To emphasize that reactor plutonium could be used to make a weapon (albeit a poor one) it renamed reactor grade plutonium "weapons-usable" plutonium. Our ignorant media fell into the semantic trap and frequently refer to power reactor plutonium not as weapons-usable but as weapons grade.[12] An unfortunate result of this fascination with a very unlikely route for a major nation to develop nuclear weapons has been a concentration of scarce IAEA resources on surveillance of civilian power reactors.

Another common semantic trap is the expression "Fast Breeder Reactor". To the public this means a reactor that breeds plutonium rapidly. What it really means is a fast neutron spectrum reactor that eventually produces more plutonium than it is loaded with. In fact, to produce plutonium rapidly one uses thermal spectrum reactors which convert U^{238} to Pu. Further, by adjusting the U^{238} contents of the reactor core and blanket one can have a fast spectrum reactor which burns or breeds Pu as one desires.

In conclusion, any power reactor will degrade weapons grade Pu: fast reactors can burn it up. The same fast reactors can simultaneously be used to transform other long-lived transuranium alpha-emitters to short-lived ones, if such elements are indeed valueless. The policy proposed: destroy Pu from weapons in power generating fast reactors. Make thermal reactor fuel from U^{235}.

3. SPENT FUEL

The subjects of Spent Fuel and Nuclear Waste Management are separated to emphasize that spent fuel is not waste. The plutonium in it, when used in fast spectrum reactors together with the depleted uranium by-product of uranium enrichment, can release roughly 50 times as much energy as has already been extracted from the fresh low enrichment nuclear fuel. With the present low demand and low price of uranium ore, and the high cost of reprocessing spent fuel, an argument can be made that it is not economic to recover it. Not every nation with a nuclear power program agrees with this assessment. But the reason fuel is not reprocessed in the US is not economic: it is because the Carter Administration wished to prevent the clandestine diversion of reactor grade plutonium into nuclear weapons. The U.S. accordingly has no <u>commercial</u> reprocessing plant. To be sure, as discussed above, the U.S. military does not need or use reactor grade plutonium. The purpose of forbidding commercial reprocessing in the U.S. was to set an example for <u>other</u> nations to follow. The hypocrisy was too evident and the example was not followed. But even though the policy was rescinded by the Reagan Administration, industry was reluctant to adventure into reprocessing faced with the open hostility of the Democratic majority in Congress.

Burying unreprocessed spent fuel has two major drawbacks. First, it does not separate the long-lived transuranic elements from the relatively short-lived fission products, and so increases the required design lifetime of a repository by orders of magnitude. Second, as noted at the end of Section 1, it is tantamount to burying the future of the nuclear industry.

4. NUCLEAR WASTE MANAGEMENT

There is world-wide consensus that disposal of high level nuclear wastes in mined geological repositories is feasible. It has been U.S. policy since 1957, following a finding by the National Academy of Sciences[13]. There have been dozens of confirmatory studies: thus the U.S. Office of Technology Assessment (1985) "studies to date have identified no insurmountable technical obstacles to developing geologic repositories"; the Interagency Review Group (1979) "Successful isolation of radioactive wastes from the biosphere appears technically feasible for periods of thousands of years provided that the systems view is utilized rigorously"; the Board on Radioactive Waste Management of the National Research Council (1990) "There is no scientific or technical reason to think that a satisfactory geological repository cannot be built."[14] Other countries have published the same conclusions.[15]

Actual demonstration of a mined repository, however, has eluded us, and despite the expenditure of literally billions of dollars, recedes continually into the future. The BRWM has recently concluded that "the U.S. program, as conceived and implemented over the past decade, is unlikely to succeed".[16] The difference can be attributed to the regulatory requirements imposed. They mandate both retrievability and permanent disposal; human intrusion after 100 years and prediction of performance for 10,000 years.[17] The science of geology is not equal to the task. Geology is a backward-looking science, whose practitioners are skilled in constructing scenarios of past events to account for the present landscape. They are even freer to construct scenarios of the future, where the endpoint is undetermined. Proof of performance beyond reasonable doubt is unlikely without protracted observations.

Geology is also a science in flux. Earth movements and volcanism are now recognized as largely governed by plate tectonics. The first NAS finding in 1957 was made six years before that theory was accepted and generally applied.

The regulations, hiding behind the doctrine of conservatism, outline a highly improbable future. Society is not going to forget the location of a repository in 100 years--barely more than one person's lifetime. The consequences of a given dose of radiation will be different after a thousand years of molecular biology. Recollect, the germ theory of infectious diseases is only 130 years old. Above all, the notion of permanent disposal presumes to decide for all eternity what elements society will find useful.

The big victory of the sponsors of the California Nuclear Initiative of 1976,[18] whose aim was to demolish the nuclear power industry, and the blunder of the utility industry statesmen who compromised with it, was that it created a pressing problem where none had existed before. Elementary prudence would allow high level wastes to cool for 100 years before trying to dispose of them. By supporting the Nuclear Waste Policy Act of 1982, the nuclear industry accepted the challenge of disposal of unsegregated and uncooled spent nuclear fuel on a fixed time schedule. The Yucca Flats Project is viewed as the prelude to a rebirth of the nuclear industry. It really is a morass.

I recently proposed the following nine point program:[19]

1 Recognize on-site spent fuel storage as a safe and environmentally adequate procedure for 100 years

2 Abandon immediate plans to build a repository

3 Recognize <u>economic</u> fuel reprocessing as a national goal

4 Continue the one mill/kwh assessment on nuclear power generation, adding it to the sums already

collected and not spent

5 Apply the proceeds to a research and development program on economic fuel reprocessing, on efficient control of high and low level wastes, and on recovery and re-use of the uranium and transuranium products

6 After a decade or so, construct, license and operate an efficient fuel recycling facility

7 After a reasonable period of operation, build a repository for the processed waste product of the recycling facility. <u>We need not decide at this time to put the repository in deep geologic strata</u>

8 Establish the real costs of the fuel cycle, including waste disposal

9 Privatize the recycling facility and the repository, and revoke the assessment

5. NUCLEAR PROLIFERATION AND CIVILIAN POWER

The word "proliferation" bears two meanings. In the vocabulary of the five permanent members of the U.N. Security Council, proliferation means the possession of any nuclear weapons by other, presumably less responsible nations, or by terrorist organizations. The second meaning, which the rest of the world adopts, and we shall use here, involves the accumulation of nuclear weapons by any nation, whether it fancies itself responsible or not. Using the second definition, proliferation already exists: it is not a <u>future</u> threat, nor was they were to regulate had not yet been designed. Specifically nuclear engineering standards were almost non-existent.

In the fifties and sixties, in the U.S. and world-wide, there was experimentation on a variety of reactor types and equipments. Considerable research and development programs were required, and relatively little effort could be spared for research on safety per se. Safety concerns eventually began to surface (e.g. seismic issues), but it is not an exaggeration to state that the general pattern was to build the reactors first and add on safety features later. We have now reversed this pattern: the U.S. is doing a great deal of safety research and building few reactors.

Following the Three Mile Island accident, the U.S. utility industry, spearheaded by the Electric Power Research Institute, organized industry-wide cooperative organisms to exchange information and advice on reactor operations among the utility owners. The Nuclear Regulatory Commission focused attention for the first time on Beyond Design Basis Accidents. The NRC and the Department of Energy stepped up research and development on reactor safety, with particular attention to the course of severe accidents (fuel-coolant and core-concrete interactions, hydrogen generation &c.)

Meanwhile, over 400 reactors world-wide continue to accumulate operating experience. Despite somewhat disorderly beginnings, the experience of the Western nations with light water reactors has been good. Given the current research on reactor safety, there is every reason to expect that the next generation of LWRs will be even safer than the last.

Unfortunately the public consciousness is the reverse. The spectacular Chernobyl-4 accident has served to confirm the worst scenarios envisaged by opponents of nuclear power. It also exacerbated the radiation phobia first spawned by the fall-out from nuclear weapons testing in the atmosphere. The public is more alarmed by calculations of future casualties from small increments of radiation over the natural background, than of real time deaths from coal mining, gas explosions, oil fires or atmospheric pollution. The public is unduly impressed by the self-confident calculations of radiation biologists. Apparently no one has noticed that their estimate of the natural background radiation level has lately been altered from 100 mrem to 300 mrem per year to account for radon in homes.

Regulatory policies cater to the public phobia. The evacuation zones around nuclear plants are based on chemically impossible iodine release levels, certainly not on TMI-2 experience. The NRC "as low as reasonably achievable" policy for radiation exposure in the workplace is not matched by the EPA policy on radon exposure in homes. Worse, exaggerated concern for the release of small levels of radioactivity can increase the chances for large reactor accidents. For example, sudden closure of BWR steam lines, mandated to stop minor releases of radioactivity from fuel rod leaks, collapses the voids in the reactor core and starts a reactivity transient. ALARA inevitably restricts plant access for inspection and repair. Another policy, intended to reassure the public that the NRC is not in league with the utilities, is that of fining utilities for nominal or unwitting violation of NRC rules or technical specifications, even if discovered and reported by the utility.

The Chernobyl reactors differ in important ways from light water moderated reactors. They are tube-type reactors, with the primary coolant boundary in the reactor core, only a few millimeters away from the fuel rods and a few millimeters thick. The LWRs are pool-type reactors, with the primary coolant boundary outside the core, inches away and inches thick. In TMI-2, although the primary coolant boundary leaked, it remained intact and retained all the fuel. The coolant which leaked went into the secondary containment. In Chernobyl-4, the primary coolant boundary ruptured, there was only partial secondary containment, and the fuel was expelled.

Accidents in existing LWRs are still possible, but they will not approach the Chernobyl event in severity. Unfortunately, accidents in existing Chernobyl-type reactors are also possible, despite recent modifications of the reactivity coefficients. It would be prudent, therefore, to remove reactors of this type from service.

7. NUCLEAR POWER ECONOMICS

The primary competitors of nuclear power plants are fossil-fueled plants. If it should be determined that CO_2-emitting power plants are indeed too destructive of the environment to be permitted, the future competitors will be from far less established technologies, such as solar, wind or fusion power. Looking ahead a mere one hundred years, the light water reactors which are today's embodiment of nuclear power will, unless nuclear power is not a major factor in world power production, be supplemented or replaced by more advanced reactor types, whose economics are as nebulous as were the economics of light water reactors in 1950. A thousand years into the future, any remaining fossil fuels are likely to be reserved for special uses, or entirely replaced by hydrogen.

The present economic comparisons are not, therefore, final measures of the future of fission power, but rather indicate the duration and financial pain of the eventual transition from fossil to renewable sources of power.

At the beginning of the commercial nuclear power industry, economic comparisons with fossil plants were based more on faith than on fact. Until plants were designed and built, the capital costs were unknown. Costs of the fuel cycle, including notably the durability of the fuel elements, were also unknown. It was believed that operating costs in nuclear plants would be lower because refueling was infrequent and the expenses nuclear weapons. Some may argue that the weapons have kept the world at peace for over forty-five years. Let us not debate the point: that peace is now happily finished.

Beyond the destruction of the nuclear weapons, decades of technical effort plus statesmanship of a high order will be required to establish a safe nuclear power economy. Is the effort worthwhile? Are the risks necessary?

We have considered in only the briefest terms the need for energy and electrical power in the Third World. We have not related it to the movement of population from the farm to the cities, or to the mechanization of agriculture thus required to support the tide of population growth. It is imprudent to the extreme to propose to less developed nations that they forego the additional energy inputs to agriculture and industry, which were the historical means for the development of Western civilization, in favor of speculations about alternate 'appropriate ' routes. We cannot expect the world to be reasonably stable without better living conditions for the billions of the dispossessed. They will not accept that the West has squandered the planet's carbon dioxide budget in pursuing its own development, and is unwilling to make the effort to replace it with longer term affordable energy. This, and not nuclear power, is the greater risk.

NOTES

1. It is worth noting that, despite the general impression that the growth of nuclear power was arrested in the mid-'70s, the number of operating plants increased by a factor of 2.5 in the decade of the '80s (Post TMI-2!).

2. Had the huge numbers of nuclear power plants optimistically projected in the early '70s been built, the expansion factor would be perhaps 5000.

3. T. Cochran, Nuclear Weapons Databook, Vol. II, Ballinger, Cambridge Mass. 1987.

4. L. Szilard, His version of the facts, MIT Press, 1978.

5. K.P. Cohen et al, Harold Clayton Urey, Biographical Memoirs of Fellows, Royal Society, London 1983.

6. Statistical Abstract of the U.S. 1990, Table 1470 U.S. Department of Commerce.

7. C. Starr et al, Science Vol. 256(1992) pp. 981-987

8. C. Starr et al, Ibid Table 2.

9. Y. Coupin & M.Giroux, Nuclear Europe Worldscan, Vol 3-4, 1992 pp. 27-28. 10. OECD-NEA/IAEA World Uranium Potential 1978.

11. W. Häfele,ed.Energy in a Finite World Table 4-8 Ballinger, Cambridge Mass. 1981.

12. A recent newspaper ad, NYTimes June 1,1992 by "Japanese citizens concerned about PLUTONIUM" introduced the term "weapon-ready" for reactor Pu.

13. National Academy of Sciences, *The Disposal of Radioactive Waste on Land* August 1957

Office of Technology Assessment,*Managing the Nation's Commercial High-Level Radioactive Waste* p.3 March 1985

Interagency Review Group on Nuclear Waste Management, *Report to the President* (1979) TID-29442 UC-70

14. BRWM, *Rethinking High-level Radioactive Waste Disposal* National Academy Press, Washington D.C. 1990

15. Norwegian Nuclear Power Commission, *Nuclear Power and Safety,* Oslo, Universitetsforlaget. 1978.

16. BRWM, *Ibid* p.vii.

17. Environmental Protection Agency, *40 CFR Part 191* 8/15/1985

18. *The California Nuclear Initiative* Stanford University Institute for Energy Studies, 1976

19. K.P. Cohen *Reflections on Nuclear Energy* ANS Annual Meeting, San Francisco, 11/27/1989

20. A.M. Weinberg et al,ed. *The Nuclear Connection* Chap.2, Washington Institute 1985.

21. J.L. Simon & H. Kahn,ed *The Resourceful Earth* Chap.14 Table 14.10.Basil Blackwell, New York 1984.