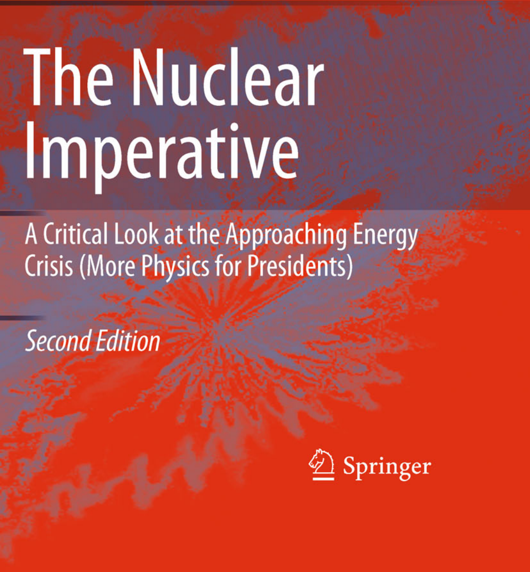
Topics in Safety, Risk, Reliability and Quality

Jeff W. Eerkens



The Nuclear Imperative

A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)

Second Edition

Springer

The Nuclear Imperative

Jeff W. Eerkens

The Nuclear Imperative

A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)

Springer

Jeff W. Eerkens
Adjunct Research Professor
Nuclear Science and Engineering Institute
University of Missouri
Columbia, USA
EerkensJ@missouri.edu

ISBN 978-90-481-8666-2 e-ISBN 978-90-481-8667-9
DOI 10.1007/978-90-481-8667-9
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2010930139

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

This book is dedicated to the memory of pioneer nuclear physicist Prof. Dr. Hans Bethe, 1906–2005

“He probed and deciphered the cosmos, revealing the enormous energy locked up in atomic nuclei”

Preface to the Second Edition

After finishing the first edition in 2005, many new developments in the energy field have emerged which necessitates some additions and modifications to my book "The Nuclear Imperative – A Critical Look at the Approaching Energy Crisis". Several new books have also been written that address the threats to our society when oil runs out. One new book written during the US election campaigns of 2008 was titled "Physics for Future Presidents" by physics professor Richard A. Muller of UC-Berkeley. Because new government administrators and presidents tend to have much influence on national energy policy, I have expanded the subtitle of my book in this second edition to "More Physics for Presidents", hoping new presidents worldwide will inform themselves of at least what I wrote in Chapters 1, 2, and 9. By "presidents", I mean here to include all decision-makers in our societies, whether future (i.e. young students) or present, liberal or conservative, corporate or government, Christian, Islamic, Buddhist, Hindu, or other, and whether European, Asian, African, or other ethnicity. Our planet Gaia does not care, as long as mankind keeps it healthy.

This book is written with emphasis on the technology of modern nuclear power and aimed at new generations who must steer our civilization through difficult times with no more oil. Of necessity the presentation is not entirely technical because there are many non-technical factors that influence the subject matter. It is a "hybrid" textbook and correctly belongs in the publisher's TSRQ series (TSRQ = Topics in Safety, Risk, Reliability, and Quality) which emphasizes the need to blend technology with societal factors. The book identifies and analyzes major upcoming energy problems in areas that will see substantial changes in the not so distant future and suggests some obvious practical solutions. It is not a nuclear engineering reactor design book of which there are already many good ones. Instead I have delved into my 50 years of experience dealing with high-technology energy systems to present my best engineering analyses (and opinions) with as little prejudice as possible. Most technical books restrict themselves to technical matter and try to avoid societal issues. However, the subject of nuclear power technology has been heavily infiltrated by non-technical influences and it is impossible to discuss nuclear power without discussing some of these.

Many from the baby-boomer generation still find it paradoxical and counter-intuitive that nuclear energy can save our planet. While growing up in the 1960s, 1970s, and 1980s they were indoctrinated to reject anything with "nuclear" or "radiation" attached to it, since it stood for bombs, deaths, and danger. They have a difficult time shedding these feelings. But knowing that the survival of their children and grandchildren depends on them, I hope that those who think rationally will now push for expanded nuclear power. Those who are still opposed should ask themselves how we will replace oil energy when it is gone. Exhortations from anti-nuclear herds asserting that wind and solar energy can take care of all future needs and that nuclear energy is not needed, are filled with very serious miscalculations. The so-called “renewables”, while helpful in supplementing small-quantity energy needs, can never sustain all future energy requirements of the world. An honest engineering study shows that at multi-gigawatt levels they are three times more costly than nuclear. Besides, one wonders why nature’s scenery and ecosystems must be spoiled with millions of man-made windmills and solar panels spread over millions of acres, when a single perfectly safe nuclear power plant can be built on twenty acres to provide the same amount of energy. In the eyes of experienced utility engineers, the renewables-only scenarios trumpeted by a variety of anti-nuclear groups are impractical unrealistic fantasies and will be costly debacles if carried out. Worse than naiveté however is that later generations will see present anti-nuclear activists as being guilty of aiding and abetting the collapse of Western civilization, which too many of our enemies fervently desire. Without greatly expanded nuclear power the world will assuredly experience a calamitous depression by 2050 with worse consequences than an all-out nuclear war.

While finishing the first edition of this book, the great nuclear physics pioneer Hans Bethe died, whom I commemorated in my book and still do. During work on this second edition, another talented independent thinker departed: movie actor and producer Paul Newman. Like James Lovelock, a renowned naturalist from England, and Patrick Moore, co-founder of Greenpeace, Paul Newman concluded also that to rescue our children from future energy starvation we must take advantage of the atom. To keep Gaia (Mother Earth) from being despoiled by millions of scenery effacing, desert-smashing wind-mills and solar panels, only green nuclear power can save it. Paul came to that conviction after careful investigations and comprehension of the true dimensions of nuclear power and the pending oil-field depletions, even though in earlier days his pacifist nature had opposed the use of nuclear energy. I was much honored to share a page with him in the Nuclear Energy Institute’s monthly circular “NE Insight” of June, 2007, which covered Paul Newman’s tour of the Indian Point nuclear power plant, and a discussion of my book “The Nuclear Imperative”.

As is almost inevitable, there were some errors that sneaked into the first edition. With this new second edition, the necessary corrections were made. An entirely new chapter on “renewables” (Chapter 4) was added, mostly about solar and wind power. They have become quite popular in the last few years and cannot be ignored when one considers future energy sources. All later chapters from the first edition were moved up one notch but otherwise cover the same topics. Except they are largely rewritten and expanded. It must be emphasized again that I wrote this book entirely on my own without support from any special interests, whether private, commercial, or government.

October, 2009 Jeff W. Eerkens

Preface to the First Edition

Part of this book was originally written in 1976 when some thirty copies were printed and distributed to interested parties. A wider distribution was planned but never carried out. In re-reading the first edition written 30 years ago, I am struck by the fact that arguments for a nuclear-powered future and the need to develop portable synfuels have remained unchanged over all these years. Also interest in international weapons control and nuclear non-proliferation is still as strong today as it was in 1976. Some of my original comments on these issues (Chapter 8) still apply today and are independent of political persuasions.

This book can be used as a textbook in an introductory course on nuclear engineering. The subject matter is excellent for a first-year college class of students planning a career in engineering, economics, political science, law, and disciplines involving the structuring of future society. The book is also recommended reading for high-school seniors contemplating a higher education. Familiarity with high-school physics and chemistry is helpful, but “one does not have to be a rocket scientist” to understand the essential issues. All technical material is based on “hard” science, as opposed to dubious “pop” or “junk” science one often sees which distorts the facts and exploits people’s predilection for the sensational.

The Three-Mile-Island (TMI) reactor meltdown in the US which occurred on March 28, 1979, and the Chernobyl reactor disaster that took place on April 26, 1986, caused an unfortunate slow-down and in some countries a moratorium on the construction of new nuclear power plants. However these accidents resulted in vastly improved safety measures in nuclear reactor operations. They also proved that a “maximum credible” reactor accident (a reactor meltdown) does not “kill thousands of people” as predicted by those opposed to the development of nuclear energy. In fact, the early safety measures built into American and West-European reactors, comprising a large steel and concrete containment vessel and other features, were shown to perform as designed. Thanks to TMI’s containment vessel and pressurized water coolant system which provides a negative temperature coefficient of reactivity, the TMI accident in Pennsylvania did not harm a single person. However the Chernobyl reactor in the Ukraine had no containment vessel and used a graphite moderator with positive reactivity coefficient. Operator error induced a runaway reactor melt-down, causing the graphite to burn chemically with atmospheric oxygen. Non-nuclear-educated firemen from nearby cities who attempted to put out the fire, received serious overexposures of radiation. They had not been warned thereof due to bureaucratic territorialism and unnecessary secrecy. Ultimately 45 people died due to the Chernobyl reactor meltdown and 30 suffered permanent disabilities according to the International Atomic Energy Agency. Today's regulations require all nuclear power reactors to shut themselves down when they get too hot (= negative coefficient of reactivity) and to provide a containment vessel around the reactor, designed to hold all radioactive debris in case of a reactor melt-down accident.

While the electric power industry suffered a set-back in the public acceptance of nuclear energy, the reasons for expanding construction of new nuclear power plants three decades ago have not changed and in fact have become more urgent. After demise of oil and gaseous petrofuels from the earth, only coal and uranium (perhaps deuterium/tritium in the next century) are left as prime sources to provide us with large-scale quantities of energy. Large quantities of prime energy are needed in the future to synthesize hydrogen, ammonia, hydrazine, and other portable "synfuels" to move our transportation fleets (cars, trucks, trains, ships, aircraft, etc.), and to energize our heavy industries (steel-production, ship-building, auto manufacturing, etc.). Uranium can satisfy this demand for at least 1,000 years with much less waste and real estate problems and with vastly better economics than "renewable" solar-cells and wind-farms ever could. In the USA, coal-fired power plants presently produce 52%, uranium fission generates 21%, natural gas and oil-burning units contribute 15%, and hydro + geothermal + others yield 12% of all electricity (3.5 billion MWh(e)/year). Burning of coal, oil, or natural gas produces heat. In a power plant this heat vaporizes water into high-pressure steam which is converted into electricity by steam turbines. In a nuclear plant, water is heated by fissioning uranium; otherwise the same electric generation is used as in coal-fired plants that is with steam turbines. However coal, oil and natural gas pollute the atmosphere enormously when burnt with atmospheric oxygen (O_2), since they produce globe-warming gaseous carbon dioxide (CO_2). In theory, without oil and uranium, coal could supply the world with all needed energy for some 100 years. But it would be insanity not to generate electricity for the next 1,000 years utilizing non-polluting fissioning of uranium instead of burning coal, knowing that uranium has little other use. When oil is gone, only coal (and wood) can still provide raw material for making plastics and other carbonaceous compounds widely used today; it should not be burnt! The oft-quoted "problem of radioactive waste" produced by reactors is highly exaggerated. "The problem" is nonexistent for nuclear engineers who have no difficulty concentrating and packing solid oxidized fission products from one hundred US nuclear power plants in a few hundred drums yearly for underground storage.

This book is not the first nor will it be the last one that warns of an impending energy crisis. The annotated bibliography lists books giving similar serious warnings, which seem to be unheeded by mal-informed governments. The main message of this book is that doom of our civilization due to depletion of oil is not inevitable if the correct measures are taken. Current government energy policies seem influenced by dogmatically anti-nuclear lobbyists who believe only "renewable" wind and solar farms can solve future energy problems. Nuclear and coal power plant experts should be consulted instead when making policy decisions. The sun provides a year-averaged 500 W of light energy per square meter, and most strong winds blow only 20% of the time. No amount of legislation can alter those facts. Also in round numbers, the earth once possessed 4 trillion barrels of oil and 20 quadrillion cubic feet of natural gas (natgas) from fossil remains, including oil from tar-sands and natgas from sea-beds. Of these, 2.5 trillion barrels of oil and 15 quadrillion cubic feet of natgas are left today. In addition earth also possesses 6 trillion tons of coal and 10 million tons of exploitable uranium at present. With average energy consumption leveling to 1.3 kW(e) per person and a stabilizing world population of 7 billion people, it would take 17 years to deplete all oil, 18 years for all natgas, 153 years for all coal, and 1,000 years to burn up all uranium, *assuming* each were the *only* prime energy source for electricity and portable fuel production. Presently (2005), world consumption is 0.7 kW(e) per person, but Asia is expected to raise this to 1.3 kW(e) in 10 years. The U.S., with 4.5% of the world population, consumes 4.4 kW(e) per capita at present. However roughly 1.2 kW(e) is spent on the electricity-intensive manufacture of exported goods (aircraft, autos, bulldozers, ships, etc) and only 3.2 kW(e) is self-consumed. Here 1 kW(e) of high-grade electrical energy is assumed to equal approximately 3 kW of heat energy.

It is important to point out that the per capita energy consumption includes each person's share of the fuel energy consumed by transportation fleets (cars, buses, aviation, etc.), by the manufacture of goods (automobiles, trains, television sets, etc.), by agriculture, by food distribution, etc. The oft-quoted figure of 0.6 kW(e) per person (2.4 kW(e) per home) applies only to the average electric grid energy consumed in rural households of North America, and does not include their consumption of petrol energy or their share in energy for the production of goods or foods they use. The latter energies must be added to their "electric bill" since primary electricity must manufacture all portable synthetic fuels when oil is gone.

Because so much misinformation has been disseminated about nuclear power generation, after the introduction, the book starts out with a review of facts and fables about nuclear energy in Chapter 2. Chapter 3 is perhaps the most important part of the book. It gives the reasons why everyone, including anti-technology environmentalists, should endorse uranium-fueled power generation lest they want to be responsible for globe-warming CO_2 from burning coal and coal-derived synthetic fuels in the next decades. If they abandon nuclear power and do not wish to burn coal either, they must be prepared to eliminate 90% of the world's population after oil runs out. Chapter 3 reviews current energy consumption rates by humans on planet earth and the finite reserves of the world's prime energy sources. The numbers show irrefutably that if we want to reduce global warming and save coal for making plastics and synthetic hydrocarbons, only full exploitation of nuclear energy can save mankind from economic collapse when fossil fuels run out. Wind and solar electric power generation is helpful but only a band-aid (Chapter 4). It could never provide the enormous quantities of energy needed to replace all oil-derived fuel with synthetic fuels to sustain our transportation fleets (cars, airplanes, etc.). Similarly, saving energy by better home insulation and improving auto engine efficiencies, is useful and should be encouraged. But they cannot change the fact that oil will still run out, as more people on the planet consume it. Chapter 5 reviews propulsion techniques using portable fuels synthesized with the help of primary nuclear electricity. The synfuels should be tested and available by 2020 to start the massive replacement of petrol in order to avoid serious economic upheavals 25 years from now. We *can* survive 2030, but planning and preparations must be started *now*. If replacements of present propulsion technologies and new synfuel productions are not initiated in time, we may see endless wars to control the last remaining oil fields and terrorist activities that make Al Qaeda's atrocities pale by comparison.

Following the first five chapters, back-up material is presented on key features of nuclear reactors, environmental concerns, radiation physics, and security issues, which have been questioned by so many. Factual material for this book was gathered from numerous reports, books, and journal articles written by nuclear professionals worldwide. With the exception of a few always-present contrarians, the vast majority of some 250,000 professional engineers in the nuclear energy field are in agreement with the material presented in this book.

In summary, this book is an admonition that the world must stop vilifying nuclear energy and rapidly expand this unique energy source so we can overcome the pending out-of-oil crisis. Nuclear proliferation concerns and nuclear security issues can be and must be resolved. We don't have any choice if we want to survive oil depletion and stop burning globe-warming coal. Some recent books acknowledging the up-coming energy crisis, project it as inescapable and forecast gloom and doom for our progeny. This book refutes such a scenario and shows a workable solution based on proven technology and scientific facts. Nuclear power should be supported by everyone, in particular by environmentalists. Providence is giving mankind one clear (and clean!) way out of the predicaments it faces when oil is no longer available.

Most derived numbers in the book are scientifically reasonable estimates. But because no one can predict exactly how many people will populate our globe in the next 30 years or how much energy each will consume, and no one knows the precise cost of (future) hardware, there are minor variations of some numbers in different chapters, with which some "preciseniks" may find fault. They do not invalidate the main conclusions of the book however. Most of this book was written in 2003 and 2004, but at the publisher's request a discussion on Risk Analysis was added as Section 1.2 in 2005. As this book was readied for publication, my attention was called to J.H. Kunstler's recent book titled *The Long Emergency*, and Alan E. Waltar's *Radiation and Modern Life; Fulfilling Marie Curie's Dream.* Kunstler expresses the same concerns about the pending energy crisis as I do, but offers no solution to overcome this crisis. My prognosis is more optimistic, *provided* the public listens to hands-on nuclear energy engineers, and ignores anti-nuclear armchair philosophers who use fictitious science. Waltar's opus complements this book and shows how important and unavoidable nuclear energy already is in our daily life.

November, 2005 Jeff W. Eerkens

Contents

List of Briefs

Abstract

The importance of uranium-generated nuclear power is discussed. The review forecasts severe shortages of oil and natural gas in 20 years, and their depletion in 40 years. With a moratorium on burning coal to prevent global warming, it is shown that uranium-produced electricity and heat is essential for large-scale future productions of synfuels (hydrogen, ammonia, hydrazine, and alcohol) made from air, water, and sunshine to replace the portable petro-fuels presently propelling our vast transportation fleets. Generation of "renewable" solar and wind power is helpful but, unlike nuclear energy, is unable to provide the enormous quantities of prime energy needed for the economic manufacture of synfuels to replace fossil fuels. Nuclear power from uranium and thorium is available as a primary energy source for 3,000 years to provide all the world's needs for electricity and synfuels at an affordable cost. By manufacturing synthetic fuels from air and water with nuclear heat or electricity, non-portable nuclear energy is in effect converted to portable fuel energy.

The introduction of the book outlines its objectives and reviews four options for combating the upcoming out-of-oil crisis. The second chapter lists common misconceptions about nuclear energy to allay public fears of this all-important energy source. It is followed in a third chapter with a survey of energy consumption rates on planet earth. The fourth chapter discusses renewable energy sources (solar and wind) while the fifth chapter is devoted to synfuel production, and combustion engines or fuel-cells that convert chemical energy from synfuels into locomotion. The last four chapters cover nuclear reactor operations, radiation effects, safety, nuclear weapons proliferation issues, and action items. A university-level education is not required for understanding the book, but exposure to some high-school physics and chemistry will be helpful.

Chapter 1
Introduction

In the next few decades, mankind will be facing two very serious problems: (1) *oil depletion*, and (2) *biosphere pollution* which is accelerating nature's *global warming* process. A unique solution which at once can solve both of these threats does exist in the form of greatly expanded utilization of modern nuclear power. Yet many malinformed governments, techno-phobes, and fringe environmentalists are trying to obstruct its development for no good reason other than an emotional one, preferring endless deliberations and political maneuvers instead of trying to comprehend the warnings by engineers. They are unaware they promote the collapse of modern civilization, a goal also sought by terrorists. This book was written without support from any special interest group, industry, or political party. It expresses the author's sincere concern about the fate of future generations.

1.1 Oil Depletion

"What do we do when the well runs dry, my honey? What do we do …." This old American folk-song reflects a very basic problem facing all humans. When the song was written more than a hundred years ago, it referred to the American pioneers who settled on the prairies of the Midwest, and whose water needs depended totally on wells. Without water man cannot survive. Today we can probably assert that without petrol (= gasoline, diesel, etc.), most of us would perish. Our water is pumped to our house by pumps run on petrol.[1] Food is brought to our markets by trucks run on petrol. We drive to our jobs and stores in cars run on petrol. Farmers

---

[1] The British "petrol", called "gasoline" in the USA, "benzin" in Germany, and by other names, will be used from here on for fuel extracted from refined crude oil. Diesel fuel is assumed to be part of petrol supplies unless mentioned separately.

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_1, © Springer Science+Business Media B.V. 2010

grow crops using machinery run on petrol. We visit family and friends in distant cities traveling on airplanes, ships, trains, buses, or cars run by petrol. Clearly our modern world depends totally on refined portable petroleum fuels, be they petrol, diesel oil, aviation gasoline, kerosene, natural gas, or other derivatives of fossil fuels. These fuels were created by sun-grown plants (solar energy) that decayed on the earth surface over a period of 300 million years and accumulated in underground reservoirs. We are burning these fossil fuels up in a few hundred years and by 2050 the world's oil fields will be exhausted as discussed in Chapter 3. The USA is consuming one fifth of the world's petrol and after reaching a peak in pumping oil from its own territories, it is now importing a third of its oil needs from other countries.

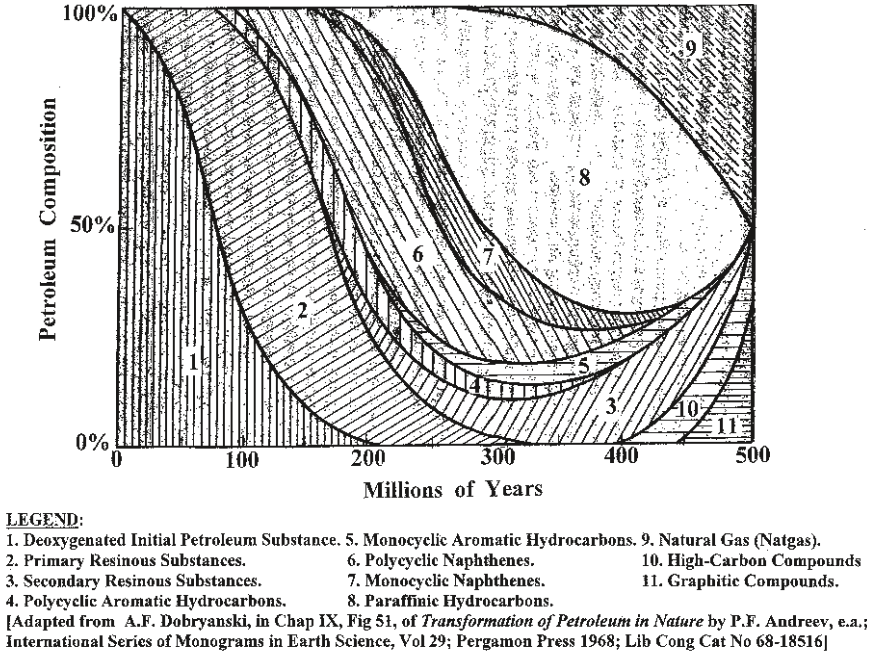
Can a new "Declaration of Independence from Oil" be formulated and enacted? Many people tacitly assume that petrol to run our cars, trucks, airplanes, trains, and ships will be available forever. If asked what they would do if there was no more petrol, they often answer "Our engineers will figure out something", or "It won't happen during my lifetime so I don't worry about it". But power engineers, who have studied the world's energy requirements and consumptions, are worried. What bothers them most is that there are workable solutions to the problem which are being ignored or obstructed by a number of governments because of misunderstandings and ignorance. Many government politicians have been persuaded by special-interest groups to subsidize costly "alternative" energy projects without consulting senior experienced energy providers and technologists who have handled power generation for decades. They are funding studies of alternative energy programs currently in vogue such as wind farms, solar cells, solar concentrators, etc., and claim that all oil can be replaced by growing bio-fuel vegetation. This lulls the public into believing that everything is under control while it is not. These "renewable" power-generation schemes can only be supplemental as discussed later. Compared to nuclear, they are economically much inferior to provide the large amounts of electric energy needed to replace present oil-based fuels with manufactured synthetic fuels and plug-in electricity for the world's transportation fleets. With a world approaching eight billion people, new nuclear energy programs must be funded *now* to prevent a serious energy crisis in the near-future.

The oil we are burning up in two centuries represents biomass from decayed plants, photo-synthesized by the sun over a period of several hundred million years. Decayed vegetation, spread out over some 20% of the earth surface and mixed with a lot of sand and mud at river estuaries, was precipitated in kilometer-thick layers that were subsequently shoved over and under continental shelves. As shown in Brief 1,[2] after hundreds of millions of years, high pressures and temperatures slowly converted

---

[2] We shall use the word "brief" for any table, chart, sketch, or figure that summarizes or illustrates a concept.

this decayed biomass into oil (see also Section 1.4.1). Biomass, whether live (e.g. wood, corn) or dead (oil), represents captured solar energy since the organic molecules in the plants from which it originates, absorbed energy-carrying solar photons that helped multiply and convert the plants into burnable hydrocarbons using nutrient molecules and water from the earth and carbon dioxide (CO_2) from the air. Effectively solar energy is thereby stored in the form of chemical energy by a process called photosynthesis. Since the solar flux at the earth surface has not changed in the past 300 million years by more than a factor of 2, it is difficult to imagine that one can match man's present oil consumption rates entirely by growing new biomass a 1,000 times faster than nature did, even with modern agricultural sophistications. Here we assume that 0.1% of all plant growth in the past resulted in oil or tar. Only with a major energy input of prime nuclear electricity to run farm equipment and distill out alcohols, could one replace US petrol consumption. Even then, one would have to plant half of all arable land in the USA with bio-fuel crops to satisfy demand. Since man must also cultivate food crops, the more likely future long-haul transport fuels will be a mix of synfuels with (10–15%) biofuels and (85–90%) hydrogen-derived ammonia synthesized from water and air (Chapter 5) with nuclear power inputs.



LEGEND:
1. Deoxygenated Initial Petroleum Substance.
2. Primary Resinous Substances.
3. Secondary Resinous Substances.
4. Polycyclic Aromatic Hydrocarbons.
5. Monocyclic Aromatic Hydrocarbons.
6. Polycyclic Naphthenes.
7. Monocyclic Naphthenes.
8. Paraffinic Hydrocarbons.
9. Natural Gas (Natgas).
10. High-Carbon Compounds
11. Graphitic Compounds.

[Adapted from A.F. Dobryanski, in Chap IX, Fig 51, of *Transformation of Petroleum in Nature* by P.F. Andreev, e.a.; International Series of Monograms in Earth Science, Vol 29; Pergamon Press 1968; Lib Cong Cat No 68-18516]

Brief 1 Transformation of petroleum in nature

This book is a warning and an alert to heed the call for prompt expansion of nuclear electric power to stave off future shortages of electricity and synfuels needed for propelling cars, trucks, trains, aircraft, and ships. By optimistic estimates, at present rates reasonably accessible oil and gas reserves will be depleted in 40 years if consumption continues to increase at current levels. Oil retrieval rates have been declining since the mid-1990s in the USA and worldwide "peak-oil" is expected by 2015. Thereafter, new demand will exceed new discoveries and oil supplies will gradually go down-hill. Unless preventive measures are taken immediately, steadily increasing oil shortages and supply interruptions will reach a crescendo by 2030, triggering a collapse of our present oil-dependent way-of-life. If anyone questions this, any doubts should have vanished when the tripling of crude oil prices to $147 per barrel in 2008 caused a doubling of petrol prices at-the-pump, which started a recession that was further aggravated by a collapse of the real estate market. Wild claims are being made that new tar-sand fields and new discoveries of deep-sea oil deposits could give us hundreds of years of added oil. But on closer scrutiny one finds that the biggest of these new finds equate to only 1 or 2 years of US oil consumption. And for some it takes more than a barrel of oil to recover one. The laws of physics are unassailable: nothing comes for nothing. Boone Pickens, a well-known US oil business legend, estimates that oil supply rates will get stuck at 85 million barrels per day in the next decade (2010–2020) while demand for oil will keep rising to 90 million barrels per day by 2019. The only way demand will go lower after peak oil is a price increase. By 2020 Pickens estimates oil will sell at $300/barrel. He believes all coal- and oil-burning power plants and transport operations should be encouraged and subsidized to burn natural gas (natgas)[3] instead. However while this may be sustainable for a decade or so, natgas will also be depleted. It is useful as an interim solution before sufficient numbers of nuclear power plants can be built to manufacture all needed portable synfuels as discussed in Chapter 5. Otherwise natgas, like coal, must be conserved as much as possible as raw material for making plastics and organics (Section 9.1.6).

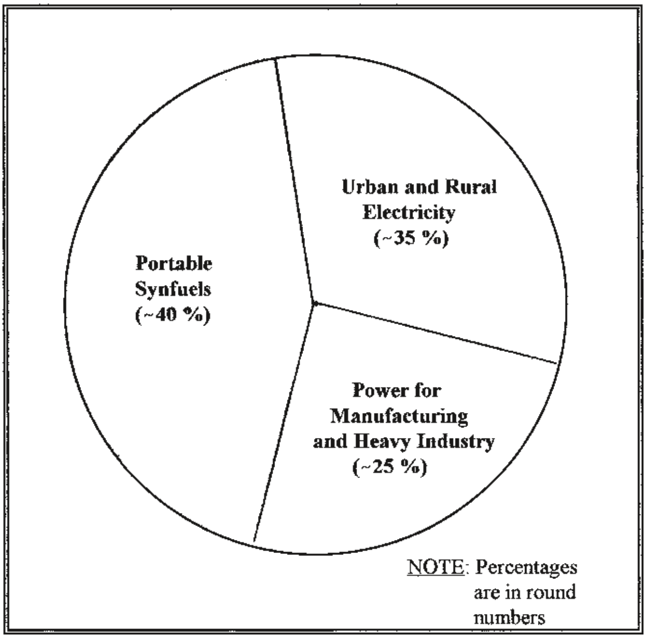
To overcome the looming oil depletion crisis, new propulsion systems must be developed that are run on new manufactured fuels (hydrogen, ammonia, hydrazine, bio-fuels, etc.) which are synthesized from air and water or extracted from biomass with the aid of nuclear- or coal-generated electricity or heat. Uranium and thorium can provide prime "mother" energy needed to mass-produce such synfuels globally for more than 3,000 years, while coal could do this for about 100 years. However coal should be preserved for the manufacture of plastics and other organics-based materials when oil is gone. In addition, coal combustion promotes global warming, and its use in generating electricity should be replaced

---

[3] From here on we shall abbreviate "natgas" for natural gas, which is a mixture of methane (mostly), ethane, propane, butane.

with non-air-polluting nuclear power plants. Unless one wants to promote a 90% reduction of the present world population by famine and wars, the only way to prevent a serious economic crisis after 2030 is to start the immediate expansion of uranium-consuming and -breeding electric power plants. Such undertakings require a lot of preparation. A typical nuclear plant takes 8 years or more to construct before it delivers its first kilowatt or liter of synfuel. Of this period, 3–4 years is spent on NRC (Nuclear Regulatory Commission) approvals, local site permits, and public hearings. The impatient public will not understand why one cannot start using synfuels much sooner. Unless certain lobbyists and misinformed politicians reconsider their stubborn opposition to nuclear power, humanity will be heading straight into a storm without fuel. Knowing that affordable multi-giga-watt nuclear power can be made available, it is economic folly to replace oil energy only with expensive wind and solar energy sources as some have proposed.

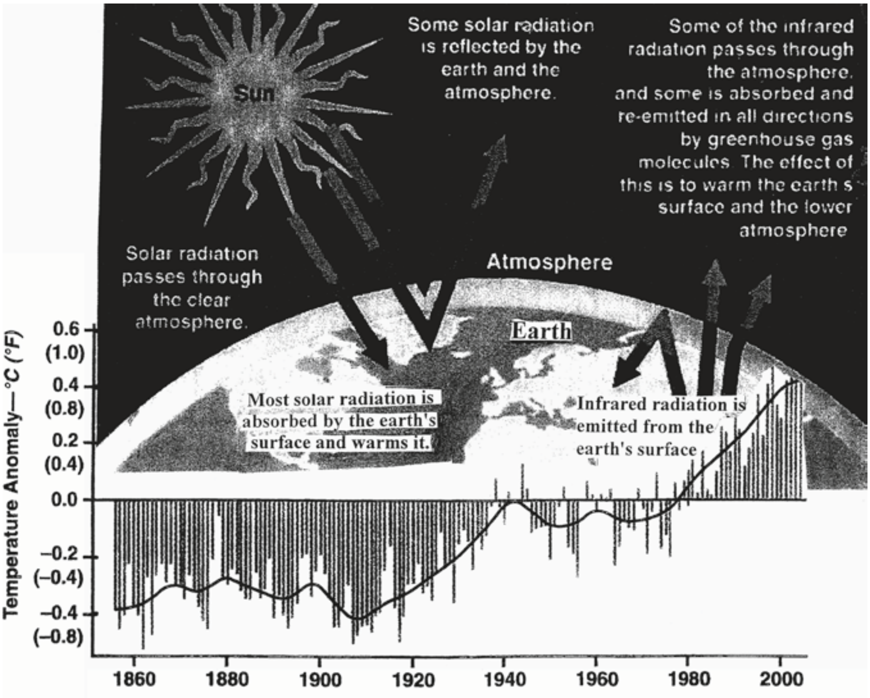
As shown in Brief 2, oil energy used for transportation comprises about 40% of man's total energy consumption. The concept of energy will be discussed in more detail in Chapter 3, but today's society uses two basic types of energy. One is in the form of portable fuels and storage batteries. These can be carried along and propel transport vehicles (cars, trucks, trains, ships, aircraft, etc.) or empower fuel-burning machines in remote locations. The other form of energy is electricity which is fed via the "grid" (= electric high-power lines) from a power plant to homes and industries to operate electric motors, machines, lights, instruments, appliances, etc. To empower electric trains, special electric contact wires are used along railroad tracks. Electricity or electric energy comprises a current of electrons which move through conducting wires. Such electric currents can induce mechanical motion in dynamos, produce heat or light by heating a resistor, or be manipulated to generate modulated radio-waves, sound, video, etc. for communication and information systems. While "plug-in" electric grid energy cannot be carried along by transport vehicles, one can convert electric energy into portable energy by charging an electric storage battery or capacitor, or by storing it in the form of chemical energy via synthesis of a synfuel such as hydrogen obtained by electrolysis of water (Chapter 5). Conversely, chemical combustion or (nuclear) heat energy can be converted into mechanical and electric energy via turbo-engines or turbo-generators (Chapters 5 and 6). Such energy transformations in either direction are never 100% efficient but always waste some energy during the conversion process. These losses can be calculated from well-established physical laws. Because of the "conservation-of-energy" law, both portable and plug-in energy usage by man can be lumped together to assess their total energy supply and demand and to determine whether resources are sufficient to sustain man's needs. Clearly if 40% of man's energy usage is suddenly unavailable as will happen when oil-fields dry up, an enormous energy crisis will result. It is therefore prudent to prepare for this in a timely manner and arrange for a gradual build-up of new portable energy sources that can replace oil energy.



Brief 2 Future global energy pie

1.2 Global Warming

In addition to a looming out-of-oil crisis, the world is also facing biosphere pollution and global warming problems believed to be due in part to increased concentrations of gaseous carbon dioxide (CO_2) in the biosphere that are produced by coal-burning power plants and petrol-burning automobiles. Clearly if petrol fuels can be replaced by "green" synthetic fuels that do not exhaust infrared-absorbing gases such as CO_2 and N_xO_y (so-called "greenhouse" gases), the two distinct problems of aggravating global warming and oil depletion are simultaneously solved. Further, by replacing coal-burning power plants with nuclear power plants, globe-warming CO_2 pollution can be totally eliminated. While observed small changes in the earth–sun orientation and orbit also tend to increase or decrease global warming and have produced our planet's ice ages in past millennia, man's contributions since the birth of the industrial revolution around 1800 (with heavy burning of coal and oil) appear real as shown in Brief 3. The bottom curve in Brief 3 shows a gradual increase of the world's average biosphere temperature in step with an increase in the CO_2 concentration of the atmosphere. Most of this CO_2 concentration increase can be correlated to the exhaust of burning coal and fossil fuels produced by increasing numbers of power plants and transport vehicles (cars, trucks, trains, ships, and aircraft). The observed melting of glaciers, receding Arctic ice-fields, sea-level rises, and warming of the oceans all seem to support global warming. It has alarmed cities, islands, and countries that are at or near sea-level for fear of future inundation. Tropical hurricanes are also claimed to become more aggressive as oceans become warmer.



Brief 3 Global warming by atmospheric greenhouse gases

The first concerns about the effects of global warming and climate change were voiced in the late 1970s in some United Nations (UN) reports. This led to the Earth Summit Conference in Rio de Janeiro in 1992, where a special Convention on Climate Change presented scientific studies showing the potential threats of global warming due to increased industrialization and deforestation programs around the world. The representatives of world governments at the Rio Convention were asked to sign 26 articles to acknowledge the serious nature of global warming, and 154 countries including the USA signed. Subsequent Conferences of the (Rio) Parties, called COPs were held at different locations. COP-1 was held in Berlin in 1995, but the most famous called COP-3 was held in Kyoto, Japan in 1997, where countries were asked to sign the so-called Kyoto Protocol and where then-Vice President Al Gore signed for the USA. However this tentative agreement to enforce the Kyoto Protocol had to be ratified by the US Congress which never took place. Upon closer examination, it became clear that highly industrialized countries like the USA were unfairly taxed and penalized under the rules of the Protocol, while developing nations were given too many advantages. The Protocol sets legally binding targets to reduce green-house gas (GHG) emissions with specific deadlines and heavy penalties for non-compliance. These differed considerably for already-developed and still-developing nations. Many legislators in the US feel that it was an underhanded attempt by a band of over-zealous environmentalists to impose their programs on the rest of the world without considering the "unintended consequences". Some believe it was even with intent to harm the US and its standard of living.

In an excellent article by Eric P. Loewen and Sama Bilbao-y-Leon published in the ANS' Nuclear News of April 2001, p. 23 (Ref. II-10), Loewen and Leon summarize the most significant features of the 1997 Kyoto Protocol as it affects the USA:

(a) Developed countries ratifying the (Kyoto) Protocol shall commit themselves to reducing the emissions of six key GHGs to at least 5% below 1990 levels during the period 2008–2012. The six GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).

(b) Reduction of GHG emissions for the highest polluting country, the USA, is to be 7% (instead of 5%) below 1,990 levels. Emissions of CO_2 in the US were 14% higher in the year 2000 (about 5.6×10^9 t) compared to 1990 (4.9×10^9 t). To meet the Kyoto Protocol, a reduction of 1.04×10^9 t would then be required. Physically such an amount is equivalent to the total emissions of all US petrol-powered vehicles (cars, trucks, SUVs, etc.), and would require the removal of all these vehicles from US roads forever.

(c) Governments are encouraged to cooperate with each other to improve energy efficiency and reform the energy and transportation sectors. Renewable forms of energy should be promoted and inappropriate fiscal measures and market imperfections should be phased out, i.e. the economics of power generation should be ignored and renewables should be favored by edict. Methane emissions from waste management and energy systems must be limited, while forests and other carbon sinks must be protected.

After the 1997 COP-3 meeting in Kyoto, additional COP-4 and COP-5 meetings were held to persuade more countries to sign the Kyoto Protocol. COL-6 held in The Hague, The Netherlands in November 2000, was devoted to better define some details for Protocol implementation and enforcement which had been rather vague. However while agreeing to promote the concept of reducing GHG emissions, the US delegation was still unconvinced that ratifying the punitive Kyoto Protocol would be in the US's best interest. As of 2005, the Kyoto Protocol had been signed by 84 country representatives, but ratified by only 24 governments. More information about the Kyoto Protocol and their organizers can be found in the paper by Loewen and Leon.

In the US, prominent climate scientists such as NASA's James Hansen and political figures like former vice-president Al Gore personally started initiatives in the late 1990s to arouse public awareness of the undesirable effect of carbon dioxide (= CO_2) emissions from coal-burning plants and oil-burning vehicles. Al Gore produced a movie "An Inconvenient Truth" showing the disastrous outcomes of unrestricted global CO_2 pollution and received the Nobel Prize for his efforts. It is estimated that worldwide 30 billion tons of CO_2 are wafted into the biosphere annually (US contributes about 6 billion tons) of which about 15 billion tons stay there for some time. The oceans and fauna of the earth also exchange large quantities of CO_2 with the biosphere which have tended to keep the amount of CO_2 in the atmosphere balanced within a range between 0.01% and 0.05% over the past 100,000 years. In 1800 it was approximately 0.028% which has risen to 0.039% in 2000 and has caused increased acidification (carbonic acid concentrations) as well as a warming of our oceans. The upward trend predicts concentrations above 0.04% in the next decade. Even though man's input to the atmospheric CO_2 load is only 2% and decaying vegetation contributes 98%, many believe this is enough to "tip" the natural equilibrium between the earth's fauna, oceans, and atmosphere in an undesirable (warming) direction. Although the US has not officially embraced the Kyoto Protocol, the federal EPA (Environmental Protection Agency) has ordered power plants and vehicles to limit their exhaust of air pollutants, while the State of California has issued even stricter regulations to curtail automobile exhausts and power plant emissions.

The concentration of CO_2 in the atmosphere is only 0.039% (in 2009), but this molecule can be shown from basic science to cause significant biosphere warming. CO_2 molecules absorb infrared (IR) radiation emitted by the earth and re-radiate a good portion of it back to earth (Brief 3). In general, IR photons can excite resonant vibrations in multi-atomic molecules that possess different atoms. The IR-excited vibrations are held for a few milliseconds but their energy is next either re-emitted as IR photons or converted into kinetic energy (= heat) in so-called VT collisions (VT = Vibration-to-Translation energy transfer) with other atmospheric molecules, mostly oxygen (O_2) and nitrogen (N_2). The mono-atomic O_2 and N_2 molecules themselves do not absorb infrared radiation. Precisely what fraction is re-emitted and how much is VT-ed depends on atmospheric temperature, pressure, and altitude, and is only coarsely predictable. While the solar photon spectrum is mostly in the visible, the sun also supplies some IR radiation that is absorbed by the atmosphere during daytime. Analyzing the balances of all these processes and their responses in the atmosphere is extremely complex and the subject of intensive theoretical as well as experimental studies by climatologists.

Besides gaseous CO_2, in 2009 the US Environmental protection Agency (EPA) added emissions of natgas, i.e. methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons ($C_kH_mF_n$), perfluorocarbons (C_mF_n), and sulfur hexafluoride (SF_6) as possible threats to the atmosphere in conformance with the Kyoto Protocol. According to a 1998 report, computer studies estimate their contributions to global warming and their anthropogenic sources to be: CO_2, 50% [from coal power plants and auto exhausts]; CH_4, 15% [from cattle farms]; N_2O, 5% [from agriculture]; $C_kH_mF_n + C_mF_n + SF_6$, 20% [from air-conditioners, refrigeration, degreasing, transformers]. These additional molecules can also absorb and re-emit IR radiation, but their main undesirable behavior is believed due to their effect on the ozone (O_3) layer that envelopes the earth which cuts down on the level of ultraviolet (UV) radiation coming from the sun before it reaches the earth surface. N_2O is quite stable and can stay in the troposphere for 100 years as a greenhouse gas. When it migrates into the stratosphere, N_2O is dissociated by solar UV photons to NO and O, after which the NO reacts with O_3 to form NO_2 and O_2. Less stable NO_2 in turn reacts with O in the stratosphere to reform NO, etc. Similarly, lighter-than-air methane molecules buoy up into the upper atmosphere and react directly with ozone, while gaseous fluorine-bearing compounds are assumed to attack ozone in steps after they are dissociated by solar UV in the stratosphere.

Many reputable scientists have questioned whether the 2% contribution of man-made CO_2 is sufficient to affect the natural heat balances in the atmosphere so that it can enhance global warming. They feel that sufficient scientific evidence is lacking and are not convinced the earth is warming up due to man. They therefore wonder if it is worth the billions of dollars needed to combat manmade CO_2 pollution of the atmosphere since it is down-grading our way of life. The counter-argument is that mankind cannot afford to be wrong with such a serious threat and must curtail CO_2 pollution of the biosphere immediately, right or wrong. The present global groundswell to suppress CO_2 emissions and punish polluters has resulted in "carbon taxations" on industries that emit CO_2. This is certainly helping the development of more "green" nuclear power. But rescuing our planet from economic collapse due to exhausted oil fields is even more important and urgent than minimizing global warming.

Environmental activists often greatly exaggerate unsubstantiated imagined threats, promoting overkill regulations which have decreased their credibility. While lightweight molecules such as methane and nitrous oxide can diffuse and rise up high into the atmosphere with relative ease, some skeptics wonder whether much heavier fluorinated molecules ($C_kH_mF_n$, C_mF_n, and SF_6) tagged by the Kyoto Protocol could rise up high enough into the stratosphere to contribute significantly to ozone depletion and biosphere warming. These gases hug the ground if released into the air. They can react with ozone (O_3) under UV radiolysis as observed in laboratories and they could attack the earth's ozone layer if intermixed. But in nature this can only happen at very high altitudes where such heavy gases hardly enter unless they are blown up there by volcanic eruptions – not by man-made activities. Lots of ozone destruction is believed to be caused by N_2O emitted from agricultural soils and some feel that the earlier finger-pointing at fluorocarbons (due to *one* terrestrial lab experiment) was exaggerated. More experimental evidence is needed to verify that these industrially important gases in air conditioning and cooling systems require the strict curtailment that has been imposed on them.

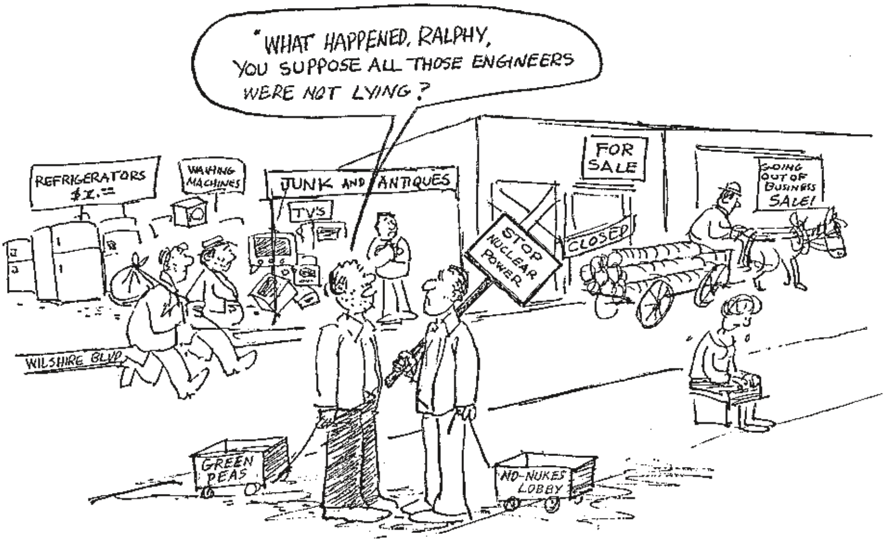
1.3 Preparations for the Impending Out-of-Oil Crisis

There are those in the general public who believe that nuclear reactors are too closely tied to nuclear weapons. Since they wish to ban nuclear weapons, they automatically oppose any expansion of nuclear power. By presenting them with the facts, it is hoped that most of them will change their minds and admit they had been misinformed. Others have convinced themselves that if government would only develop conversion of garbage into fuel and forced everyone to cover their house with solar panels and/or a wind turbine on their roof, all future energy problems can be solved. It may reduce urban and rural usage of electricity from the grid by 10–15% at great cost, but cannot solve severe base-load energy shortages in industrial countries when oil runs out by mid-century. A similar "small-is-beautiful" notion was once implemented in the 1960s by the old communist regime in China, who forced every community to build furnaces for melting scrap iron to meet the needs for steel. The whole scheme quickly fizzled because it was not cost effective. Only after China's government reformed its infrastructure and introduced economies-of-scale and capitalistic solutions to provide ample materials, goods, and energy as is done in Western countries, did the Chinese people enjoy a big surge in comfort, health, and wealth made possible by modern engineering and science.

In the pending energy crisis case, many forget that for manufacturing autos, aircraft, bridges, houses, appliances, and the transport of people and goods by cars, trucks, trains, ships, and airplanes, enormous quantities of electricity and petrol are consumed. This energy load must be shared by every man, woman and child. Wind-farms are great for low-power applications in wind-blown regions of the globe, but they cannot practically and economically solve the global fuel shortages we face 20 years from now. Solar-cells, wind-mills, and energy-conservation measures for homes and small businesses are useful, but can only provide a minor assist to reduce global oil consumption; they may extend the "out-of-oil" date by a few years. Solar and wind energy industries have been generously subsidized for more than 30 years. Their products have matured and found many markets for small-quantity electricity needs (remote communities, traffic signals, sail-boats, etc.). But to be considered as electricity providers to feed heavy industries and to manufacture oil-replacing synfuels for the transportation fleets of the world, they must be able to withstand the test of a rigorous comparative engineering evaluation. It is shown in Section 4.5 that "renewables" fail that test when competing with non-air-polluting nuclear power. Unless antiquated legislation-caused delays will continue to hinder its rapid development, uranium-generated power can decidedly and safely rescue us from a rapidly approaching out-of-oil crisis at an affordable cost. It is the *best long-term "green" energy fix* mankind has, whereas solar and wind power qualify only as *expensive "green" energy aids* and are very costly to maintain. Yet some stagnation-prone governments irrationally continue to favor the latter if only to prove the common believe that they always choose the most expensive and least logical solution to solve a problem.

Many non-technical people seem not to appreciate *scales* (*magnitudes*) and *rates* of consumption or supply, two concepts very familiar to engineers. Clearly a 100,000 gallon (378,500 L) storage tank filled with biomass-derived alcohol fuel, could never feed a million cars in a big city if each car burns four gallons (15.14 L) per day on average, and bio-fuel growers can only provide enough alcohol on a continuing basis to refill the tank once a day. It could take care of 25,000 cars but not 1,000,000. Yet promoters, aided by the media and some celebrities, insist that production of alcohol fuel derived from corn, switch-grass, or other biomass source, is the solution to our pending out-of-oil crisis; nuclear is not needed. They don't realize that without (nuclear) electricity, one needs twice the entire land surface of the USA to produce enough alcohol for its fleets of cars, trucks, and airplanes to replace petrol consumption (Section 1.4.2 and Chapter 4). Presently (2009) the total power need of man is approximately 3.7 TWe (Tera-Watt-electrical) for the USA and 16 TWe for the entire world which one expects to grow to about 20 TWe by 2020.

The energy concerns expressed in this book are focused on the USA for which statistical data were readily available to the author. However it is clear they apply equally to all nations in the world. Many parameters (e.g. needed replacement fuels) can be scaled in proportion to the population in each country and their degree of prosperity. Governments should focus on exploring realistic solutions to prevent the large-scale fuel shortages that are sure to develop in the not-so-distant future when oil runs out. They must recognize the critical problems correctly and assist with effective methods that may require billions of dollars which only they can lend or allocate. Too many are misled by stubborn anti-nuclear demagogues who have a "kill the messenger" mentality when confronted with unpleasant facts in conflict with their own cultural indoctrinations. They seem to have no concept how serious the looming energy crisis is, and stubbornly continue to find fault with nuclear power even though it is the only affordable sure energy source that can rescue the world. Former USA House Speaker Sam Rayburn once said: "Any jackass can kick down a barn but only a skilled carpenter can build one". It is time we kick out the jackasses and let the carpenters go at it!



Future shock?

1.4 Ways and Risks to Overcome the Pending No-Oil Crisis

This book should convince most technologists and engineers that there is an urgent need for more nuclear power to overcome the pending energy crisis. However environmentalists, public policy makers, and financiers like to see a risk assessment of the nuclear option compared to other possible solutions (Refs. VII-1–VII-3). Such stakeholders want to be convinced that an expansion of nuclear power plants can be done safely and economically before they will give it their support. They are apprehensive because a multitude of fear-instilling misrepresentations have been circulated in the media about nuclear power (see Chapter 2). Many of these stakeholders favor development of more solar, wind, and biomass energy at the exclusion of nuclear power without considering the scale, cost, and feasibility of these so-called "renewables" to replace the vast quantities of portable fuels presently extracted from oil fields. In the following subsections we shall examine the viability and risks of various approaches to solving the looming energy crisis.

Before addressing various means of expanding power generation ("supply") we should consider the "demand" side and see how far we might realistically reduce it to lower the supply side of the supply = demand equation. Regardless of what major remedy is launched to overcome the looming out-of-oil crisis, it makes a lot of sense to conserve energy as much as possible by improving lightbulb efficiencies, home and building insulations, automobile mileage, etc. Recently new LEDs (light emitting diodes) were developed that reduce the energy for lighting present incandescent lamps by 50–75%. Approximately 18% of urban and rural electricity consumption in the US is for lighting so this can be reduced to about 6%. Then if these LEDs are used worldwide, according to Brief 2 this would lower the total per capita energy usage for lighting to 2% (14 W) of the average 0.7 kWe that a world citizen consumes today (Section 3.2). The energy efficiencies of other home utilities like washers, dryers, air conditioners, and home heating, which consume the other 82% have been greatly increased in the last decade by improved insulation and electronics. They can probably be further improved by another 5% in the near future. All these energy savings would lower the total electric energy consumption by urban and rural sectors by about 7% below present values. Similarly it is estimated that transport and heavy industry sectors (Brief 1) can also save 7% by improved energy usage. If this occurs worldwide and if world citizens did not increase their present 0.7 kWe per capita energy consumption with a world population remaining at 6.5 billion, these energy savings could stretch the out-of-oil and no-coal dates by 10–15 years. However the effect of such savings dwindles to only a few years if the average per capita world consumption increases to 1.3 kWe and the world population climbs to 7 billion by 2030 as expected (Section 3.2). While helpful, energy savings cannot avoid the enormous energy shortfall that the world faces when there is no more oil. Only greatly expanded nuclear, coal, wind, or solar power generation which we shall now examine might possibly satisfy future energy demands on a sustainable basis.

We define the risk of an undertaking as the probability of encountering negative effects involving: (a) hazards to human health, safety, welfare, environment; (b) technical feasibility, operability, the ability to deliver; and (c) financial feasibility. We further assume that all stakeholders believe in a democratic world that favors the well-being, health, happiness, and freedom of all citizens on our planet. That is, we exclude consideration of dictatorships and societies that would not hesitate to eliminate a substantial portion of the world's population to balance energy supplies and demands for the benefit of a few.

While items (b) and (c) are reasonably quantifiable, (a) is more difficult to measure since it involves intangible human fears and perceptions. As discussed in Ref. VII-1, most people give more weight to one large accident that kills 3,000 humans than 3,000 single deadly traffic accidents, even though the same total number of fatalities occurs. Also a loss of $1,000 in the stock market often hurts more than the satisfaction of gaining $1,000. That is, values (enormities) in sociometry are often not linearly related to some calamity parameter such as a human death or a monetary loss. This skewed nature of human perception gives rise to numerous disagreements between stakeholders, and sometimes leads to the selection of non-optimal solutions when alternatives are considered. To minimize controversies, it is necessary to carefully define objectives and risk factors, and to insure that the concerns about nuclear power of all stakeholders are recognized. Such concerns are repeatedly addressed throughout the book.

In the present case we want to find the best means of overcoming the pending no-oil energy crisis, and we shall assess risks associated with (1) the "nuclear millennia option", (2) the "renewables-only option", (3) the "century-long coal-burning option", or (4) the "do-nothing option". The postulated scenarios of these four options are as follows:

1. *The Nuclear Millennia Option*. In this option we propose to use heat and/or electricity from nuclear power plants to desalinize seawater and to manufacture synfuels (synthetic fuels) and biofuels for replacement of all present portable petroleum fuels. Synfuels are primarily hydrogen, ammonia, hydrazine (and derivatives) made via electrolysis of water and Haber-Bosch compression with nitrogen (air), the processing energy being supplied by nuclear electricity. The combustion products of these synfuels are again non-polluting water and air. Agriculture and forestry (corn, soybeans, wood, etc.) are also engaged to produce bio-fuels extracted from plants with the aid of nuclear electricity. Biofuels are mostly alcohols and heavy oils that build up in sun-grown vegetation and algae. Furthermore all coal-burning power plants are replaced with nuclear plants; that is, all electricity is derived from uranium fission. This program requires an eightfold expansion of all existing nuclear power plants and the introduction of breeder reactors (Refs. I-28, II-18, II-22). Concurrent development of new automotive engines (combustion or fuel-cell) which consume the new synfuels is part of this scenario. To minimize dependence on portable fuels, most rail transport systems are electrified (diesel engines replaced by electric motors) and for short-haul urban transport, vast fleets of electric plug-in automobiles are developed.
2. *The Renewables-Only Option*. In this approach, massive deployment of new solar panels and windmills are proposed to supply all prime energy for electricity and for making synfuels. Electric energy obtained from solar and wind power stations is used to manufacture synfuels and biofuels as in (1). Geothermal, hydro-, and ocean-wave power might also be placed in this category, but are rather restricted and don't have the large-scale expansion possibilities offered by windmills and solar energy.

3. *Coal-Burning Option*. Global-warming is ignored, although attempts are made to sequester carbon dioxide exhausts in porous underground reservoirs. Heat or electricity obtained from additional coal-fired plants is used to manufacture synfuels and biofuels as in (1). This option (3) is identical to option (1) except coal replaces uranium. Option (3) with manufacture of synfuels to replace fossil fuels, is sustainable only for another century compared to three millennia if uranium and thorium resources are mined.
4. *The Do-Nothing Option*. As the label implies, under this option nothing is done. A massive world-wide recession ensues as oil runs out. The world will return to primitive living conditions that existed before the nineteenth century, except there are 10 times more mouths to feed (Ref. I-19).

In what follows we briefly examine risk categories (a), (b), and (c) for options (1), (2), (3), and (4).

1.4.1 Risks in the Nuclear Millennia Option

1.4.1.1 Safety Considerations and Biosphere Effects

The most debated safety issues raised by environmental groups regarding nuclear power programs are: (i) disposal and transport of nuclear wastes; (ii) radiation effects on people due to reactor accidents caused by unintentional or intentional (terrorist inflicted) malfunctions; (iii) intentional diversions and modifications of nuclear fuel to make nuclear weapons.

In Chapter 6 we shall show that the transport and disposal of radioactive waste can be carried out as safely as the moving and disposal of any other hazardous chemical. After valuable unused fuel is separated from fission products, the amount is much smaller than claimed by anti-nuclear propaganda. It amounts to one aspirin per year per person using nuclear electricity or about one household-garbage-can full per year for a 1,000 MWe reactor. Even in the event that an accident occurs during transport of spent nuclear fuel elements from a reactor site to a storage facility, the exposure of the public to radiation is virtually nihil. From transportation statistics and collision tests with armored nuclear casks it is estimated that one out of every 100,000 radioactive material transports might experience an accident in which the transport cask is penetrated via a crack or terrorist bullet hole. The risk that someone in the public is subsequently exposed to harmful radiation due to such a breach is estimated to be less than 10^{-4} so the overall probability of a harmful radiation exposure due to the movement of radioactive materials is less than 10^{-9} per transport.

Concerns about diffusion of radioactive chemicals through soil from a nuclear repository to aquifers tapped for drinking water have been extensively studied (Ref. II-15). The probability that a nuclear storage chamber will leak and be exposed to leaching ground water during 100 years of underground storage is on the order of 10^{-3} while the probability that a person will get cancer after drinking radioactive water from soil-penetrating chemicals that migrated from a nuclear storage site to an aquifer 30 miles away is on the order of 10^{-4} in a period of 100 years (Section 6.3.3, Brief 35). Thus the overall risk that a person may get cancer from drinking contaminated water near a nuclear storage site is on the order of 10^{-7} in 100 years or 10^{-9} per year. This compares with a chance of 10^{-4} per average trip for an automobilist to have a collision and a probability of 10^{-7} per flight to be in a plane-crash for air travelers.

The probability of a death in the public outside a nuclear power plant due to a reactor accident is discussed in Chapter 7. The only public deaths due to a nuclear power plant accident occurred in1986 at Chernobyl in the Ukraine. The total death toll including thyroid irradiation victims who (unwarned) drank contaminated milk from cows that had grazed on grass covered with particulate fall-out, came to 57 people. Predictions of additional future deaths due to latent cancers induced by radioactive fall-out are without foundation and lack credibility (Section 7.6). After 10^7 MWe-years of worldwide nuclear power that was generated over the past 30 years, the observed worldwide risk of causing a human fatality in the public due to a reactor meltdown is thus 6×10^{-6} per MWe per year, based on the one accident at Chernobyl. For typical 1,000 MWe reactors the risk of causing a human death would then be 6×10^{-3} fatalities per year or one death in 150 years per Chernobyl-model reactor. In comparison, the worldwide average risk for underground coal mining is more than one fatality per year per mine.

In the USA, which presently generates about 10^5 MWe with 104 reactors, there was one reactor meltdown in 1979 at Three-Mile-Island (TMI). In this maximum credible accident, no one in the public was over-exposed to radiation thanks to the reactor's heavy containment vessel that confined all radioactive debris. Thus for the USA alone, the probability of causing a fatality due to a nuclear reactor meltdown is 0 per year per MW after 40 years of operations. After the TMI and Chernobyl accidents, many new sophisticated accident prevention techniques and public safety measures were introduced at all nuclear power plants around the world. Russia has (and nearly all other nations have) also adopted most new reactor safety features now mandated in the US and the EU. This makes another Chernobyl-like accident virtually impossible (Chapters 6 and 7). For a modern water-moderated 1,000 MWe power reactor with a properly designed containment vessel (absent at Chernobyl), the probability of public exposure to particulate fall-out radiation after a reactor core meltdown or destruction (by earthquake, plane-crash strike, or suicide terrorists), is estimated to be less than 10^{-6} per year. Assuming all future reactors are built under the same rigorous regulations imposed today, this translates to a risk of 4×10^{-3} public radiation exposures per year or 1 in 250 years for *all* 4,000 reactors expected to be in operation worldwide after 2050.

Issue (iii) under (a), that is the diversion of nuclear reactor fuel to make nuclear weapons by increasing isotope enrichments or extracting and purifying neutron-bred plutonium, is discussed in Section 6.3. As explained in Chapter 8, the probability for a terrorist group to make a nuclear weapon is extremely remote unless they are aided by a sovereign nation. The theft of a completely functional nuclear weapon from a heavily guarded military facility is also very unlikely as discussed in Section 8.2. Only an independent country could design, build, and test a nuclear weapon at great expense (over $2 billion) if its government wants to do so. The chance of such an event is independent of the operating risks associated with building nuclear reactors for manufacturing synfuels. With a strong internationally monitored Non-Proliferation-Treaty (NPT) program (Section 8.3), it appears that the probability of nuclear weapons proliferation can be held to a low level if all countries sign up for the NPT and abide by it. There is no reasonable logic to add this risk in the assessment of the nuclear power millennia option (1). Avoidance of building future nuclear power plants under option (1) will not prevent any determined nation from developing nuclear weapons. The know-how to do so is readily available in the world literature. Today, with a few billion dollars any sovereign nation can avail itself of a nuclear weapon within 5 years if it decided to violate the NPT.

Regarding effects on the biosphere, nuclear power plants produce no air-pollution or globe-warming gases like coal-fired power plants do. All "burnt" uranium products remain encapsulated in solid fuel elements which can be safely disposed of as discussed in Sections 6.3.2 and 6.3.3. In summary, type (a) risks involved in developing more nuclear power plants are several magnitudes less than many commonly accepted industrial endeavors that keep us alive on planet earth. The fact that nuclear power generation produces absolutely no air pollution or global warming is a very strong plus. On the negative side, concern about nuclear weapons proliferation has added a public fear factor and an irrational opposition for everything "nuclear", even though weapons proliferation (Chapter 8) is a separate issue independent of building nuclear power plants. While the same uranium is used as raw material (but isotope-enriched and purified to much higher levels for effective weaponry), a nuclear power plant is entirely different from a nuclear weapon, and one cannot be converted into the other as explained in Section 6.2.3. It would be as senseless to halt nuclear power plant development as it is to stop making jet aircraft or bulldozers because the latter could be converted into military fighter planes and tanks, or because their materials of construction can be diverted into making bombs.

When oil fields run dry, new portable synfuels must replace today's highly developed petrol fuels. They must be readied for mass production concurrently with an expansion of nuclear power plants. Simultaneously, all petrol-burning engines must be replaced by new engines powered by the new portable synfuels. Since the massive quantities of carbon dioxide gas exhausted from present engines appear to cause excessive global warming, exploration of new synfuels has focused on those fuels that do not add any new carbon dioxide to the atmosphere. These include hydrogen, ammonia, and hydrazine synthesized from water and nitrogen from the air, whose exhausts are again non-polluting water and nitrogen after a reaction with atmospheric oxygen in the new engines. Other acceptable synfuels are biofuels like alcohols and oils extracted with the aid of (nuclear) electricity from plants that consume carbon dioxide from the air during plant growth and return it to the air when the biofuel is burnt. Two types of engines can be powered by the new synfuels: internal combustion engines (ICEs) and electrochemical fuel cell engines (FCEs). Chapter 5 gives more details of such possible future engines and synfuels. Under option (1) then, the prime energy needed for fuel synthesis is provided by nuclear electricity or heat so that in effect non-portable nuclear energy is transformed into portable fuel energy. Suitable synfuels are recycled through the biosphere's enormous reservoirs of water, air, and carbon dioxide without depletion of any feed material.

It is estimated that the cost of synthesizing hydrogen or extract bio-alcohols with nuclear electricity or heat, is 1.5–2.0 times higher per captured Joule than pumping and refining crude oil. In the US, instead of $0.50 per liter or $2 per gallon (including tax), the new synfuel price would then be about $1 per liter ($4 per gallon), or $64 for traveling 600 km (373 miles) on a tank-full of synfuel, assuming government taxation rates remained the same. After gaseous hydrogen is generated by electrolysis of water or other scheme, current practice is to further liquefy it to be transportable in a reasonably sized fuel tank. Alternative bladder adsorption or ultra- high compression of gaseous hydrogen in an acceptable volume has been found inadequate in spite of years of research. Instead of liquefying pure hydrogen however, one finds that compressing hydrogen together with nitrogen (air) into portable liquid ammonia is less expensive than hydrogen liquefaction. Presently the cost of liquid ammonia per combustible Joule is about the same or less than that of petrol and half of liquid hydrogen. Aided by nuclear energy, one might consider retrieving carbon-dioxide from the atmosphere and reconstitute it into hydrocarbons like trees and plants do naturally. However there is only 0.03% carbon-dioxide gas in the atmosphere, and reforming it with hydrogen into hydrocarbons takes lots of energy and would cost much more than making bio-alcohol using plants, sunshine, and nuclear electricity.

As discussed in Section 5.1, while liquid ammonia looks at present to be most practical as a portable synfuel, bladder-storage or safe compression of gaseous hydrogen into acceptable tank volumes at 300 atm (= 4,400 psi) for automobile travel might be worth of more research and development. Also the safe distribution and handling of alcohol, ammonia, and hydrogen fuels in enormous quantities for public use needs more studies. Hydrogen effuses through many plastics and embrittles a number of metals, so special gas-tight pipes are needed. For hydrazine which is a liquid like water at room temperature, stabilizing additives and special storage tanks have been proposed to minimize possible unintended ignitions or explosions in the presence of atmospheric oxygen. But so far this potential synfuel does not appear suitable for public use, leaving ammonia as the most practical synfuel. Many experimental programs are under way in industry, universities, and government labs to advance the state-of-the-art of mass-handling hydrogenous synfuels and to develop durable ICEs and FCEs that use them. Actually the risks of distributing and storing flammable petrol are not much different from those of alcohol and ammonia, but the latter are less explored. As shown in Section 5.1.1, flammabilities of alcohol, ammonia, and hydrogen in air, while not the same, are comparable to that of petrol.

Unless problems with compacting hydrogen can be solved, bio-alcohol and ammonia (or their mixture "almonia") appear presently to be the most acceptable green synfuels from the aspect of portability, affordability, safety, and handling.

They both can replace petrol in internal combustion engines. In the case of ammonia, high-temperature oxide fuel-cells can use ammonia fuel directly in contrast with low-temperature fuel-cells with proton exchange membranes (PEM). In the latter case, ammonia must be decomposed back to hydrogen and nitrogen by a catalyst. Under modest pressure (about 10 atm), ammonia is a liquid and has been used extensively as a fertilizer in agriculture for many decades. Its handling and distribution is well developed and similar to that of petrol. Handling liquid bio-alcohol should likewise present few problems. As mentioned, hydrazine is unstable and decomposes if heated. It is a liquid at room temperature and has been used for rockets. It might fuel future aircraft if the addition of a suitable stabilizing agent for safe storage and handling can be found. Substantial amounts of hydrazine and hydrogen have been used safely in a number of aerospace programs. Clearly, handling and distribution techniques of the new synfuels are not new but more investigations are needed (mostly for hydrogen and hydrazine) for applications involving the public. In conclusion, the main social risk in carrying out option (1) may prove to be the safe handling and massive distribution of alcohol, ammonia, hydrogen (and possibly hydrazine) rather than the nuclear component.

1.4.1.2 Technical Feasibility, Operability, and Ability to Deliver

The technical feasibility part of option (1) faces few risks since nuclear power plants are well developed. They have excellent safety records (except for Chernobyl) during more than 40 years of operation. However to fully achieve more than two millennia of uranium-provided energy, current "burners" must be retro-fitted into "breeders" in the next 20 years (see Section 6.2.2 and Refs. I-28, II-18, II-22). Burners consume the less abundant (0.7%) U-235 isotope of uranium only, while fast breeder reactors utilize almost all of the uranium, thereby extending the sustainability period for uranium fuel by more than a practical factor of 60 (theoretically 140) from 50 to 3,000 years, and with thorium to more than 4,000 years! Quite a number of experimental breeder reactors have been built and tested in the last 40 years and performed as expected. But because they are slightly more expensive and their spent fuel must be reprocessed, the nuclear power industry has built mostly burners so far. Currently only France, Russia, and Japan have one experimental breeder reactor each and have dedicated programs to gradually replace burners in their country with breeders in coming decades. The USA also explored breeder reactors but halted their development not for technical reasons, but because of flimsy anti-nuclear claims that the need to reprocess breeder fuels might expose them to possible diversions for weaponry in other countries. Even when Argonne National Labs developed a proliferation-resistant integral fast reactor (IFR) whose fuel is worthless for use in a nuclear weapon, a myopic US government foolishly shut it down in 1986 (Refs. I-28, II-22). This mentality is akin to halting all air transport because terrorists can fly aircraft into skyscrapers.

Besides complete energy extraction from uranium fuel, another advantage of breeder reactors is that final quantities of nuclear waste material are much lower than for burners. National nuclear waste repositories like Yucca Mountain can be used for hundreds of years before they are filled, instead of only a few decades under a burner regime. Before new nuclear breeder reactors can be built in great numbers, tests are needed to select a few optimized models for mass deployment. In summary, the technology for building and running breeder reactors is in hand but needs stimulation by government planners and regulators.

Another benefit offered by nuclear power plants besides being non-air-polluters is that in generating electricity, two-thirds of the nuclear-produced energy is low-temperature heat which could be made available for some other application. Presently this heat is dumped into river water or a cooling tower and is thus essentially wasted. In coastal areas where there are fresh water shortages (e.g. California, Arabia), this heat can be profitably used to desalinize seawater. Several dual-purpose nuclear power plants have been designed and investigated in the last 40 years, but so far only Russia has operated one. Probably only when water shortages become severe, will action be taken to use this side benefit. Irrational public fear and ignorance has so far hindered this application of nuclear energy in the US. Besides supplying heat to evaporate seawater, waste heat from nuclear power plants can provide central heating for clusters of buildings in cities with very cold climates such as Ulaanbaatar in Mongolia and Yellow Knife in Canada's Northwestern Territory.

Synthetically manufactured portable fuels and automotive engines powered by them, involve non-nuclear technologies that have been researched and developed for over a century. However no synfuel has been mass-produced on the same scale as the present extraction of petrol fuels from oil fields. Although not handled on the same scale as petrol, large quantities of hydrogen, ammonia, alcohol, and hydrazine have been produced by the chemical industry for agriculture (ammonia), the space program, semiconductor manufacture, and scientific research. A 100-fold increase in the production of these synfuels should pose no basic technical problems except for possible delays in the construction of enabling energy-providing breeder reactors. The latter delays will arise because of the enormous increase in labor and materials needed for construction of 700 new breeder reactors in the USA (4,000 worldwide) in trying to meet a 2050 deadline (Section 9.3).

Regarding development of new internal combustion (ICEs) and fuel-cell engines (FCEs) powered by hydrogen-based portable synfuels, there are no fundamental impediments to mass-produce them by the year 2030. Internal combustion engines using hydrogen and ammonia in place of petrol have been successfully built. Although water (H_2O) and nitrogen (N_2) are the main exhausts to the biosphere, because of the high temperatures in ICEs, air-polluting nitric oxide (NO_x) gases might also form as byproducts. However in the last 2 decades, the automotive industry has successfully learned to eliminate NO_x with catalytic converters, and the exhausts of some recently developed ammonia-burning engines are NO_x-free (Sections 5.1.1 and 5.2.1). Further refinements and tests are needed however before safe synfuel-burning ICEs can be mass-marketed. FCEs with ammonia fuels which are catalytically decomposed to provide pure hydrogen on PEM's have also been demonstrated, while high-temperature solid oxide fuel-cells (SOFs) can be run directly on ammonia (Refs. III-8–III-11). Most FCEs have no NO_x exhaust problems. However unless hydrogen compacting problems can be solved, slightly compressed (10 atm) liquid ammonia (the “other” hydrogen) for FCEs and ICEs appears presently most practical for running the engines of our future long-haul transportation vehicles.

While the technical feasibility for implementing option (1) seems assured since needed technologies have been demonstrated, a large challenge will be to field 700 new breeder reactors in the USA (4,000 for the world) by the year 2050/2060, when most oil fields will be exhausted and oil-replacing synfuel production must be in place. The hundred-and-four reactors presently (2009) operating in the USA (430 worldwide) will be unable to provide the needed expansion of prime energy for massive synfuel manufacture. It means that the USA must build on average some 16 new breeder reactors each year for the next 45 years. This will put a big strain on the availability of skilled labor and materials. The most practical approach initially would be to double and triple the number of nuclear reactors at existing reactor sites, since these sites have already been cleared for reactor operations. New sites must ultimately be developed however to accommodate the new nuclear/synfuel age. The overall effort would be comparable to WW-II when the USA produced hundreds of military aircraft, ships, and tanks weekly. We have a war for survival on our hands which must be won to avoid an economic disaster and collapse of our civilization after 2040/2050. Former leaders like Admiral Hyman Rickover and General Leslie Groves (Section 6.3.1) are needed again to help the USA get through the next 2 decades. If nothing is done, there will be no more aviation fuel to fly our airplanes, no more diesel to move our food and freight by trucks, trains, or ships, and no more petrol for cars and buses. The engines in all these vehicles will be useless. Due to past public opposition to nuclear power and passage of many anti-nuclear regulations in the 1980s and 1990s, the number of companies in the USA capable of designing and building nuclear reactors has dwindled to a few, from an original eight in the 1960s. The goal then was to build 200–300 reactors by 2000. It is likely that most of the new reactors will be built by French, Japanese, Russian, Chinese, and Indian firms who have overtaken nuclear power plant design and construction, a field once dominated by the USA.

Opponents of nuclear power mistakenly believe that solar and wind power can remedy future energy shortfalls and that nuclear is not needed (Section 2.4). But for an industrial engineer it is not difficult to see that compared to nuclear plants, solar and wind power could never economically generate the multi-terawatts of steady reliable power needed for massive synfuel and biofuel production worldwide. Only nuclear power can provide this affordably. However to have 700 additional 1 GWe reactors operating in the US by 2055, is an enormous undertaking. Such a build-up will probably follow a gradual rise as discussed in Section 9.3 (Brief 47) starting with five new operating reactors each year after 2017, and gradually increasing to 22 reactors per year between 2025 and 2055. Skeptics think this is impossible, but with government resolve it can be done. US utilities, reactor vendors, and universities will have to train and graduate some 2,000 new nuclear engineers by 2020, to be expanded to 10,000 by 2030, and to 80,000 by 2050, exclusive of technicians and other staff. Some 9,000 reactor construction workers would also be needed by 2020, increasing to 40,000 by 2050. The Nuclear Regulatory Commission (NRC) would likewise need staff increases of 200 nuclear engineers by 2020 and 500 by 2030 besides 1,000 engineers in other specialties. These are very coarse order-of-magnitude numbers requiring more analysis. With proper planning and uninterrupted implementation such a program is possible however if there is a will to carry it out. In WW-II, a million new jobs with training programs were initiated to build thousands of aircraft, ships, and tanks each week, needed to win the war.

In the USA, antiquated anti-nuclear laws need to be repealed and the manipulation of nuclear programs by politicians and lawyers must be minimized. Only experienced (nuclear) engineers should determine safety issues and the most affordable path to sustain the country's energy needs. In the USA, any technophobe can file a lawsuit to impede any technical project involving nuclear energy, with the US government paying for all of her/his legal expenses. This is what an overflow of lawyers in litigation-happy USA succeeded to have cast into law. Even without such special government compensation, many major projects in the US have become stalled. Recently a Dutch dike-building civil engineer was consulted about the disputed construction of new river flows, levees, dikes, dams, and canals in the Delta Estuary region near Sacramento, California. He parted with the comment that any building plan or design was impossible to implement as long as rivers and dikes were owned, maintained, or supervised by too many different parties such as the US Army Corps of Engineers, municipalities, farmers, cattle ranchers, fishing interests, etc., each one of which was allowed to sue the other with teams of lawyers. He suggested that one "Delta Authority" be established which owns or is empowered to operate all dikes and rivers, and which is run by diploma-ed government engineers as is done in Holland. However with more lawsuits per capita than in any other country, it is doubtful the US can avoid legal morasses. If the USA expects to keep up with a rapidly changing world, it must streamline its procedures for planning and execution of communal food, water, energy, and transportation programs. It can no longer afford prolonged litigations of such programs or support costly unworkable plans that are promoted by incompetent special interests. While a sensible democracy is to be preferred, the oft-quoted "terror of democracy" could ultimately destroy the USA internally, a goal also sought by today's terrorists.

1.4.1.3 Financial Feasibilty

In 2005, the cost of building a 1,200 MW(e) nuclear power plant was estimated to be approximately \$2 billion. To build seven hundred new reactors by 2050 would then cost a total of \$1.4 trillion in 2005, or \$35 billion per year for the next 40 years. With the USA's annual GDP on the order of \$10 trillion, this level of development is financially sustainable, particularly if economic survival is at stake. However as mentioned, to build 17 reactors per year in the USA or 100 worldwide for the next 40 years, will require an enormous build-up of skilled labor and materials. Shortages are almost certain to develop initially which will impede progress. Because of this, the nuclear build-up program may have to be stretched out to 60 instead of 40 years, and global warming may have to be tolerated for a few decades longer by having coal-burning power plants provide energy for synfuel manufacture (Sections 1.3 and 9.2) until they can be replaced by non-air-polluting breeders. The risk of a reactor meltdown, estimated to be 1×10^{-3} per year for 800 reactors in the USA or $\sim 10^{-6}$ per reactor, requires an insurance policy costing about $1 billion per year for all 800 reactors to cover public liability and physical plant damage or $1.25 million per reactor per year (about 0.02 ¢/kWh).

1.4.2 Risks of the Renewables-Only Option

1.4.2.1 Safety Considerations and Biosphere Effects

The most quoted "renewable" sources of energy are solar, wind, and biomass. Solar panels have been extensively developed since the beginning of the space program in the 1960s, while modern wind-driven turbo-generators have seen an enormous growth in the last 2 decades. These energy sources have gained a lot of popularity and are useful for providing electricity in small-scale applications. However they are limited in capacity and cannot be deployed economically on the large scale needed for replacing the portable fossil fuels that presently propel our vast transportation fleets and heavy industries (see below and Chapter 5). In regard to type (a) risks, at first sight, solar panels seem not to pose any environmental risks. However if they were to be produced in very large numbers, one must consider the toxic hazards associated with the use of arsenic, selenium, indium, gallium, and siloxanes in their manufacture. If one considers generating 1 TWe (10^{12} W) of electricity with solar cells to satisfy all the USA's future energy requirements, one would need an inventory on the order of 1,000,000 tons of these special chemicals, assuming it takes 1 g per solar Watt. In addition one would need approximately 25 million acres (100,000 km^2) of sunny desert land to extract 1 TWe of year-averaged solar power. Since solar cells deteriorate due to sand erosion, rainstorms, bird droppings, etc., they must be replaced every 10–20 years. This means one must handle 50,000 t of poisonous arsenic, gallium, etc. per year which presently exceeds the mining capacity of these chemicals. This compares with about 3,000 t of uranium per year to fuel 800 reactors which together generate 1 TWe.

To generate a year-averaged 1 TWe of wind power requires 2,000,000 windmills of 2 MWe deployed over 100 million acres (400,000 km^2) of windy land, assuming an average of 25% wind availability. A big problem with windmills is that they kill thousands of birds and spoil ecosystems and landscapes. Because of this, environmentalists in Massachusetts and the Netherlands have protested any further expansion of windmills. The opposition to windmills and solar farms has been steadily increasing in the last 10 years because of their encroachment of large land areas and the spoilage of beloved scenery. The steady cyclic whooshing sounds of wind-mills have also been attacked as highly disturbing by those living near wind-farms.

Regarding the use of bio-alcohols and bio-diesel extracted from biomass and seaweeds to fuel our transport fleets, one finds that unaided by electricity, the USA would need 3 billion acres of arable land and/or ocean to provide 1 TWe of net biomass fuel energy. This is more than the entire surface area of the USA of 2.24 billion acres. One finds the same result for the rest of the world (Section 4.1). If nuclear energy is used to help cultivate and harvest corn, sugarcane, or other biomass and help extract its alcohols, only 0.6 billion acres would be needed. However man also needs arable land for growing food, thereby reducing the available land for biofuel cultivation. This further limits the cultivation of bio-fuel vegetation considerably.

A positive argument for bio-fuels is that it is "carbon neutral". Vegetation acquires gaseous carbon-dioxide from the air which it converts into combustible hydrocarbons by sunlight-aided photo-synthesis. The same amount of carbon-dioxide is later returned to the atmosphere upon fuel combustion. Thus there is no net addition of globe-warming carbon-dioxide to the biosphere when bio-fuels are burned. Bio-fuels are therefore said to be "carbon-neutral" and future use of them can be expected when fossil fuels are exhausted.

Risks associated with developing facilities to manufacture synfuels with prime electric energy from solar or wind power complexes are similar to those discussed under option (1). Like in option (1), the storage and distribution of synfuels for public use will need close examination to insure public safety.

1.4.2.2 Technical Feasibility, Operability, and Ability to Deliver

As already alluded to, while technically well developed, solar and wind power require enormous land areas. Although empty inexpensive desert lands could be employed, a large network of energy storage units (batteries), many miles of access roads for maintenance and collection/distribution power lines would be needed. This adds considerably to capital and maintenance costs when compared to a single coal or nuclear power plant housed in one building. If 1 TWe is needed for oil replacement in the US, solar alone would require about 1% of all US territory while wind power would need 4% of all its land mass. If one grows bio-fuel-producing plants with exclusion of nuclear energy inputs, one could never replace all present fossil fuels since it requires more than all arable land in the USA. Only with the aid of uranium-generated electricity could bio-fuels replace all petro-fuels; and provided one-third of all lands in the USA are made available for cultivation of bio-fuel-producing plants. The most likely outcome will be that biofuels will replace some 10–20% of presently consumed petrol, with the balance coming from hydrogen-carrying synfuels obtained by electrolysis of water using nuclear electricity.

To generate 1 TWe of solar power requires a million tons of special chemicals for the manufacture of solar cells. Solar-cell replacements to maintain this power level would demand 50,000–100,000 t per year of special processed materials (Si, Cd, Te, Se, etc.), some of which may exceed present supplies and the mineral resources from which they are extracted.

1.4.2.3 Financial Feasibilty

As discussed in Chapter 4, the cost of producing 1 TWe of electric power from solar energy stations is calculated to require an investment of about $9.1 trillion, while wind power would need $7.2 trillion compared to $1.4 trillion for nuclear power, all in 2005 dollars. With a US gross domestic product (GDP) of $10 trillion, the commitment to a renewables-only program for replacing oil, would strain the financial community. Although fuel costs are "free" for wind and solar power, maintenance costs are very high because of the large expanse and number of solar panels and wind-turbines. Compared to generating coal or nuclear power, one finds solar and wind power to be at least 3 times more expensive at the 1 TW level. This applies to both capital and operating costs. While nuclear power plants must pay for fuel, those costs are less than 15% of operating costs. Costs for insurance against natural disasters such as hurricanes, sand-storms, and earthquakes which could damage vast areas of solar or wind power complexes, must be added to overall operating expenses of course. It will likely be two to three times higher than insurance for the nuclear option (1), because of the large land areas covered which have a higher exposure to natural forces. A country that decides to rely *entirely* on solar and wind power is sure to become impoverished and dependent on imports of synfuels from other countries (OPEC → OSEC) who will produce them with nuclear power.

1.4.3 The Coal-Burning Option

1.4.3.1 Safety Considerations and Biosphere Effects

Conversion of coal energy into mechanical and electric energy via a steam cycle has been utilized for centuries. Coal-burning power plants can be substituted for uranium-consuming nuclear plants and vice versa to supply the energy needed for manufacturing future synfuels to replace fossil fuels. However coal reserves would be depleted in 100–200 years compared to known uranium/thorium reserves that can last for 3,000–4,000 years in a breeder reactor economy. In addition, and even more important, coal-burning produces carbon dioxide gas which has been found to cause irreversible warming of the earth atmosphere due to the green-house effect. If coal were to be converted into petrol by the SASOL process (Sections 5.1.1 and 9.2.6), the globe-warming problem is not solved since the combustion of carbon-carrying petrols also creates carbon-dioxide (CO_2) gas in automobile exhausts. It has been proposed to capture and sequester CO_2 emissions from coal-burning power plants and automobiles instead of releasing it to the atmosphere, but this requires extra energy and will greatly increase the cost of using these fuels. It appears impossible to remove all CO_2 emissions from coal plants and cars worldwide in a practical cost-effective manner.

Besides producing globe-warming gaseous carbon dioxide, coal-burning plants also inject air-polluting mercury, uranium, and other undesirables entrained in particulate matter into the atmosphere (Section 6.1). Scrubbers recently installed on coal-burning plants to remove particulate emissions, have lessened air pollution but considerably increased the cost of using coal energy. Carbon which makes up coal, is an essential element in all compounds widely used in plastics, paints, lotions, pharmaceuticals, etc. This raw material should be preserved for future generations, and not burnt and dispersed as carbon dioxide gas through our biosphere.

It is difficult to determine the risk factor for burning coal (and petrol). At international conferences on global warming, it is claimed that millions of people will be displaced and die, when climate changes due to global warming cause flooding of coastal areas and islands. Also it is forecasted that global warming will increase hurricane activities. Finally, mercury inhalations from polluted air cause additional casualties. Risks involved with manufacturing, storing, and distributing synfuels were discussed in Section 1.2.1 and are the same as for option (1).

1.4.3.2 Technical Feasibility, Operability, and Ability to Deliver

Coal-generated electricity has been a major prime energy source for more than a century, and technologies using its heat of combustion are well developed. Coal is somewhat more abundant than the petroleum fuels found in the earth crust. As shown in Chapter 3, coal-derived electric power may be available for two more centuries if used as the only prime energy source for biofuel farming and synthesis of portable hydrogen-based fuels to replace fossil fuels. If the coal option (3) is chosen exclusively, a fourfold expansion of coal-burning power plants would be needed over the present number of coal plants, together with a fourfold increase in coal mining operations and coal transportation by rail.

Carbon dioxide gas has been pumped into depleted underground oil reservoirs in some experimental programs in Norway. But if coal energy is consumed on a tera-watt scale, it is very problematic if such sequestration techniques can be carried out successfully and affordably.

1.4.3.3 Financial Feasibilty

The total cost of a fourfold expansion of present coal-fired power plants in the USA would be approximately \$0.8 trillion (in 2005 dollars) for five hundred 1,200 MW(e) coal-fired power plants at \$1.6 billion each. A fourfold expansion of current rail transport and delivery of coal may cost another \$0.1 trillion for a grand total of \$0.9 trillion. These costs are affordable if they avoid an economic meltdown.

1.4.4 The Do-Nothing Option

1.4.4.1 Safety Considerations and Biosphere Effects

A worldwide economic recession will result under option (4), after oil sources dry up. Famine and warfare will likely break out, causing the deaths of many urban dwellers and combatants. Warfare results because of a desire to conquer and control the last remaining oil fields which will be defended by the military. The world's population will decrease severely in one generation due to the inability to transport adequate amounts of food, water, and goods (no petrol), resulting in starvation and disease like experienced on a small scale in New Orleans after hurricane Katrina. Some environmentalists may applaud a decrease in the world population, but this sentiment will not be shared by those who wish to live and survive.

1.4.4.2 Technical Feasibility, Operability, and Ability to Deliver

Clearly doing nothing is quite feasible and often the course taken by a laissez-faire public and undecisive bureaucracy, until a calamity strikes (Refs. I-16–I-19).

1.4.4.3 Financial Feasibility

Since no funds have to be expended under option (4), this path of no resistance is certainly feasible.

1.4.4.4 Conclusions Based on the Risk Assessment of Options (1), (2), (3), and (4)

In a democracy, option (4) would in principle be rejected outright, since too many people would perish. This leaves us with options (1), (2), and (3), or a mixture of them. In all of these three options, a program for extensive synfuel manufacturing is included which is to be developed concurrently with an expansion of prime energy providers, whether uranium, renewables (solar and wind), or coal. The technology of manufacturing synfuels is essentially identical and can be evaluated independently of possible prime energy suppliers. In Section 5.1 it is shown that electrical and mechanical storage batteries may be used for short-range commuter travel. But they are impractical for long-haul applications as alternates for providing locomotion. Only synfuels produced from air and water with the aid of nuclear electricity, together with some input of sunshine for bio-alcohols, are adequate as substitutes for current petrols.

Several different processes are available to synthesize hydrogen, ammonia, and hydrazine from air and water, some of which are discussed in Chapter 5. While new nuclear power plants are being designed and constructed to supply needed synthesis energy, the most efficient chemical synthesis schemes must be selected via pilot plant experiments. This can presently be done with non-nuclear heat or electricity. Simultaneously, tests should be conducted to explore concepts for safe handling and compact storage of the new synfuels for applications in the public automotive world. This latter task is very important and should be completed within the next 10 years. Finally in another concurrent 15-year development program, tests must be carried out with new ICE and FCE designs fueled with ammonia, hydrazine, hydrogen, alcohol and/or mixtures thereof. A determination must be made which engine is most suitable for civilian cars, which for buses, which for trains, which for ships, and which for aircraft. The three R&D programs of synfuel production, synfuel handling, and new engine development must be integrated of course and timed so that they can be ready for mass production when the first synfuel production plants come on stream.

In addition to portable synfuel production, it would be prudent for the USA to (re-)electrify transport systems (trams, trolleys, buses, and trains) nationwide as much as possible, like is done in many parts of Europe. Concepts to provide cars with electric power via overhead electric lines on major freeways as is done for electric trams and buses, might also be considered. When the cost of petrol sky-rockets after 2020 due to oil shortages, vast fleets of electric plug-in cars will most likely become popular for short-haul urban transport between home and work. The electric power for this scenario can only come from a greatly increased number of nuclear or coal-fired power plants. For long-distance (mountains and deserts) driving, hybrid automobiles (Chapter 5) will be necessary, whose super-batteries are charged by power from synfuel-burning combustion engines when away from electric power sources, or recharged from electric outlets when those are available. Whether for all-electric plug-in automobiles or hybrids, it is clear that many additional nuclear power plants must be built to replace the energy of substituted petrol.

Next, let us examine the practicality of prime-energy-production by options (1), (2), and (3) to serve the energy requirements of future transport systems. To provide 1 TW of electricity to the USA, option (3), coal-burning, is the least expensive at $0.8 trillion, compared to $2 trillion for nuclear, $7.2 trillion for wind, and $9 trillion for solar energy. However option (3) will be rejected by environmentalists who believe global warming and air pollution is a serious threat that must be avoided. Also the finite amount of coal and its essential role in synthesizing organic materials when oil is gone, may pursuade them to support options (1) and/or (2) instead. The risks involved in greatly expanded coal mining operations with its attendant human fatalities may also be a factor against option (3) even though it is least expensive.

In option (2), several unfavorable factors stand out. In the first place, enormous land areas are needed. For solar energy generation, presently there are insufficient quantities of arsenic, gallium, indium, and selenium to make all the solar cells needed to provide 1 TW (terawatt) of year-averaged power on 25,000,000 acres (100,000 km^2) of sunny desert lands. The toxic nature of some of the solar cell ingredients, particularly if used in kiloton quantities, pose a health hazard (worse than uranium), and safeguards are needed to protect the public. In the case of wind power generation, the

2,000,000 large turbines (at 2 MW(e) each) placed on 100,000,000 acres (400,000 km^2) of windy prairies to generate a year-averaged TW(e), will kill thousands of birds and spoil the landscape. Actually it is problematic whether such large numbers of solar panels and/or wind-turbines can be manufactured and installed in a 40-year time-frame by the year 2050 when oil reserves are depleted. Regarding biofuels, if unaided by nuclear electricity, not enough land is available to grow enough biomass fuel for substitution of fossil fuels. Finally, the capital costs and operating costs of energy derived from solar and wind-power systems are at least three times higher than those for nuclear power. Despite these severe negative factors, some environmentalists may still prefer the "Renewables-Only" option (2) over option (1) because of the fear of "things nuclear". However for the survival of us all, common sense must prevail over the irrational fears of a few.

While solar and wind-power systems certainly have a niche in small-scale energy applications, for example to power small remote villages, these prime energy sources cannot economically provide the large amounts needed for our heavy industries and future synfuels manufacture. If nevertheless option (2) were to be adopted over option (1) in the USA, it would be very difficult for US manufacturers to sell goods on the world market in competition with countries that adopt nuclear option (1), because of their threefold higher costs of electricity. Many jobs would be lost as a result, and poverty would increase.

Option (1), the Nuclear Millennium, is technically and financially feasible. It is less expensive than option (2) by a factor of at least 3. Nations that adopt option (1) will become future providers of mass-produced synfuels (OSEC) and will replace the current petroleum-exporting OPEC countries that control the world's major energy supplies. The main problem foreseen at present with nuclear option (1) is the difficulty of fielding seven hundred new burner and breeder reactors by 2050, when oil is expected to become very scarce. A compromise may have to be made that allows prime energy to be provided by coal-burning plants for an interim period until nuclear reactors can take over. If 2050 is the target date for final switching to the new synfuels age, the USA must build 17 new reactors each year (100 per year for the world) for the next 40 years! This is an extremely ambitious program and probably will have to be spread over a longer 60-year time span, at 12 new reactors per year (70 per year worldwide) using interim coal-power. To bridge time delays in implementing option (1), coal-burning power plants will have to be kept in service longer, producing undesirable carbon dioxide gas. This will have to be tolerated a while for the sake of survival until nuclear plants can replace all coal plants. To successfully implement option (1), a dedicated, focused, and skillful commander will be needed like admiral Hyman Rickover who forged the formation of an operating nuclear navy in an incredible 6 years, or general Leslie Groves who during the WW-II Manhattan Project managed to have the design, testing, construction, and operation of gigantic isotope separation plants and first-ever nuclear fission machines completed in four short years.

Our firm conclusion is that option (1) is optimum and imperative in the long term for overcoming the pending energy crisis. Because of logistics and time constraints, replacement of coal-burning plants with nuclear power plants will have to be postponed for a while. Sequestration of CO_2 gases from coal plants if practical should be explored to minimize biosphere pollution. Also where appropriate, some wind and solar power generation and more economical use of energy (better home insulation, etc.) can help replace petroleum energy perhaps by as much as 15%. While there is still sufficient oil, activities must be set into motion to ward off the collapse of the global economy by 2040/2050. The risks involved in executing option (1) are infinitely smaller than the certain deaths of millions of people that will result if the "Do-Nothing" option (4) or the "Renewables-Only" option (2) is followed. Had the US government supported the original plan in the 1950s and 1960s to install at least two hundred nuclear power plants by the year 2000, the USA would be in much better shape today to confront global warming and the impending out-of-oil energy crisis. Instead, after the Three-Mile-Island and Chernobyl reactor accidents, it caved in to public fear-mongers and affected a temporary moratorium which kept the total US reactor fleet to the present one hundred and four nuclear power plants. This short-sightedness will be (and already has been) the cause of recurring waves of energy shortages and increasing poverty in the US. All of this could have been avoided if government leaders had listened to experienced energy engineers instead of to the flawed anti-nuclear propaganda from armchair philosophers and their lobbyists. Unless quickly remedied while there still is time, the advanced civilization built by the pioneers that settled America will unravel (Refs. I-16–I-19). Some stubborn self-appointed energy gurus are still trying to promote marginal band-aid energy like solar and wind at the expense of nuclear power expansion. Such neo-luddites are only aiding today's terrorists who want to destroy Western civilization. Future generations will hold them responsible for their foolish (in)actions.

1.5 Organization of the Book

A review of common misconceptions about nuclear energy is given in Chapter 2 in the form of questionable assertions (fables) and factual answers (facts). It was felt important to present this material at the beginning of the book instead of at the end. The answers in Chapter 2 have been embellished to include deductions given in later chapters and to summarize the book's main message that an immediate acceleration in new construction of *uranium-breeding nuclear power plants* (*not weapons*) *is essential for our long-term survival*. Chapter 3 which reviews global energy demands and resources is probably the most important part of the book. It shows the necessity and means of developing alternative portable synfuels to replace petrol when oil and natural gas are gone. Chapter 4 reviews the possibilities and limitations of popular "renewable" energy sources, while Chapter 5 discusses current and future automobile engines and portable synfuels required to power them. Chapters 6 through 8 constitute a primer on nuclear electric power. Chapter 6 discusses nuclear reactor operations while those concerned about nuclear radiation effects should read Chapter 7. Chapter 8 discusses international measures to prevent diversion of fissionable fuels for use in nuclear weapons, a subject known as “nuclear non-proliferation”. Chapter 9 presents concluding remarks and a list of action items.

The science and technologies described in this book cover large areas of engineering and physics which can obviously not be discussed in depth. Only general descriptions of the basic concepts are given. It takes many years of college-level studies to master nuclear engineering-physics, mechanical, electrical, chemical, and electronics engineering, as well as economics, geology, radiation physics, environmental law, international law, and many other fields that are involved in nuclear power generation and synfuel production. The objective of the book is to give an introduction and overview of the fascinating field of nuclear energy and its importance when oil fields approach depletion. Hopefully there is enough material to raise the interest of anyone who wants to broaden his knowledge base or who is considering a career in energy and nuclear power, whether as an engineer, physicist, chemist, public policy maker, lawyer, physician, or any other discipline. As a minimum it should give him/her an idea what is involved in making sound energy decisions in the critical decades to come. Some books in Section I of the annotated bibliography provide additional insights and forecasts about the radical changes in energy supplies and usage that are sure to come in the not-so-distant future. For those who want to dig deeper, more detailed technical information on nuclear reactor physics, neutronics, physical chemistry, fuels, batteries, and countless other topics may be found in several textbooks in Sections II through VI of the bibliography. While some (not all) books or articles are referenced, the main purpose of the annotated bibliography is to provide access to additional background information.

Chapter 2
Nuclear Fables and Facts

Many misconceptions have entered the nuclear folklore in recent decades. Major fables propagated by opponents of nuclear power are summarized here, and countered with facts. These facts are based on studies and data published by professional societies, representing some 250,000 diploma-ed engineers from around the world. Factual statements are backed up by data in later chapters. Some controversial issues were already touched upon briefly in Chapter 1.

2.1 Fable (1): "Nuclear Reactors are Like Nuclear Bombs"

Fact: This half-truth is frequently suggested by newspaper journalists who have little or no background in science and engineering. It is as erroneous and flawed as assuming that nitro-glycerin medicine used by heart-patients is as dangerous as nitroglycerin used in explosives, or that dihydrogen-oxide (water) is a dangerous chemical that kills (drowns) many people and should be banned. The uranium in a reactor is dispersed through a collection of fuel elements through which a coolant passes that absorbs the heat from fissioning uranium and which drives turbogenerators. Nuclear reactors are designed so fissioning rates due to neutron multiplications are balanced and controlled by neutron-absorbing "control rods", yielding steady heat production. In today's reactors, if the core gets too hot, thermal expansion of moderator/coolant reduces neutron multiplication ("negative reactivity"), *and the reactor shuts itself down automatically*. This happens even if control rods are accidentally stuck and not instantly inserted in the core as would normally occur if a pre-set temperature is exceeded. In other words, the reactor *always* shuts down if it gets too hot. In a worst-case accident scenario,

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_2,

when the emergency-core-cooling system also fails, the afterheat from decaying radioactive fission products can melt the fuel elements in a reactor core, but an explosion is physically impossible. Some vapors could develop but they will be contained and adsorbed.

The design of a nuclear fission *weapon* is entirely different. It comprises two halves, four quarters, or some other configuration, each with highly enriched nearly critical fissionable uranium or plutonium. When slammed together for instance by springs or chemical explosives, neutron multiplication runs away and a sudden production of enormous amounts of fission heat is initiated. This heat instantly evaporates all bomb material. If detonated in the atmosphere, it induces a shock-wave that overturns and destroys any object in its path within a radius of a few kilometers. The physical arrangement that can cause a nuclear weapon to explode is *totally absent* in a power reactor. It is physically impossible for a reactor to explode like a bomb, just as it is impossible for a nitroglycerin-carrying heart-patient to be ignited and explode.

2.2 Fable (2): “We Don’t Need More Nuclear Power; There Is Plenty of Natural Gas, Oil, and Coal”

Fact: In the 1990s, demand versus supply curves of natural gas and oil (petrol) in the USA crossed over, as predicted by Hubbert (Ref. I-13). Increased oil imports from foreign sources have balanced US demands since then, but increased worldwide demand is now starting to exceed discoveries of new oil deposits. With these trends, oil and gas production is expected to peak around 2015 (“peak-oil”). Thereafter petroleum fuels will become increasingly in serious short supply. Coal, if substituted for oil and uranium to provide all global energy needs might last for 150 years. But if GEN-IV breeder reactors are put into service, uranium and thorium can supply the world with electricity and synfuels for at least 3,000 years in place of oil, gas, and coal. Like petrol, coal-burning power plants produce enormous amounts of air pollution and emit globe-warming carbon dioxide gas. Once oil is depleted, coal is more valuable as raw material for making organic chemicals, and should not be burnt. Non-air-polluting nuclear plants presently produce 20% of all US electric power. To avoid global warming, they should ultimately replace coal-burning power plants. The NEI (Nuclear Energy Institute) fact-based cost figures for electricity in ¢/kWh for 2005 are: 1.71 (0.45) for nuclear, 1.85 (1.36) for coal, 4.06 (3.44) for natural gas, and 4.41 (3.74) for oil, where parentheses give fuel and fuel loading costs (Ref. II-10). Clearly, aside from the not-too-distant threat of no more oil, nuclear energy is competitive and affordable despite false claims to the contrary by anti-nuclear propaganda.

2.3 Fable (3): "Nuclear Power Plants Create Lots of "Dangerous" Radioactive Waste, Which We Don't Know How to Transport or Store Safely. Coal-Fired Power Plants Are Much More Bio-Friendly"

Fact: This is one of the oldest stale fabrications parroted by anti-nuclear faithfuls. Instead of dispersing the combustion products into the atmosphere as is done by coal-burning plants, the radioactive fission waste produced by nuclear plants is always contained and mostly solid. Small quantities of gaseous fission products such as xenon-133 and krypton-85 diffuse into special plenums inside solid reactor fuel elements and are periodically vented and retrieved for valuable use in other nuclear applications. Useless nuclear waste is ultimately placed in some underground repository after removal of valuable radioisotopes and un-burnt uranium fuel. Most nuclear power plants are refueled once every 2 years with uranium encapsulated in solid fuel elements which are shipped in a few trucks. During refueling, the spent fuel elements containing internal fission-product wastes and un-burnt uranium are pulled out of the reactor core and replaced with fresh fuel elements. After a certain cool-down period in a pond, spent fuel elements are placed in collision-proof casks for transport to a nuclear fuel reprocessing plant. Here, after removal of valuable un-burnt fuel and non-radioactive or short-lived radioactive species, non-usable long-life radio-isotopes are concentrated and shipped in special containers to a repository with underground storage vaults. The quantity of final radioactive fission waste has been enormously exaggerated by anti-nuclear bigots. For a 1,000 MW(e) reactor, it amounts to about 1,200 kg per year whose volume is about 0.15 m^3 (5.3 ft^3) equal to that of one household-garbage-can, or one aspirin tablet per person per year who uses electricity from a nuclear plant.

The *annual* fission product waste from *all* 104 nuclear power plants in the USA, which produce nearly *one trillion* (10^{12}) kilowatt-hours of electricity per year, can be extracted, concentrated, and compacted as ceramic marbles in 200 drums, for underground storage in a national nuclear waste repository such as Yucca Mountain in the Nevada desert. Because of anti-nuclear politicking, completion of the Yucca facility which was supposed to have been ready by 2000, has suffered long delays. Even though collision-proof casks will be used which have been extensively crash-tested, anti-nuclear activists still oppose transportation of nuclear wastes over US highways and railroads. This has forced nuclear plant operators to temporarily store used fuel elements in water-shielding swimming pools until Yucca is operational. If properly prepared, temporary swimming-pool storage of spent fuel elements is safe. But it is still better to store final waste in one place rather than at a 100 different sites. Aside from civilian nuclear power plants, the US Nuclear Navy has similar spent-fuel loads to dispose of and has done so safely without problems for half a century. There appears to be a misconception among nuclear-power opponents that "dangerous" radioactive waste can somehow explode like uranium through nuclear fission. *Radioactive waste can not explode and is not fissionable. It only suffers* *from slow nuclear decay*, which entails emissions of betas (= fast electrons) and gammas (= high-energy photons similar to x-rays).

When uranium fissions, its energy is conducted through solid material to heat adjacent water or gas that runs the steam or gas turbines. In this heat transfer, radioactive fission products stay in the solid fuel elements, in contrast to coal burning, where species embedded in coal are sent into the atmosphere when coal is burning with oxygen from the air. As mentioned, fissioned uranium products can not undergo further fission or explode. After the original kinetic energy burst from a uranium fission, the fission products only generate low-level heat from internal radioactive decay. Even if a spent fuel element were exposed to air during its transport in a collision-proof cask (e.g. if a terrorist fired a bullet into the cask), the solid form of the radioactive products in fuel elements prevents their entry into the air. The heavy steel casks are designed to tolerate external bomb blasts and it would take a cask-piercing missile with high explosives to vaporize a fuel element into radio-active aerosols.

Coal power requires continuous coal transports using hundreds of railroad cars and the release of tons of carbon-dioxide and natural radioactive elements into the atmosphere. A 1,000 MWe coal-fired power plant which consumes four million tons of coal per year, releases annually 900 lb of coal-entrained uranium, 530 lb of mercury, 120 million lb of sulfur oxides (SO_x), 59 million lb of nitrogen oxides (NO_x), and 22 billion lb (~11 million tons) of carbon dioxide (CO_2) into the biosphere. Comparing the safety of mining coal versus uranium, one finds that many more accidents occur in coal mines with loss of life. Also the daily transportation of 12,000 t of coal by 120 railroad cars is more accident-prone than the monthly uranium transport of 2 t of uranium yellow-cake with one or two trucks needed to fuel a 1,000 MWe U-235 burning reactor (Section 6.3.2). Coal is also more valuable as a raw material for making plastics and other organics when oil is gone. It should not be burned (Section 2.5).

2.4 Fable (4): "Nuclear Power Is Not Needed. "Free" Renewable Solar, Wind, Hydro, and Geothermal Power Will Do. The Utilities and Government Should Invest More in Them"

Fact: A 1,200 MW(e) nuclear plant (e = electric) operating with a 90% capacity factor, produces 9,500 million kWh of electricity per year, compared to about 40 million kWh/year from a large SOLAR-2 station generating 15 MW(e) peak sunshine power with a 30% year-averaged collection factor. Thus it takes 238 SOLAR-2 stations occupying 25,000 acres (100 km^2) of land and an investment of \$10 billion, to replace *one* nuclear plant occupying 40 acres of land, costing \$2.5 billion (2005 dollars). Solar energy is *not* free. Energy production has three cost components: fuel, maintenance, and capital write-off. While fuel costs are zero, it takes large maintenance crews and vehicles to keep solar panels or mirrors free from dust, rain stains, and bird droppings, and to replace panels or mirrors that are eroded or damaged by sand-, dust-, rain-, and snow-storms or hail. Also storage batteries whose electrodes require periodic replacements must be maintained. Many square kilometers of solar collector or photo-voltaic surfaces and a million storage batteries require enormous capital investments whose write-off costs dwarf the fuel costs for equivalent nuclear electricity. With 10-year solar-cell replacement cycles, one finds that hazardous chemical wastes in manufacturing silicon, cadmium-telluride, or copper-indium-diselenide for solar cells far exceed uranium fuel wastes, when one compares 238 SOLAR-2 stations with one nuclear plant, each producing a year-averaged 1,000 MW(e).

Regarding wind power, one comes to similar conclusions. Five-hundred 2 MW(e) wind-turbines costing $1.0 billion, put on 25,000 acres (100 km^2), could yield 1,000 MW(e) of electric power at full capacity. However the wind is not always blowing and typical year-averaged utilization factors for wind-farms are 25% to provide 1,000 MW(e) on average for a whole year, electric storage batteries are needed which add costs, and four times as many wind-turbines must be placed on 100,000 windy acres (400 km^2). In short, one needs 2,000 wind turbines of 2 MW(e) capacity at a cost of $4 billion + $2 billion for buffer energy storage systems, or a total of $6 billion to provide an average 1,000 MW(e) year around. The typical capacity factor of a nuclear plant is 90%, so a 1,200 MW(e) reactor costing $2.5 billion can provide 1,000 MW(e) continuously during a year. Here all costs are round numbers in 2005 US dollars. Besides the high cost of maintaining 2,000 windmills, wind-farms have the problem of killing hundreds of birds, ruining local ecosystems, and spoiling nature’s scenery.

In summary, while the sun and wind may provide free fuel, it is not steady and highly diluted compared to enormously concentrated, reliable nuclear fission energy. To deliver large quantities of solar and wind-generated electricity, great expanses of energy collection equipment are required which vastly increase maintenance and capital costs relative to nuclear power plants. Solar and wind farms are very useful in providing electricity for small communities in remote locations (e.g. Alaska) or for low-power applications. However they cannot economically replace nuclear or coal-fired power plants to feed an industrialized city with sufficient energy for producing steel, aluminum, bridges, buildings, or to synthesize massive quantities of portable fuels for moving our transportation fleets of cars, trucks, ships, and aircraft.

As a final example, let us compare in round numbers what it takes to generate a total of one trillion equivalent electrical watts (1 TWe = 10^{12} Watts-electrical) of total energy presently consumed in the US, using either wind, solar, or nuclear power. With solar power, one finds that one must build 238,000 advanced SOLAR-2 plants, each producing a year-averaged 4.5 MWe, and costing $10 trillion to provide a year-averaged one million MWe. This exceeds the US gross domestic product (GDP) of $9 trillion. Similarly to deliver one million MWe (= 1 TWe) of wind-power averaged over a year, requires 2,000,000 wind-turbines of 2 MWe peak power at a cost of $6 trillion. This compares with 1,000 nuclear power plants of 1,200 MWe each, which feed 1 TWe to the entire USA with 85% capacity factor, costing $2.5 trillion. It is rather obvious what capital investors will prefer when choosing between $2.5,

$6, and $10 trillion. Note there are already 438 nuclear power plants worldwide and 104 in the USA. The latter provide 20% of all electric grid power in the USA.

Hydroelectric power generation is maxed out in the USA. Most suitable rivers have already been dammed to feed hydroelectric turbogenerators; in fact environmentalists want to dismantle some hydroelectric dams. In Cobb, California, a geothermal power plant generating 55 MWe in the 1960s, experienced large drops in steam pressure and after 6 years was shut down. Some recent geothermal projects are more promising but only useful in a few locations for perhaps a few decades.

2.5 Fable (5): "We Only Have 50 Years of Uranium Ore to Sustain a World Fueled by Fission Power. Coal Reserves Would Last at Least 150 Years, so We Should Concentrate on Cleaning Up Coal Power"

Fact: The oft-quoted 50-year limit on uranium availability is based on "burning" the fissionable U-235 isotope of uranium only. Breeder reactors have been developed at a slightly higher capital cost than U-235 burners, which consume U-238 as well as U-235 via in-core conversion of non-fissionable U-238 to fissionable plutonium-239. This happens after U-238 absorbs a neutron (Section 6.2.2). Since uranium ore contains 140 times more U-238 than U-235, consumption of U-238 (→ Pu-239) gives the world uranium-based electricity for $140 \times 50 = 7{,}000$ years, or about 2,100 years with 30% recovery utilization. Thorium, after neutron absorption, yields fissionable U-233, whose reserves can provide another 3,000 years of nuclear energy. Several experimental breeder reactors have been built and are being evaluated in France, Japan, Russia, and the US. They are presently about 10% more expensive than "burners" but will replace the latter in a few decades.

Coal is an alternative raw-material source for making industrial hydrocarbons such as plastics. Presently, oil provides the raw chemicals for manufacturing plastics, in addition to supplying petrol for the world's transportation fleets. When oil reserves are gone after 2050, it would be foolish to burn coal to deliver electricity, when non-polluting uranium fission power is available to generate all needed electricity. Coal burning also emits globe-warming carbon dioxide and other air-pollutants. It should not be burned.

2.6 Fable (6): "We Should Wait for Development of Nuclear Fusion Which Produces No Radioactivity"

Fact: Fusion reactors *do* generate radioactive isotopes in containment materials due to neutron activation. They burn deuterium and tritium making helium and neutrons. Removable neutron-absorbing inner linings have been proposed for fusion reactor chambers and these will become radioactive. Making fusion viable for nuclear power generation is much more difficult than generating electric power from fission. The minimum plant size to extract energy from a controlled fusion reaction (a miniature sun) is many times that of a uranium fission reactor. It is estimated it will take at least another 50 years of research and development before the first fusion power plant might be built if ever. We have waited 50 years already for a net-electric-energy-producing fusion pilot plant, and the no-oil period is approaching fast. Clearly we must proceed now with the expansion of proven uranium fission breeder technology.

2.7 Fable (7): "Hydrogen-Consuming Fuel-Cell Engines and Electric Energy Storage Batteries Can Replace Petrol-Burning Automobile Engines in the Future; Nuclear Is Not Needed"

Fact: To be able to replace all present petrol-burning auto engines with fuel-cell engines, will depend on (nuclear) electricity or heat to produce the massive quantities of gaseous hydrogen (H_2) fuel needed for these new engines. Fuel-cell enthusiasts neglect to mention that H_2 gas is not a primary earth resource like oil, and must be manufactured. One needs electricity or heat from power plants to make lots of hydrogen. In effect this means that non-portable nuclear, solar, or wind energy must be transformed into portable hydrogen energy. The production of hydrogen fuel to replace petrol presently used in transportation fleets can be achieved by electrolysis or chemical reduction of water (H_2O), yielding hydrogen (H_2) and oxygen (O_2). Based on geological estimates of uranium, thorium, and coal reserves, providing primary electricity or heat for this can be sustained globally by nuclear power for more than 3,000 years or by coal-fired plants for about 150 years. In remote locations, solar and wind farms might also produce some hydrogen by electrolysis when oil is gone. But to replace the world-wide tera-watt quantities of presently used petrol and petrol-burning engines with hydrogen and fuel-cell engines is only economically feasible with nuclear- or coal-based "mother" power plants.

There are at least five practical propulsion systems that could replace present automobile engines when oil is depleted. These are: (a) combustion engines burning synthetically made fuels (synfuels) instead of petrol, (b) hydrogen-consuming fuel-cell engines, (c) high-energy flywheels, (d) electric battery packs, and (e) steam engines. Solar- and wind-driven cars are fun for sports but cannot transport large numbers of people and goods. For long-haul transport, future cars, trucks, ships, trains, and airplanes will most likely be propelled by synfuel-burning internal combustion engines (ICEs) or hydrogen-consuming fuel-cell engines (FCEs). ICEs or FCEs can be run by combustion of H_2 fuel with atmospheric oxygen to move pistons or make electricity, and exhaust only water. That is, the water used for making H_2 fuel by electrolysis is returned to water again in the exhaust. This is an eco-friendly cycle in contrast to globe-warming carbon-dioxide exhausts from petrol-burning ICEs.

Experimental electric fuel-cell car engines have been developed and have confirmed their superior energy utilization efficiency of about 70% versus 30% for combustion engines. But one big obstacle to the large-scale introduction of clean H_2-fuel-cell-powered cars is the H_2 storage problem (Section 5.1.1). Replacement of the space presently occupied by an automobile fuel tank with the best H_2-adsorbing bladder or compressed-gas tank, results in a vehicle that can be driven for only 1 h or 100 km (60 miles). A porous bladder sucks up hydrogen gas and adsorbs it on its inner surfaces, releasing it again when slightly heated. Present techniques for H_2 bladder storage or gaseous high-compression still need a fivefold density increase to make H_2-fuel-cell-powered cars range-competitive with present-day petrol-fueled autos. An insulated fuel tank with liquefied hydrogen might be used instead, but liquefying and distributing hydrogen more than doubles its cost. There is a better solution to the hydrogen storage problem however. This solution is to compress H_2 with N_2 (air) to make liquid ammonia (NH_3) at 12 atm pressure. This process is less expensive than H_2 liquefaction. A hydrogen-carrying liquid synfuel that can be mass-produced from electrolyzed water and air with the assistance of nuclear power is thus ammonia. Ammonia can run solid oxide fuel cells (SOFCs) directly, but to empower fuel-cells with PEMs (= proton electron membranes; Section 5.2.2) it must be decomposed back to hydrogen and nitrogen on a catalytic electrode surface. Another big advantage of ammonia is that it can also fuel the well-developed ICE. ICEs will probably remain in use for some time as vehicle movers until FCEs become more practical and affordable. Bio-alcohol and bio-diesel obtained from sun-grown corn, sugarcane, algae, or other vegetation, which are harvested and processed with (nuclear) electricity may also be economically viable when oil is gone. To be efficient, the energy packed into a portable synfuel must not greatly exceed the amount of electric energy needed for its manufacture, but reasonable conversion losses are acceptable.

It has been proposed to distribute H_2 gas through pipelines to people's garages where it could be compressed into either ultra-high-pressure (600 atm) cylinders to be carried on-board automobiles, or stored in H_2-adsorbing bladder fuel tanks. Or it could be liquefied by cryogenic refrigerators and stored in an ultra-cold (20 K) insulated fuel tank. It was also thought that utility tap water might be electrolyzed to hydrogen and oxygen with available electric grid power in people's garages during the night and the hydrogen transferred to a special H_2 fuel tank. However pipeline delivery or production of H_2 in garages is quite expensive and not very safe. Even if H_2 were to be generated from water at public fueling stations and one could refill fuel tanks with compressed hydrogen gas or liquefied hydrogen, one finds that such schemes are fraught with safety problems and rather expensive. Manufacture and distribution of ammonia instead of pure hydrogen appears presently the most practical and economic solution for providing long-haul transport vehicles with hydrogenous synfuels. Because it will take a few decades before sufficient nuclear power capacity becomes available for the production of mega-tons of ammonia synfuel to replace petrol, there will probably be an interim period (from 2020 to 2040) during which liquefied natgas (mostly methane, CH_4) will be used to empower long-haul transportation vehicles and hybrid automobiles. However like oil, natgas will also be exhausted soon after 2050.

Besides H_2 storage, another big problem with fuel-cells is electrode fouling and cost. Progressive fouling of fuel-cell electrodes may require their periodic replacement, like worn spark-plug replacements in today's combustion engines. This may be acceptable if the costs are reasonable, but so far the only well-performing electrodes contain very expensive platinum. Should further development of FCEs for automobile propulsion prove difficult, use of well-developed ICEs might be continued for some time by fueling them with manufactured portable "synfuels" like ammonia instead of petrol, after oil and gas reserves are gone. With assistance of electric power, coal and water could be converted to syn-petrol (synthetic petrol) as is presently done in South-Africa's SASOL plants. However it is more prudent to preserve coal as a raw material for making organic materials when oil is gone (Section 9.2.6).

A nuclear power plant does not fit in a car of course but its generated electric energy can be converted into synthetic fuel energy to run transportation vehicles. To make abundant uranium-generated energy available for automotive use, some losses are justified when this energy is step-wise converted and locked up in portable synfuels and biofuels. In a no-oil world, sustainable (nuclear) electricity must be used to help extract alcohol from sun-grown bio-fuel vegetation. It must manufacture fertilizers, operate farm machinery, and provide energy for fermentation, distillation, processing, etc. Combustion energies of bio-alcohol or bio-diesel fuels are generally less than the electric energy used for producing them, so a pure bio-alcohol-only economy is unsustainable. Use of bio-fuels is practical only if its production is aided by grid electricity from nuclear, solar, or wind power. One big limitation on producing large quantities of bio-fuels is competition for arable lands needed for growing food crops.

Burning methane (CH_4) or ethanol (C_2H_5OH) in a combustion engine still produces undesirable carbon dioxide (CO_2) emissions, while hydrazine (N_2H_4) or ammonia (NH_3) synfuels (e.g. for aviation) may generate unhealthy NO_x gases. Even if pure H_2 is used as synfuel in an internal combustion engine, high temperatures can cause formation and exhausts of NO_x from reactions of oxygen (O_2) with nitrogen (N_2) which are both present in air. Fortunately well-developed catalytic NO_x converters and scrubbers are available today that can remedy NO_x problems should they arise, thereby making synfuel-burning ICEs attractive if fuel-cells remain problematic.

Electric storage batteries and flywheels are other possible means for providing automotive power. However the most advanced flywheel systems and lightest (lithium) battery packs developed to date are only able to provide enough energy to drive a small car a 100 km (60 miles). Flywheel or electric storage systems face the problem of diminishing returns: more energy storage to achieve a longer driving range means more battery or flywheel mass, which means more batteries and flywheels, etc. (Sections 5.1.2 and 5.1.3). However for short-distance automobile travel such as commuting to and from work, the use of an electric battery which can be charged in garages and parking places is quite feasible. Presently the most practical car of the future appears to be the "electric plug-in hybrid" which runs on a battery for distances up to 100 km (60 miles) and is powered by a synfuel-burning ICE for longer ranges up to 600 km (400 miles). Energy from the ICE can either keep charging the battery and run the car electrically, or it can move the car mechanically via a crankshaft when the battery is exhausted. Unless a major breakthrough occurs that increases the kilowatt-hours/kilogram capacity of batteries and flywheels more than fivefold, at present it appears that combustion engines running on ammonia and bio-alcohol synfuels (or mixtures dubbed "almonia") are most promising to empower the next generation of long-haul transportation vehicles, and to enable hybrid passenger autos to achieve a range of 600 km (400 miles) on one tank-full of synfuel. In the transitional interim period between 2020 and 2040, before sufficient nuclear power plants are built to produce the needed giga-tons of ammonia, almonia, or hydrogen synfuels, use of compressed natgas (mostly methane, CH_4) might be best for fueling long-haul land and sea transports. Natgas reserves are somewhat more abundant than oil, but they too will eventually be exhausted not long after mid-century. For propelling aircraft, liquid ammonia and/or stabilized hydrazine are more suitable than compressed natgas, so the aviation industry will probably spearhead such synfuels sooner.

2.8 Fable (8): "Nuclear Reactor Operations Are Unsafe"

Fact: Two "maximum credible" nuclear power plant accidents involving core meltdowns occurred in the last 50 years, one at Three Mile Island (TMI) and the other at Chernobyl. They proved the soundness and safety of US and Western-Europe designed reactors, while they high-lighted the poor regard for safety and accident prevention under the former USSR regime. The Chernobyl power reactor had no heavy steel and concrete containment vessel as required in all other countries, and was housed in a hangar. It also used graphite (very pure carbon) as moderator, which has a positive temperature coefficient of reactivity. In layman's terms this means that when the Chernobyl reactor core accidentally heated up beyond the desired level, it promoted increased uranium fissioning which can cause a run-away power surge followed by a meltdown, unless halted by insertion of neutron-absorbing control rods. In contrast in Western Europe and the USA, civilian reactors using water as moderator and coolant have negative coefficients of reactivity. When they get too hot the chain reaction terminates automatically and the reactor shuts itself down.

The TMI accident happened because operators mistakenly forced it to overheat (thinking they were lowering the power level), causing the core to partially melt. However the safety features designed in the water-moderated TMI reactor fulfilled their function. The containment vessel held all radioactive core material in place. Except for minor escapes of tritium gas, no nuclear fall-out occurred. In the Chernobyl accident, maintenance technicians pulled out control rods in error, inducing runaway fissioning in the reactor core. The graphite moderator (a form of coal) got very hot and started burning with oxygen from the air as in a coal fire, because there was no containment vessel and thus an unrestricted inflow of air. Firemen who had never been briefed about nuclear reactors tried to put out the fire but unknowingly exposed themselves to lethal levels of radiation. The three maintenance technicians instrumental in starting the Chernobyl accident were killed instantly by flying debris, while 28 firemen and rescue-workers died from radiation overdoses within months. Heart attacks killed 3 more, while 11 succumbed from medical complications years later. Another 30 rescue-workers exposed at the Chernobyl site suffered permanent disabilities (Section 7.6 and Ref. II-20).

The fear of nuclear power plant accidents seems irrational when compared to air and car accidents. Air and car crashes kill thousands of people each year, yet few people want to abolish cars and airplanes. In the past 50 years, less than a hundred people worldwide died in nuclear accidents, even though nuclear power provides 20% of all electricity in the USA, 85% in France, and 15% worldwide. To produce clean non-air-polluting electricity in the USA, it is imperative that more nuclear power plants be built to replace coal- and natgas-fired units. The latter will be inoperable when gas reserves are depleted.

2.9 Fable (9): "The Longer the Lifetime of a Radioactive Element, the More Dangerous It Is for Man"

Fact: Just the opposite is true. The intensity of radiation from a gram of radioactive material is lower the longer its decay lifetime. Conversely it is higher, the shorter its half-life is. We are surrounded by natural long-lifetime radioactive materials on our planet. In fact, each human is internally radioactive because of potassium (K) and carbon (C) present in every human cell. Natural potassium has 0.12% radioactive potassium-40 (K-40) isotope in it and omni-present carbon has the radioactive C-14 isotope in ppb (parts per billion) concentrations. K-40 emits beta and gamma radiation and decays with a half-life of a billion years while C-14 decays with a half-life of 5,700 years by emission of only a beta (= high-energy electron). This compares with a four billion year half-life for uranium-238 decay by the emission of alpha particles and gammas. Both alpha and beta particles are totally stopped by our skin and only massless gammas can penetrate it to some degree. A recent uproar in Europe over depleted uranium-238 used in military projectiles shows the technical ignorance of "green" politicians who are easily brain-washed by anti-nuclear propaganda. Another lament has been the alarm over mildly radioactive "yellow-cake", a uranium oxide produced after mining and pre-processing of natural uranium. It is not a "nuclear explosive" as some mistakenly seem to believe. Yellow-cake is as harmless as natural potassium-carrying minerals or thorium-oxide mantles used in Coleman lanterns whose radioactivity is comparable to what we already have inside our bodies. Besides unremitting exposure to internal K-40 and C-14 radiation, man is constantly bathed in natural radiation coming from cosmic sources and from the earth. He has evolved just fine with all this radiation. Recent studies show mild radiations may even be beneficial (Ref. II-16).

2.10 Fable (10): "Thousands of People Will Die After a Nuclear Plant Meltdown"

Fact: There have been two major nuclear reactor meltdown accidents since the beginning of the nuclear power era, one in the USA and one in Russia. The actual fatalities are zero deaths in the USA from the Three Mile Island (TMI) accident, and 46 in the former USSR at Chernobyl in the Ukraine (see Section 7.6 and Ref. II-20). The author personally visited Chernobyl and the regional hospital near Pripyat, and talked to local residents and operators of the three Chernobyl reactors (only one had a melt-down). Shortly after the Chernobyl accident, scare-mongers announced that thousands would die later from fall-out radiation. This is total nonsense. Actual nuclear fall-out victims in the Chernobyl region were children who drank contaminated milk from cows that had eaten contaminated grass (avoidable if authorities had warned farmers). Some of these children accumulated radioactive iodine in their thyroids. By administration of iodine-displacement therapy and waiting till the radioactivity subsided (Iodine-131 has an 8-day half-life), the affliction disappeared for most of them after a few months. Of an estimated 3,000 people exposed to fall-out, a dozen or so people were reported to have died 10–20 years later allegedly (but not proven) from exposure to Chernobyl's nuclear fall-out.

Claims of thousands of future cancers due to Chernobyl fall-out made by anti-nuclear groups are based on distorted probability calculations not acceptable to statisticians. Under-reported pre-Chernobyl cancers, and cancer cases due to modern chemicals which cannot be distinguished from nuclear-fallout-generated cancers, produce flawed statistics. As all mortals do, most of the 140,000 evacuated inhabitants in the direct fall-out path of Chernobyl's radioactive plume will die between ages 60 and 100. Based on world-wide cancer-death statistics, at least 28,000 (~20%) of them are expected to die from cancer *due to non-nuclear causes*. Anti-nuclear propaganda claims *all* these deaths will be due to Chernobyl, a totally untenable charge. It is akin to claiming that coffee kills 20% of all people, based on the fact that 20% of all people drink coffee and all will ultimately die.

2.11 Fable (11): "Exposure to "Radiation" Can Cause Long-Term After-Effects in One's Body"

Fact: The word "radiation" is repeatedly misused by lay people and substituted for radioactive particles (see below). This causes a lot of confusion. In physics, gamma radiation from radioactive processes falls in the same class as visible light radiation, infrared heat radiation, and radio waves. All are made up of massless electromagnetic waves or photons that are evanescent and which can be absorbed or reflected only once. They do not "stick" as some people mistakenly believe. Like heat which emits infrared photons, a little bit of radiation is harmless and even beneficial (e.g. a heating pad), but too much can kill you (heat in an industrial furnace incinerates you). Nuclear reactor cores emanate alpha and beta particles, neutrons, and gammas. Emanations that possess mass such as the beta particles (which are fast electrons) and alphas (helium ions), are stopped by less than a millimeter of metal, or concrete, while neutrons are absorbed or reflected back into the reactor core. Only gamma radiation emitted by decaying fission products requires thicker stopping materials. Massless gamma radiation is similar to massless solar ultraviolet light, except the photon frequency and energy is higher. Reactors have enough shielding around them to absorb most massless gammas, allowing only an insignificant harmless number to get through.

A person's exposure to a beam of gamma photons emitted by a radioactive compound can cause breakage of a few biochemical bonds in body tissue. However the body does not differentiate between broken biomolecular bonds from a skin-scratch, a knife-cut, cosmic radiation, or from gamma photons. A scratch may be more detrimental than gamma damage since broken bonds are closer together in a scratch, while molecular breakages due to gammas are spread out. Most people have no idea what it means when told they have been exposed to "100 millirems of radiation". This number can be put in perspective by knowing that body damage from a 2 cm long × 0.1 cm deep scratch on one's skin causes biomolecular bond breakages equivalent to about 100 millirems (Section 7.2). The human body repairs broken bonds rapidly and has done so during a million years of evolution in a radiation-rich environment.

A much more important nuclear safety concern is inhalation or ingestion of radioactive particles or dust present in the "fall-out" plume of atomic bombs or in the debris cloud from the meltdown of a reactor without a containment vessel such as Chernobyl. In this case such particles can "stick" inside the body and expose it internally to emitted alpha, beta, and gamma radiation. Some body organs (e.g. thyroid gland) and bones have an affinity for certain uranium fission products, mainly radioactive iodine, cesium, and strontium. The body can extract these elements from inhaled or ingested radioactive dust, and concentrate them unless they are eliminated. When lodged in the body, decaying radio-isotopes steadily emit betas and gammas in surrounding tissue that will irritate or destroy it. This is exploited in nuclear medicine to kill cancer cells, but in that case cancerous tissue is selectively targeted. Some "anti-radiation" pills are available today that can force the body to expel certain undesirable elements like radioactive iodine.

In the unlikely event one is in the path of the debris cloud from an atomic bomb or Chernobyl-like reactor fire, the best protection against fall-out is to enter a shelter with closed windows. If outside, one should filter the air one breathes using a wet handkerchief or gas mask, and wash off all dust by taking a swim or shower after the cloud has passed. If available, one should take anti-radiation pills. Of course the best protection is to run or drive away from the usually slow-moving cloud.

To avoid possible radioactive fallout from nuclear melt-downs entirely, *all* power reactors in the world today must and do have a steel and concrete containment vessel surrounding them. This vessel must keep all nuclear reactor debris contained under the worst imaginable ("maximum credible") accident such as a core melt-down, an M-7 earthquake, airplane crash, (non-nuclear) bomb attack, sabotage, etc. The (almost incredible) Three-Mile-Island (TMI) accident proved its effectiveness in limiting damage.

2.12 Fable (12): “Nuclear Plants Consume Millions of Gallons of Water, Depriving Others of This Commodity”

Fact: This fable is one of the latest fabrications composed by opponents of nuclear energy. Cooling water for a power plant, whether nuclear, coal-, or natgas-fired, provides the low-temperature limit needed to move and condense steam that drives electricity-generating turbines in the so-called Carnot cycle. It is like the radiator cooling water for automobile engines that rejects low-temperature heat so as to move pistons and thus the car in an engine’s four-stroke Otto cycle (Section 5.2.1). By the second law of thermodynamics, without a low-temperature heat dump one cannot generate electricity or provide mechanical motion using cycled high-temperature steam or gas.

Cooling-water should not be confused with reactor core coolant. The latter is the electricity-generating working fluid which is often also water but can be another liquid or gas (Chap. 6). The high-temperature reactor-heated working fluid, after passing through a turbine, is cooled down to a lower temperature in a heat exchanger where it transfers its heat to a secondary cooling-water circuit outside the reactor. The cooled low-temperature working fluid is then circulated back to the reactor core where it is reheated. If near an ocean or river, cooling-water can be used once-through, but for inland locations, one recycles water through cooling towers and/or cooling ponds. While some water is evaporated and lost during the cooling process, most is collected at the bottom of a cooling tower or far end of a cooling pond and re-used. Instead of water-cooling which is least costly, one can also air-cool the working fluid at the low point of the cycle. However air-cooling requires large expensive heat exchangers and fans. The millions of gallons of water that are circulated to cool exhausted steam in a power plant has nothing to do with nuclear fission and is necessary for any heat-based power plant if one wants to generate electricity. Only photo-voltaic solar cells can generate electricity without cooling. Solar concentrator systems also require water or air cooling, and even wind power needs large atmospheric temperature gradients that move air and induce strong winds.

Chapter 3
Energy Consumption and Energy Sources on Planet Earth

3.1 Definition of Energy and Units for Energy and Power

Energy, while an abstract concept, is well-defined in physics and science. Unfortunately the word “energy” has been stolen by psychologists and others to describe a mental state: “he/she has lots of energy”, or “I can transfer energy through my hands to you”. This sounds like energy is something mysterious and fleeting. But this is *not* the energy considered here. As taught in every high-school, it takes kinetic energy for something to move. This energy of movement can be acquired by release and conversion of stored-up (potential) energy. Without physical energy and energy conversions, the whole Universe would be dead and we would not exist. Since we will be discussing energy usage, exchanges, and supplies, it is necessary we first define a unit of energy. For example how many units of energy are in a liter or gallon of petrol.

The word “energy” comes from the Greek meaning “inherent work”. Although others before him had hinted at the conservation of mechanical work and heat, it was Sir James Prescott Joule (1818–1889) who first carefully measured and proved the inter-convertibility of heat and mechanical work, firmly establishing the abstract concept of energy and conservation of energy. He developed calibrated thermometers and reproducible means of measuring temperature and heat energy. After quantifying energy he proved that a certain amount of heat energy can be converted to produce a certain amount of mechanical motion energy and showed that a big wagon needs more energy to be moved than a small one in proportion to its weight.

The laws of energy conservation and energy conversion are the cornerstones of physics. One can define energy on the microscopic as well as macroscopic scale. Microscopic atoms, molecules, electrons, protons, neutrons, nuclei, photons are all endowed with energy, in addition to mass, charge, etc. Likewise cars and trucks moving over a highway possess mechanical kinetic energy, acquired by converting petrol-fueled heat of combustion in their engines into mechanical motion of their wheels and thence onto their vehicle. People who drive cars can visualize energy best by equating it with liters or gallons of petrol. They know their car needs 60 L or 16 gal of petrol to fill their tank to allow them to drive 600 km or 373 miles.

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_3,

In technical parlance, the chemical energy contained in 60 L (16 gal) of petrol when liberated as heat of combustion, is converted by the engine to mechanical energy of wheel rotation, taking the car a distance of 600 km (373 miles). Thus one can equate 1 L of petrol energy with 10 km of mechanical work, or 1 gal (3.8 L) to move an average 2005-model car 23 miles (1 mile = 1.6 km).

Energy can be in the form of kinetic energy, e.g. a falling stone, or potential energy, e.g. a stone on the edge of a cliff ready to fall, one being convertible into the other. Chemical energy stored in molecules like petrol, and nuclear energy present in atomic nuclei, are both forms of potential energy that can be converted into kinetic energy under certain conditions. Heat is the total kinetic energy from swarms of chaotically moving or vibrating molecules or atoms. Heated molecules in a gas can be directed to push a piston, thereby converting heat into mechanical energy of motion. When hydro-carbon (C_mH_n) molecules in petrol react with heated atmospheric oxygen (O_2) in a combustion engine, C, H, and O atoms are rearranged into new molecular compounds (CO_2 and H_2O) with liberation of kinetic energy in the form of heated gases that move pistons. Similarly a neutron flying into the nucleus of a uranium atom, can cause a re-arrangement of protons and neutrons in the nucleus (Chapter 6). This results in the splitting (fissioning) of a uranium nucleus into two halves and liberation of kinetic energy imparted to the two recoiling fission fragments which generate heat in the solid that embeds them. The amount of energy liberated in the fission of a nucleus is generally ten million times larger than that liberated in a chemical reaction. This is the reason why a nuclear plant can produce so much more power from a kilogram of nuclear fuel (uranium), than a coal- or oil-fired power plant can generate from a kilogram of petro-chemical fuel.

The physicist's unit of energy is aptly called the Joule, abbreviated J. Power is defined as the energy delivered per unit time or the energy *rate*. In physics, the standard unit of power is the Watt (W) or Joule per second (J/s). That is, 1 W = 1 J/s. Comparing energy with water, one can liken power to the cups of water that pour out of a faucet per unit time, and energy to the number of collected cups of water. The antiquated "horsepower" (HP) unit, originally based on the strength of horses, is still used to rate car engines. It equals 746 W, that is 1 HP = 746 W = 746 J/s. Historic definitions of various other units for energy and power can be found in physics textbooks. For example the calorie energy unit which is still used, is based on heating 1 g of water by 1°C (Celsius) measured by a thermometer, and equals 4.2 J (1 cal = 4.2 J). For multiples of a basic unit, one uses k for kilo (thousand or 10^3), M for mega (million or 10^6), G for giga (billion or 10^9), and T for tera (trillion or 10^{12}). Thus 1 kW = 1,000 W of power, 1 MW is 1 million watts of power, etc. A peculiar energy unit is the kWh or kilowatt-hour which is disguised as if it is a power unit. It actually is an energy unit and represents energy delivered at a rate of 1 kW = 1,000 W = 1,000 J/s for a period of 1 h = 3,600 s. Thus 1 kWh = 1,000 (J/s) × 3,600 (s/h) = 3.6 million J = 3.6 MJ.

In dealing with large quantities of energy, three commonly used units are the Giga-Joule = 1 GJ = 1 billion Joule; the MegaWatt-hour = 1 MWh = 1 million Watts for 1 h; and the MBTU = 1 million BTU (British Thermal Unit) = 1.055 GJ.

Another “super-unit” used in the English system is the quad = 10^{15} BTU = 10^9 MBTU. They are related as shown in Brief 4. Conversion factors are needed so that one can compare published data from different energy sources that use different units. While calories, BTUs, and kilowatt-hours will probably stay around for a while, to avoid confusion we shall use (and get used to) mostly modern units of Joules and Watts for energy and power in this book. A senseless unit often used in newspaper reports is MegaWatt-hours per year to give the output of a power plant for example. Mentioning “for a year” is often omitted but implied. Here one oscillates from using power units MW (= MJ/s), converting to energy units MWh = 3,600 MJ, and then back to power again: 1 MWh/year = 3,600 MJ/8,760 = 0.41 MW.

Besides units, in comparing amounts of energy generated from a kilogram of oil, coal, or uranium, it is important to specify whether the energy is in the form of heat, electricity, or mechanical motion. We follow the convention of placing (e) or (m) in parentheses after units of energy for the latter two; otherwise it is assumed to be heat. Often the parentheses are omitted. Thus 1 GJ(e) ≡ 1 GJe designates electric energy, while 1 GJ is a quantity of heat energy. The distinction is important because electrical and mechanical energy are of a higher grade than heat. That is, electrical and mechanical energy are more adapt at carrying out man-desired tasks. Most of man’s energy usage involves mechanical motion or electricity, which is obtained by conversion of heat energy via a steam or gas turbine/engine, or by direct conversion of electrochemical energy into electricity. The laws of thermodynamics reveal that only 30–40% of gaseous heat (= chaotic molecular motion in all spatial directions) can be converted via a turbine or combustion engine into uni-directional macroscopic mechanical motion by turbine wheels or pistons and via dynamos into electricity.[1] In such energy conversions, high-temperature heat carried by a gas or steam enters an engine or turbine and after performing mechanical work, is transferred at a lower exhaust temperature to a coolant that dumps the left-over heat content to air or water. This heat dump can be a cooling tower or heat exchanger using water from a pond, river, lake, or ocean. Conversion of chemical energy directly into electricity in fuel-cells and the subsequent production of mechanical motion via an electric motor is more efficient than conversion of heat. It takes place with overall efficiencies of 55–85%. In evaluating world energy resources, published fuel supplies are usually listed by mass or volume and density, whose energy content is given as latent heats of chemical combustion. On the other hand hydro, wind, or solar energy sources specify electric outputs. In comparing these energy forms, we shall assume a coarse conversion factor of 33% for conversion of heat into electricity, while for electrochemical conversions we shall assume efficiencies of 55%. For inter-conversions of mechanical and electric energy we shall assume ~100% (Brief 4).

---

[1] The “second law of thermodynamics” states that the maximum mechanical energy extractable from heat is given by the Carnot fraction $(T_1 - T_2)/T_1$, where T_1 and T_2 are the inlet and outlet turbine/engine absolute temperatures in K or R.

ENERGY:

$1\ \text{GJ} = 10^9\ \text{J} = 0.278\ \text{MWh} = 278\ \text{kWh} = 9.48 \times 10^5\ \text{BTU} = 0.948\ \text{MBTU}$
$1\ \text{MWh} = 1000\ \text{kWh} = 3.6\ \text{GJ} = 3.413 \times 10^6\ \text{BTU} = 3.413\ \text{MBTU}$
$1\ \text{MBTU} = 10^6\ \text{BTU} = 1.055\ \text{GJ} = 0.293\ \text{MWh} = 293\ \text{kWh}$
$1\ \text{Quad} = 10^{15}\ \text{BTU} = 1.055\text{x}10^9\ \text{GJ}$

POWER:

$1\ \text{GJ/y} = 31.71\ \text{J/s} = 31.71\ \text{W} = 0.03171\ \text{kW}$
$1\ \text{W} = 1\ \text{J/s} = 3.6\ \text{kJ/h} = 31.54\ \text{MJ/y}\ \ (1\ \text{y} = 3.154 \times 10^7\ \text{s})$
$1\ \text{kW} = 1\ \text{kJ/s} = 3.6\ \text{MJ/h} = 31.54\ \text{GJ/y}$

CONVERSION OF HEAT ENERGY TO ELECTRICAL OR MECHANICAL ENERGY:

3 GJ ~ 1 GJ(e) ~ 1 GJ(m); 3 MWh ~ 1 MWh(e) ~ 1 MWh(m)
3 MBTU ~ 1 MBTU(e) ~ 1MBTU(m)

AUTOMOBILE FUEL REQUIRED FOR INTERNAL COMBUSTION ENGINES TO GIVE 600 km (373 mi) RANGE, CONSUMING 2.2 GJ ~ 0.72 GJ(m) OF ENERGY:

One "tankful" petrol ≈ 45 kg petrol ≈ 60 liters (16 gal) of liquid petrol

One "tankful" alcohol ≈ 82 kg C_2H_5OH ≈ 107 liters (28 gal) of liquid alcohol

One "tankful" ammonia ≈ 98 kg NH_3 ≈ 163 liters (43 gal) of liquid ammonia @ 12 atm

One "tankful" methane ≈ 42 kg CH_4 ≈ 60 liters (16 gal) of compressed CH_4 gas @ 67 atm

AUTOMOBILE FUEL REQUIRED FOR FUEL-CELL ENGINES TO GIVE RANGE OF 600 km (373 mi), CONSUMING 1.3 GJ ~ 0.72 GJ(m) OF ENERGY:

One "tankful" hydrogen ≈ 10 kg H_2 ≈ 143 liters (38 gal) liquid hydrogen @ T = 20 °K , or
≈ 600 liters (160 gal) compressed hydrogen gas @ 245 atm

One "tankful" ammonia ≈ 58 kg NH_3 ≈ 97 liters (26 gal) of liquid ammonia @ 12 atm

NOTE: (e) = (electrical) ; (m) = (mechanical)

Brief 4 Units and conversion factors for energy and power

It is helpful to recall here that a tankful of petrol in a medium-sized automobile contains about 60 L (16 US gal). This contains 2.2 GJ of chemical combustion energy which can be converted to mechanical motion to propel the car an average distance of approximately 600 km (373 miles). Conversely 1 GJ of heat energy is stored in 27 L (7.3 gal) of petrol which moves a car 273 km (170 miles). Brief 4 lists the approximate equivalences for automobile propulsion and travel using petrol, alcohol, ammonia, methane, and hydrogen fuels. The heats of combustion in ICEs are assumed to be convertible to mechanical energy by a factor of 0.33, while the efficiencies of FCEs are assumed to be 0.55 in Brief 4. Ammonia, hydrogen, and bio-alcohols may become the main fuels of the future for automotive fuel-cells and combustion engines (Chapter 5).

3.2 Amounts and Forms of Energy Consumed by Man

According to statistics supplied by the US Census Bureau and Department of Energy (DOE), there were 281,422,000 people living in the USA in 2000, who consumed a total of 1.18×10^{11} GJ/year of heat-equivalent energy from the primary energy sources listed in Brief 5. The US consumption rate was thus 419 GJ/year = 13.3 kW or 4.4 kWe per person. This compares with a total world consumption of 4.01×10^{11} GJ/year of heat energy by 6,157,401,000 people or 67 GJ/year (0.71 kWe) per person in 2000. These per-capita consumption figures might indicate that a US resident is consuming six times the world average. However a lot of hardware (cars, planes, ships, bridges, tractors, etc.) is used in non-US countries but were fabricated in the USA. So some of the energy for their manufacture must be allocated to non-US residents. This increases the 67 GJ/year figure and decreases the US figure of 419 GJ/year. These considerations apply primarily to Asia, Africa, and South-America who buy such hardware in exchange for labor-intensive (non-petrol-consuming) goods, oil, and raw materials. Europe and Japan, like the USA, also make energy-consuming hardware products traded throughout the world. Without considering detailed balances of world trade and energy exchanges, coarse estimates change the above figures for the year 2000 to about 73 GJ/year or 0.77 kWe per person for the world and about 300 GJ/year or 3.2 kWe per US citizen, still four times the world average.

Energy Resource	Annual Quantity Consumed	Equivalent Heat Consumption	Percentage
Oil	$7.08x10^{9}$ barrels/y	$4.0x10^{10}$ GJ/y	33.90%
Natgas (Natural Gas)	$2.38x10^{13}$ cu.ft/y	$2.5x10^{10}$ GJ/y	21.18%
Coal	$1.70x10^{9}$tons/y	$3.74x10^{10}$ GJ/y	31.68%
Uranium[1]	20,000 tons/y[1]	$0.85x10^{10}$ GJ/y[1]	7.20%
Hydroelectric[2]	------------	$0.33x10^{10}$ GJ/y	2.80%
Geothermal[2]	------------	$0.034x10^{10}$ GJ/y	0.28%
Wood/Bio, Wind, Solar[3]	------------	$0.35x10^{10}$ GJ/y	2.96%
TOTAL:		$11.80x10^{10}$ GJ/y	100%

NOTES: [1]With present U-235 "burners", only 0.5% of the intrinsic uranium energy is utilized. With U-238 breeder reactors, only 400 tons/y would be needed to provide $0.85x10^{10}$ GJ/y; [2]Hydro and geothermal are close to the maximum available in the USA; [3]Bio-fuels, wind, and solar may expand ten-fold in the next twenty years but most likely will never provide more than 15% of total energy needs.

Brief 5 Annual energy resource consumption in the USA in year 2000

Although the numbers in Brief 5 apply to the year 2000, numbers for 2008 have not changed much except that wood/bio, wind and solar energy have seen a 100% increase approximately, raising their year-averaged contribution from 2.69% to about 5.4% of total consumption. Energy conservation such as home insulation, improved auto mileage, etc., have balanced the increases in energy use due to US population growth to 300 million in 2008. In the next 20 years non-US energy consumption will increase, particularly in China. Global consumption rates are approximately five times the US rates listed in Brief 5. They are estimated to reach 123 GJ/year = 3.9 kW = 1.3 kWe per person when averaged over two decades from 2005 to 2025 with a world population of 6.1 billion in 2000 nearing a plateau of 7.8–8 billion predicted for 2025. These figures forecast a world energy consumption rate totaling 0.86 trillion (10^{12}) GJ per year averaged over the next 20 years. With total primary energy reserves as listed in Brief 6, one then calculates depletion times of 16.4 years for oil, 18.4 years for natural gas, 153 years for coal, and 1,100 years for uranium, *assuming* all needed heat-equivalent energy is supplied *only* by oil, or *only* by natgas, or *only* by coal, or *only* by uranium. Exploitation of 1.5 trillion barrels of oil from shale and tar-sands, and 10 quadrillion cubic feet of natgas from sea-beds, requiring less than 50% of contained fuel energy for recovery, are included. If tar-sand oil and sea-bed natgas are excluded, only one trillion barrels of oil and five quadrillion cubic feet of natgas are left, and depletion periods change to 7 years for oil and 6.5 years for natgas. Of course it is unrealistic to assume that *only* oil, *only* natgas, *only* coal, or *only* uranium will be used to support *all* of man's energy needs. Nevertheless these calculated solitary depletion periods are useful to indicate the relative mortality of these resources, showing uranium and thorium's superior long lives as energy sources.

Resource	Quantity	Heat Content	Conversion Factor	Depletion Time @ 123 GJ/y per man (Popul'n = $7x10^9$)
Oil (including tar-sands)	$2.5x10^{12}$ barrels	$1.41x10^{13}$ GJ	5.65 GJ/barrel	16.4 years
Natgas (including sea-bed hydrates)	$1.5x10^{16}$ cu.ft	$1.58x10^{13}$ GJ	1.05 GJ per 1000 cu.ft	18.4 years
Coal	$6x10^{12}$ tons	$1.32x10^{14}$ GJ	22 GJ/ton	153 years
Uranium	$1.1x10^7$ tons ($^{235}U + ^{238}U$)	$8.60x10^{14}$ GJ ($^{235}U + ^{239}Pu$)	$8.6x10^7$ GJ/ton	1100 years
Thorium	$3x10^7$ tons	$2.87x10^{15}$ GJ (^{233}U)	$8.6x10^7$ GJ/ton	3330 years
TOTAL:		$3.89x10^{15}$ GJ		

NOTES: Depletion times assume all mankind's energy needs are provided by one resource only.
1 barrel = 42 gallons = 159 liters; 1 gallon = 3.785 liter; 1 cu ft = 28,316 cm^3 = 28.316 liters;
1 ft = 30.48 cm; 1 mile = 1.609 km; 1 lbs = 0.454 kg; 1 (short) ton = 2000 lbs = 907.19 kg;
1 (metric) ton = 1000 kg = 2204.62 lbs; 1 year = 365 days = 8,760 hours = 525,600 min = 3.154×10^7 sec.

Brief 6 Estimated world reserves of prime energy resources in 2005

In the real world, the transportation sector which comprises our vast fleets of land, air, and sea vehicles, consumes most of the available oil. In the USA, this amounts to about 35% of all energy consumption, but world-wide the percentage for transportation is closer to 40% with the balance of 60% mostly electricity, since less energy for heavy industry is used. At 3.44×10^{11} GJ/year, the actual availability of petrol beyond the year 2005 would then be 24 years without tar-sands oil, and 41 years with tar-sands oil included.

While locomotion of most transportation vehicles is obtained via petrol-burning combustion engines, electricity is generated by means of steam or gas turbines that utilize heat obtained from coal, uranium, or natgas. Additional small quantities of electric energy are provided by geothermal sources, hydro-turbines, wind-turbines, and solar cells. To extend the epoch of the well-developed petrol-burning combustion engine, natgas can be compressed or liquefied and used in place of petrol for cars. In the 1970s when the price of petrol skyrocketed during the oil embargo, many automobilists started using LPG (liquified petroleum gas), which is mostly compressed propane and butane (at ~10 atm) extracted from natgas in Pennsylvania, Siberia, and elsewhere. Compressed methane gas (at ~120 atm) also became popular when that fuel became less expensive than petrol. In the US oilfields, the percentage of methane (CH_4) in natgas varies from about 68% in Pennsylvania to 96% in mid-continent. The balance is a mixture of the higher alkanes in progressively smaller amounts: ethane (C_2H_6 ~30%), propane (C_3H_8 ~8%), and butane (C_4H_{10} ~2%). Thus compressed or liquefied natgas can be substituted for petrol to propel automobiles when oil becomes scarce and expensive. For this reason, it would be prudent to preserve natgas for near-future use as a portable fuel and not burn it up for electric power generation. The latter can easily be run on coal and uranium alone. If we assume that all of the presently available five quadrillion cubic feet of natgas (*not* including speculative retrieval of methane-hydrate from sea-beds) will be available for fueling our transport vehicles in addition to 2.5 trillion barrels of oil, the period for continued use of fossil-fueled combustion engines might be extended. Instead of 41 years, it then would take 56 years to exhaust fossil fuels. This is with the proviso that oil and natgas are used *only* for vehicle fuels, and electricity is produced *only* by coal, uranium, and renewables. Under this scenario, more time is available to develop new propulsion systems and synfuels for aircraft, ships, and long-haul land transport. Many believe the above time estimates are too optimistic and that most probably the out-of-oil time-point will be reached in 40 years and the out-of-natgas time-point in 50 years after 2010.

If burning coal and natgas in electric power plants were to be halted to reduce global warming and to conserve them as raw materials for making plastics,[2] one finds that present nuclear power generation must be expanded fourfold to replace fossil-fueled power plants. For the USA, this means that 300 new uranium-burning plants must be added to the existing 104 operating nuclear power plants as soon as possible. However to replace fossil fuel energy used in transportation, a further

---

[2] The word "plastics" is used here to include organics, hydrocarbons, carbon nanotubes, fibers, and all materials or products presently derived from petrochemicals.

expansion of nuclear power plants from 400 to 800 units of 1,200 MWe each would have to be in place by 2050. Additional supplies of nuclear electricity must accommodate vast fleets of new electric plug-in automobiles and the manufacture of portable synfuels. The portable synfuels are essential for running new propulsion systems of long-haul transport vehicles (e.g. aircraft) when they can no longer use petrol or natgas. Prior to total oil depletion, severe oil shortages can be expected to develop well before mid-century, as production from different oil fields are reduced or halted (prices increased!) when they are approaching exhaustion. It is estimated this will happen in about 20 years! Though it is impossible to set a precise date, we believe *we will see few petrol-driven cars after 2030.* As indicated in Brief 5, electricity from "renewables" (hydro, geothermal, wind, solar, bio-mass) helps. But for them to produce enough portable synfuels for the world's vast fleets of long-haul transport vehicles would be far too costly compared to nuclear generation (Chapter 4). To field eight hundred new nuclear power plants in the US by 2050 is nearly impossible unless a WW-II-like concerted effort is undertaken; in WW-II the US was able to build more than 10,000 aircraft per year. A mis-informed government, manipulated by anti-nuclear advocates who believe all energy needs can be handled by "renewables", will probably impede such a development until serious (avoidable) power shortages and brown-outs make their appearance. By then it is too late to implement a full nuclear power rescue program. The more likely scenario is that 300 new nuclear plants will be running by 2050, and that several hundred coal-burning air-polluting power plants will continue to operate till the end of the twenty-first century until they can be replaced with nuclear plants (Chapter 9).

In the manufacture of portable synfuels there are of course losses in converting prime heat or electricity into chemical energy of a synfuel. As shown in Chapter 5, synthesizing hydrogen, ammonia, or hydrazine from air and water can be done with an energy conversion efficiency between 10% and 60%. That is, 40–90% of prime energy is lost in converting it into portable synfuel energy. As long as there is an abundant source of prime energy (uranium or coal), this poses no problem. Even if it would take 10 GJ of prime energy to make 1 GJ of synfuel energy, there is no bottleneck. To a traveling automobilist, portable synfuel energy is more valuable than non-portable nuclear reactor heat. He does not mind if a substantial amount of the original nuclear heat used for chemical synthesis is lost, just like he is quite willing to waste 70% of the heat produced in his internal combustion engine as long as the balance of 30% is converted so as to move his vehicle. On the other hand if the only source of prime energy is biomass-generated alcohol, and it takes more alcohol fuel to grow alcohol fuel (due to running of farm equipment, distillation process, etc.), the situation would be unsustainable in a no-oil, no-coal, no-uranium future. Only with uranium-generated electricity or heat to provide base-load energy needed for cultivating and harvesting plants and to extract their alcohol, can bio-alcohol become a practical synfuel by converting non-portable nuclear energy into a portable fuel.

Electricity is one of the greatest gifts to mankind allowing him to communicate by telephone, radio, television, and to have all the comforts of a modern home such as electric lighting, air-conditioning, refrigerators, heating, cooking, etc. Without electricity we would have candles and torches for lighting, cold water for bathing, spoiling food, and swelter in hot dwellings during summer. Instant communications around the world would also be impossible. It is very fortunate that nature has provided us with very light negative electrons that can pass swiftly through metal conductors such as copper. If electrons would have been heavy (with the same mass as positive protons), there never could have been readily available inexpensive electricity as we know it. Because of the properties of electrons, electric power can be delivered rapidly and distributed widely with minor propagation losses, to the great benefit of man. The same comment applies to uranium fission which allows the entire world to have at least a thousand years of electric energy and more than 3,000 years when breeding thorium is included (Chapter 6). In the early days of electric power, protesters tried to block its distribution, claiming that thousands of people would die if high-voltage AC power lines would be stretched out over the land. In 1811–1816, a body of laborers in England protested the introduction of labor-saving machinery. Led by Ned Lud these "luddites" rioted and set fire to factories. Similar self-damaging protests are made by today's anti-nuclear technophobes or "neo-luddites" who try to impede the expansion of nuclear power. They are probably unaware that their goals coincide with those of terrorists who wish to destroy Western civilization. Senator Robert Kennedy once observed that in almost every national issue "One-fifth of the people are always against," and that the contrarians are quite bull-headed. Philosophically one can argue whether electricity and nuclear power are a blessing or curse to man. It is up to man to use these gifts of nature for good or evil. One hopes destructive uses can be rooted out and all of mankind will band together to enjoy the benefits of ample uranium-generated electricity for millennia.

3.3 A Brief History of Energy

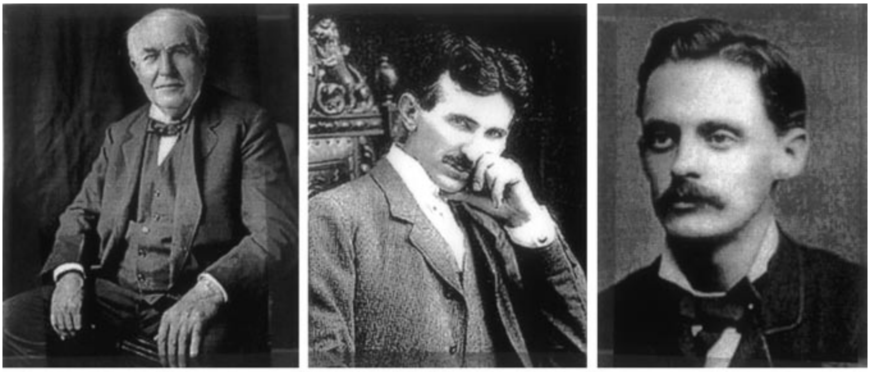
In 1650, the world was populated by 550 million people, or less than 10% of the present population. Besides sunshine which energizes agriculture, controllable energy resources available to man were:

Human Labor (via contracts, indenture, slavery, or prisoners to build structures, roads, etc.).
Animal Labor (horses, donkeys, camels, elephants, dogs, for transporting people and goods).
Wood, Oils, and Coal (burned for lighting, cooking, heating, melting/forging copper and iron).
Wind (windmills grinding wheat, pumping water; sailing ships transporting goods and people).
Water Flow (waterwheels grinding wheat, aquaducts, drainages, etc.).

These main forms of energy were all utilized in one way or another to satisfy man's basic needs and wants for water, food, warmth (heat), housing; or for manufacture of goods such as clothes, candles, furniture, saddles, carriages, ships, armor, weapons for hunting, defense, and warfare, etc.; or for moving people and goods (transportation). They are still available, but now we have six billion people.

In the eighteenth, nineteenth, and early twentieth century, several discoveries and inventions were made that profoundly changed the world's energy picture. First came the steam engine, originally demonstrated by James Watt of Scotland in 1770. It burned coal that heated water in a boiler, converting it into steam which in turn pushed pistons that turned wheels. It was actually preceded by an "atmospheric pump" that used condensing steam to pull a vacuum for suction, invented in 1712 by Englishman Thomas Newcomen, to pump water out of flooded mines. However it was not until 1807, after engineer Robert Fulton (USA) made improvements in the mechanical linkages and conversion cycle of heat to mechanical motion, that steam-ships and steam-locomotives were developed worldwide. Starting in the 1820s, steamships plowed the oceans and big rivers of the world, while trains pulled by steam-locomotives traveled over railroad networks all over the globe, connecting widely separated land-locked territories. Coal became a very important commodity and many new coal mines were opened to feed the hungry steam engines of the 1800s. Some coal-fueled steam-powered automobiles were also built, but only the rich could afford them.

Probably the three most prolific inventors who developed electric power and its many applications were Thomas Alva Edison (1847–1931), Nikola Tesla (1856–1943), and Elihu Thomson (1853–1937), shown in Brief 7. Edison was born in the USA in Milan, Ohio, while Tesla's birthplace was Smiljan, Lika, in the former Austro-Hungarian province of Croatia, and Thomson (founder of General Electric) was born in England but grew up in Lynn, Massachusetts. Edison started his career as a telegrapher and after improving telegraph equipment, became almost instantly famous for inventing the phonograph in 1877. After that, he made numerous additional inventions such as the incandescent light-bulb and the motion picture camera, acquiring over 1,000 patents. He started one of the first industrial research labs in Menlo Park, New Jersey. Tesla came to the United States in 1884, after studying physics, mathematics, and electricity at the Realschule in Karlstadt in 1873, the Polytechnic Institute in Graz, Austria, and at the University of Prague. He began work as an electrical engineer with a telephone company in Budapest in 1881, then joined Continental Edison Company in Paris where he designed dynamos. Wile in Strassbourg in 1883 he conceived of the AC (= alternating current) induction motor. But he was unable to interest anyone in Europe to develop his invention. So he decided to go to work for Edison directly in Menlo Park, where he set out to improve dynamos. Tesla got a letter of recommendation to give to Edison from Charles Batchelor who wrote: "I know two great men (who understand electricity). One is you and the other is this young man" (Ref. I-5). However when Tesla tried to convince Edison of introducing AC instead of DC (= direct current) electricity on power lines to run electric motors and other equipment, Edison refused to listen to him. Edison had little faith in mathematics and physics taught in his days and presumably wanted to protect his capital investments in all the DC electrical apparatus and facilities he had built. Tesla then left Edison and after a brief interlude while he filed for AC motor patents, he gave lectures on electricity. In 1888 Tesla presented a famous lecture on AC motors and transformers at the American Institute of Electrical Engineers (now IEEE) which moved industrialist George Westinghouse to buy Tesla's patents and to ask Tesla to work for him.



Thomas Alva Edison
(1847-1931)

Nikola Tesla
(1856-1943)

Elihu Thomson
(1853-1937)

Brief 7 Pioneers of electric power development and its applications

Although Edison was a brilliant inventor and businessman, he had a stubborn streak. He held on to defending the use of DC electricity and combated Tesla's and Thomson's innovative AC electric power generation by declaring that AC power distribution was extremely dangerous and should be banned. Elihu Thomson, founder of General Electric, had also become convinced that generation and distribution of AC electric power was superior to DC. Between 1885 and 1892, Thomson and Tesla invented several versions of today's ubiquitous AC electric induction motors as well as gaseous electric discharge lights (neon) and other products run by AC electricity. AC voltages are much easier converted and boosted and AC power distribution over copper wires is less lossy than Thomas Edison's DC electricity which powered the street-lights of New York in the 1890s. That is in general, AC power can be delivered more efficiently over large distances than DC power at voltages between 1,000 and 100,000 V. George Westinghouse who was now financing Tesla's work, built and exhibited the first commercial hydroelectric turbo-generator at the 1893 World Fair in Chicago and in 1895 completed the first Tesla-designed hydroelectric plant powered by waterfall-driven turbines at Niagara Falls. It delivered a "whopping" 1.1 MW(e) of electric power that ran the lights and streetcars of Buffalo, NY, 26 miles away. General Electric built the first power lines for this venture. In 1880, Elihu Thomson who taught science and his colleague Edwin Houston had started a company in Philadelphia called Thomson-Houston to sell arc lamps. Later they developed fog-piercing signal equipment using radio-waves just discovered by Heinrich Rudolf Hertz. In 1892, financier John Pierpont Morgan merged Thomson-Houston and Edison General into General Electric making it the biggest manufacturer of electric lighting in the world.

The invention of a coal-burning steam-driven turbine by Sir Charles Parsons in England in 1884 provided an alternative to the waterfall-driven turbines used in hydroelectric power plants. In Parson's scheme, a boiler heated by burning coal converts water to pressurized steam which in turn drives a turbine that can generate electricity. Steam turbines are now the major generators of electricity and coal is the prime energy source for 52% of all electric power generation in the USA, as it is similarly worldwide. Only 5% comes from hydro-electric power plants since the use of most rivers in the USA suitable for dams and large-scale electric power generation has been exhausted. In the US, additional steam-turbine electricity is now (2009) generated by heat from uranium fission (21%), and by burning natural gas (12%), petroleum/oil (3%), or industrial waste such as wood, biomass, alcohol (3%). Geothermal steam, wind-power, and solar-cells provide the remaining 4%.

Two additional world-changing developments were the introduction of the petrol-fueled internal combustion engine for automobiles in 1889 made by Gottfried Daimler in Germany, and the flight of a petrol-engine-powered airplane in 1904 by Orville and Wilbur Wright. Mass-production of autos in 1908 by Henry Ford in the USA, and selling his cars on the installment plan, were another two revolutionary steps that changed the world. After 1908, mass-produced petrol-powered cars overtook steam automobiles and horse-drawn carriages, while many coal-burning locomotive and steamship engines were replaced by diesel engines. The rapid expansion of automobile usage and aviation, with increased demands for petroleum, created today's large oil companies which recover, refine, and distribute enormous quantities of refined oil for a worldwide market.

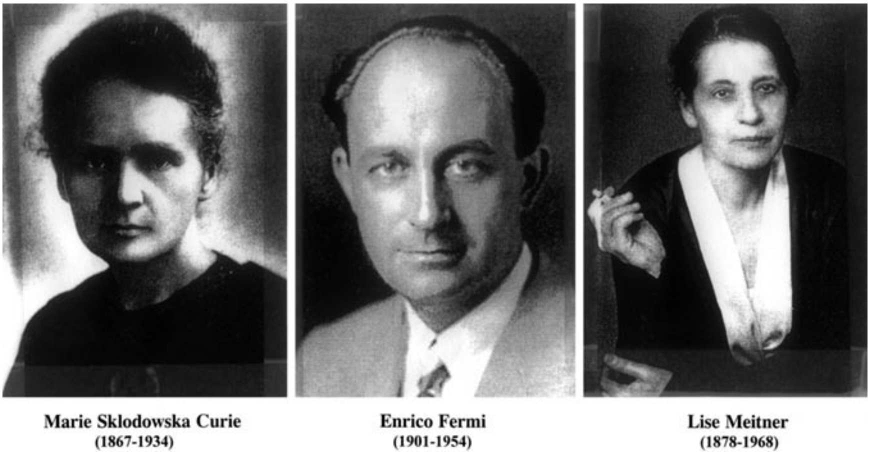
In the Middle East, underground sources of oil were known to exist for centuries and exploited to provide fuel for oil-burning lamps and stoves. When it appeared that oil could power automobiles, William D'Arcey, an Australian businessman, obtained a 60-year concession in 1901 to drill and extract oil from 500,000 square miles or five sixths of what is now Iran (Ref. I-3). He formed the Anglo-Persian Oil Co, later to become Anglo-Iranian and still later British Petroleum (BP). Similarly, in 1904 in what is now Iraq, the Armenian C.S. Gulbenkian recognized the enormous potential of oil and persuaded the Turkish Sultan Abdul Hamid to transfer ownership of immense tracts of land from the Ministry of Mines to private ownership (mostly himself), establishing the Iraq Petroleum Co. Later on, BP and Royal Dutch Shell obtained contracts to exploit the oil fields in Iran, Iraq, and Arabia and to export the oil. US companies Exxon and Mobil, which had their starts in the oil fields of Pennsylvania, Texas, and California, entered the Middle East arena in 1928, when they became part owners of the Iraq Petroleum Company. Gulf, Standard Oil of California (Chevron), and Texaco got involved somewhat later. Control over the Middle East oil fields stayed firmly in the hands of these "seven sisters" until 1973, when host governments demanded more control and revenue from their mineral and petroleum wealth. Today the oil-producing nations of the world have united under OPEC (= Organization of Petroleum Exporting Countries) which regulates the world's oil production rates and prices.

In summary, two energy sources already known in the middle ages but previously consumed in only modest amounts, were suddenly catapulted into major world commodities, namely:

Coal – experiencing a large increase in demand after 1820 to empower steam engines; and after 1900 to vaporize water for electricity-generating steam turbines.
Oil – expanding enormously after 1901 to fuel automobile combustion engines.

Today's oil consumption continues to rise, driven by ever expanding fleets of petrol-burning transport vehicles and craft, while the continuously expanding use of coal is due to increasing demands for electricity. Oil has allowed mankind to transport goods and people all over the world quickly and affordably, while electric power enabled man to develop many new manufacturing techniques, products, and services. Electricity provides modern homes with light, heat, cooling, electric stoves, refrigerators, radios, televisions, telephone service, etc. Increased use and availability of oil and coal has also promoted world population growth and a desire in the less developed countries to acquire modern comforts. Oil and coal consumption rates have thereby reached a level where depletion of oil is forecast to occur in a few decades (one generation), while coal is expected to last only one century if world demand continues to rise at the present rate and no alternatives are introduced. Without oil, it is impossible to maintain current forms of transportation, and without trucks and airplanes it is not feasible to produce and distribute enough food to feed the six billion people that are presently on our planet. Fortunately, nuclear fission was discovered in 1939, and sufficient extractable uranium and thorium has been found on earth to generate all the needed electricity for manufacturing portable fuels for the entire world for the next 3,000 years. It appears that divine intervention wanted man to discover this new energy source in time to avert a human catastrophe when oil runs out.

One of the first scientists to analyze the large amounts of energy locked up in the nuclei of heavy atoms as revealed by nuclear decay and emissions of particles, was Madame Marie Curie (Brief 8). She was born in Poland in 1867 as Maria Salomea Sklodowska. After self-studies of mathematics and physics under difficult circumstances in her native Poland due to the occupation of Poland by Russia, Maria went to Paris where she obtained degrees in science (1893) and in mathematics (1894) at the Sorbonne as one of only two and one of only five women. She met Pierre Curie at the university and married him in 1895. Professor Pierre Curie was an expert in the physics of magnetism as well as a superb instrument designer, and Madame Curie had joined him in his lab as his assistant. They heard of a curious observation by Henri Becquerel that a photographic plate left totally in the dark together with some uranium salt showed images normally only produced by exposure to the sun. Marie decided to find out what caused it and started with some pitchblende which contained uranium. Using Pierre's special instruments and her expertise at separating chemicals as a physical chemist, she discovered that thorium in the pitchblende was also radioactive as well as the uranium, and that still other elements in the mineral were even more radioactive when separated and concentrated. One of those elements she named polonium after her native Poland and another radium. After 3 years of tedious work, she managed to isolate radium which became a standard for research on nuclear emanations and nuclear physics research. In 1903, Pierre and Marie Curie as well as Henri Becquerel received the Nobel Prize for their discovery of the new radioactive elements. Madam Curie discovered that the nuclei of some heavy atoms decayed while emitting three different particles which were labeled α, β, and γ (alpha, beta, and gamma). However in 1903, the make-up of a nucleus and an explanation of that decay was still a mystery. One had deduced earlier that the nucleus of an atom contained protons and that these nuclei were surrounded by electrons to make the atom neutral. It took the 1932 discovery of neutrons by Chadwick in England before a satisfactory picture of nuclei filled with protons and neutrons could be formulated. It explained many previously puzzling observations about radioactive decay but it was too late for Madame Curie to get involved. She died in 1934. However Marie Curie's daughter, Irene Joliot-Curie (1897–1956) who followed in her mother's footsteps to become a radiochemist, did participate in unraveling the mysteries of nuclei. In 1935, Fred Joliot and Irene Curie received the Nobel Prize for their discovery of the artificial induction of radioactivity in aluminum when bombarded with high-energy alpha particles (Ref. II-21).



Brief 8 Discoverers of uranium radioactivity and fission

Having learned that some elements can be made radioactive by bombardment with high-energy nuclear particles, it did not take long before artificial neutron-induced fissioning of uranium was discovered. The history of this discovery is very interesting and full of intrigue. Some of the following information is from Richard Rhodes' fascinating book (Ref. I-6). In Italy in the mid-1930s, Enrico Fermi (Brief 8) was bombarding uranium with newly discovered neutrons, and observed that neutrons (atomic mass M = 1) were absorbed by uranium (atomic mass M = 238),[3] causing the latter to transmute into new product elements with different atomic mass. Based on

---

[3] ‘A nucleus is made up of Z protons and M − Z neutrons. Each of the Z protons has unit atomic mass and unit charge. They determine the total positive charge of a nucleus; hence Z is also called the atomic charge number. The neutron mass is almost the same as the proton mass but has no electric charge. The total number of "nucleons" is the sum of protons and neutrons in a nucleus and is called the atomic mass number M. A given element has a fixed number of protons Z, but can have different "isotopes" with different numbers of neutrons and thus different mass number M. Uranium's most abundant isotope is U-238 with M = 238 and Z = 92, i.e. 92 protons and 146 neutrons, while fissionable U-235 has 92 protons and 143 neutrons.

previous research, it was believed that atomic masses of new transmuted elements had to either gain 1 amu or lose 1–4 units from the original atomic mass M = 238 of uranium. But he found that many product atoms did not have the expected chemical properties of such transmuted species with say M = 239 and Z = 92 and instead found some species with what appeared to be M ~ 95. In Dahlem, Germany, at the Kaiser Wilhelm Institute (KWI), Otto Hahn, Lise Meitner, and student Fritz Strassman decided to redo Fermi's reported experiments. Like Fermi, they also found products with for example M = 144 and Z = 56, disagreeing totally with prevailing theory.

While Hahn and Meitner were pondering this result, Hitler invaded Austria in 1938 and incorporated it into Germany. Lise Meitner who was Austrian, faced new ugly Nazi laws that suddenly applied to her. She learned that her government-funded contract with KWI was about to be canceled because she was part Jewish, in spite of pleas by her colleagues. With the help of Dutch physicist Dirk Coster who picked her up in Dahlem, she went on a train to Holland and fled Germany. From Holland she went to Niels Bohr's institute in Copenhagen, Denmark for a brief rest before going on to Stockholm, Sweden to work with Karl Siegbahn, a renowned researcher of nuclear phenomena. In December 1938, Meitner got a letter from Hahn telling her he had repeated the experiments with neutron bombardment of uranium. He wrote that after careful chemical analysis of the products, he and Strassman found one product was definitely barium with Z = 56, *not at all* close to Z = 92. Did she have any ideas how to explain that?

Meitner (Brief 8) met with her nephew Otto Frisch during Christmas 1938 in Sweden, and discussed Hahn's letter with him. After expressing skepticism but still preoccupied with Hahn's observation of barium, Meitner suddenly remembered a statement by Niels Bohr that he believed the nucleus of an atom such as uranium was like a pulsating liquid drop. They then conceived of the possibility that a nucleus could split in two halves during a drop-stretching waist-producing pulsation after absorption of a neutron. They estimated this could happen if the atomic charge number exceeded Z ~ 90 because of repulsion between the two halves, each half being filled with many positively charged protons. Uranium with Z = 92 protons, was close to this value. The two "fission" products should each have atomic charge numbers whose sum was close to 92. That is if barium with $Z_1 = 56$ was one product, the charge number of the other fission product had to be near $Z_2 = 36$ if protons were to be conserved. Fissioning uranium actually yields product atoms with Z_1 and Z_2 spread over a range of values rather than one particular set and the proton sum $Z_1 + Z_2 \approx 92$ does not quite hold as we know now (Section 6.2.1). Additional calculations convinced Meitner and Frisch that their hypothesis was physically plausible. They also determined that the liberated energy had to be enormous: ~200 MeV per fission or 82 GJ per gm of U-235 which according to Brief 4 equals ~40 tankfuls of petrol per gm U-235. This also equals about 0.94 MW-day of released heat energy per fissioned gram of U-235 in a power reactor or 1 MW delivered all year long by a steadily fissioning 384 g (0.85 lb) of U-235.

Frisch who worked at Bohr's institute in Copenhagen returned to Denmark right after the Christmas 1938 visit with his aunt in Sweden. He told Niels Bohr what he and Lise Meitner had deduced from the data of Hahn and Strassman. Bohr himself had proposed the liquid-drop model for a nucleus, and immediately concurred with their conclusion, stating this was a very important discovery. Next, Frisch put together an experiment using an ion chamber he had in his lab. On January 13, 1939 he found that the masses M of some products from neutron-bombarded uranium atoms detected by the chamber, were much larger than the usually observed protons (M = 1, Z = 1) or helium ions (M = 4, Z = 2). They had indeed values of about half the mass of a uranium atom (M = 238). This was experimental proof that neutron-bombarded uranium can fission. Niels Bohr had left by boat to lecture at Princeton, USA, where he informed his colleagues about the Meitner-Frisch findings on January 17, 1939, after receiving a telegram from Meitner. One of these colleagues was Enrico Fermi who had just arrived in New York on January 2, 1939 after returning from Stockholm where he had received the Nobel Prize for his pioneering work with neutrons. Fermi had decided not to return to fascist Italy under Mussolini, because his wife was Jewish and faced persecution.

The splitting uranium story told by Bohr was quickly passed around by the small US "nuclear club". Within two weeks, experiments with ion chambers were conducted at the National Bureau of Standards, which confirmed the astounding observations by Frisch. Shortly thereafter, Einstein wrote a letter to President Roosevelt warning him Hitler might develop a super weapon using uranium fission. Thence the secret US Manhattan Project was born. To prove that uranium fission could work on a macroscopic scale, Fermi designed and built the first nuclear reactor at the University of Chicago, which went "critical" on December 2, 1942. Next, in an incredibly short 2 years, plutonium production reactors were erected at Hanford, Washington, and a gigantic gaseous diffusion plant was built at Oak Ridge, Tennesee, to separate fissionable U-235 isotopes from natural uranium (0.7% U-235, 99.3% U-238). At Los Alamos, New Mexico, a team of the brightest scientists in the world under the leadership of Robert Oppenheimer worked feverishly to develop a nuclear bomb, thinking Hitler might be ahead of them. After testing the first bomb at Alamogordo, N.M. on July 16, 1945, WW-II was ended with the detonation of two additional nuclear weapons, one on August 6, 1945 at Hiroshima, and the other on August 9, 1945 at Nagasaki, Japan. The irony is, that the three fascist-ruled nations who had banded together to conquer the world, were ultimately defeated by an international group of superb scientists, many of whom, like Lise Meitner and Enrico Fermi, had been driven out of their countries because Hitler alleged they or their families were ethnically inferior!

After WW-II ended in 1945, vigorous development of nuclear *power reactors* (not to be confused with weapons!) occurred worldwide for the purpose of generating electric power by converting fission heat → steam → electricity. Today uranium produces 21% of all electricity in the USA, 85% of all electric power in France, and close to 50% of all electric power in Japan. Other countries like China and India are quickly following. Clearly the latest and today's most valuable energy resource is:

Uranium and **Thorium**, starting around 1950.

Aside from electricity, so-called "research" reactors produce special "radioisotopes" used in thousands of hospitals by physicians specialized in nuclear medicine. The radioisotopes are tagged onto special pharmaceutical agents used for diagnostics or for therapeutic cancer-fighting applications. Radioisotope-tagged molecules are also used widely as tracers in biotechnology and pharmaceutical research, revealing biological processes and the effects of experimental drugs in the human body. One popular medical radioisotope used in diagnostics is Molybdenum-99 (Mo-99), which is chemically extracted from uranium fission products. Mo-99 decays in 67 hours to radioactive Tc-99m (Technetium-99m) which in turn decays in 6 h to virtually stable Tc-99 with the emission of a gamma-ray (0.140 MeV). The radioactive Mo-99 is shipped in shielded canisters ("cows") that can be filled with saline that extracts ("milks") the short-lived Tc-99m but not the Mo-99. After saline extraction, the Tc-99m is bonded to a bio-organic molecule and injected into a patient's bloodstream. This molecule is designed to be absorbed by certain internal organs whose image and condition is then revealed on an X-ray photo via the emitted 0.140 MeV gammas. The 6-h half-life of Tc-99m insures this element is no longer active for more than a day and easily excreted.

Another application of nuclear power is to use its dumped heat for the desalinization of seawater (California) or for mass urban heating (Mongolia). In the electricity-generating steam cycle, about two thirds of reactor heat is dumped at a lower temperature (see footnote 3 of Chapter 1). This can be profitably used for other applications.

3.4 Summary of Primary Energy Sources

Natural prime energy sources are either "renewable" or "non-renewable". Non-renewables are extracted from the earth with energy expenditures that are a fraction (~50% or less) of the potential heat of combustion possessed by the energy source. However because there is only a finite supply, they are depletable. Renewable energy on the other hand is assumed to be always available. Thus natural primary energy sources can be divided into two catagories:

1. *Non-renewable sources*
    (a) Fossil fuels: oil, natural gas, coal
    (b) Nuclear fuels: uranium/thorium, deuterium
    (c) Geothermal energy: heat pockets
2. *Renewable sources*
    (a) Sunshine (Solar Energy)
    (b) Wind energy
    (c) Water falls (hydro energy) and tidal waves

Energy sources can also be classified as portable or fixed. Of energy sources (1a) through (2c), only item (1a), oil, natural gas, or coal, are portable and can be taken along in an automobile, truck, or airplane to power it. Refined oil yields portable petrol (hydrocarbon mixtures rich in octane (C_8H_{18})) as well as portable diesel (crude oil distillates with higher boiling point), both of which are liquid at room temperature. Natural gas (natgas) contains mostly methane (CH_4) but also fractions of ethane, propane, butane (C_2H_6, C_3H_8, C_4H_{10}). As mentioned, liquified (111 K) or compressed (~120 atm) in portable high-pressure tanks, natgas can fuel car engines. Coal can of course be carried along as lumps and be burnt to make steam that powers a steam engine as was done in the 1800s. But today most coal and natgas resources are burned in power plants to provide super-heated steam that generates electricity via a turbine (Chapter 6).

Regarding item (1b), nuclear powered ships and submarines have been built and nuclear rockets or aircraft are feasible, but it is not practical nor safe for automobiles to carry nuclear reactors under the hood. Nuclear fission power to propel aircraft and rockets has not been implemented because of problems arising in potential crashes. Electric-grid energy, whether produced by uranium, coal, or other means, is clearly not in a portable form that can be carried by surface vehicles or aircraft as a replacement for petrol, when oil and gas are gone. However electric-grid energy can be converted into portable synfuel energy, as discussed in Chapters 5, 6 and 9. In large cities and parts of Europe, electric trains have been developed that use (nuclear) electric energy from the power grid by means of sliding blades that contact bare high-voltage overhead wires or ground-level trenched conductors.

The harvesting of renewable solar and wind energy is primarily useful in remote locations that need electric power. Assuming wind is available, wind turbines can provide 1 to 2 MW(e) peak power per turbine at an installation cost of about $1 million/MW(e) in 2005 dollars. Solar power may be useful in desert regions, but installation and maintenance costs of solar stations with energy storage systems are quite high even though prices of solar cell arrays have come down considerably in the last 20 years. Of course winds are not always blowing and the sun is not always shining, which limits the use of solar and wind energy in many parts of the world. To replace petro-fuels exclusively with solar and wind energy was reviewed in Section 1.4.2. Chapter 4 discusses the possibilities and limitations of renewable energy sources (2a), (2b), and (2c) listed above in some detail.

For transportation applications, wind-powered sailing ships have of course been used for millennia, while sail-driven or solar-cell-powered cars have been built and do exist. Today these are great for sports but they could not replace the combustion engine to run bulldozers, trucks, cars, or any mass transportation vehicles. One finds in general that solar and wind energy, while attractive, lack sufficient power density to compete with modern compact high-power engines and fuels, and with nuclear power generation. High-density power generation lowers capital costs immensely compared to costs of large-foot-print systems like solar and wind.

Chapter 4
"Renewable" Energy Sources and Their Limitations

In this chapter we shall briefly examine renewable energy sources which have become quite popular in the last decade and which some aficionados believe will enable mankind to overcome all future energy shortages. The so-called "renewables" are principally wind, solar, hydro, geothermal, biomass, and ocean-wave sources. Too many people forget that well-proven laws of physics place strict limits on how much and how fast energy can be produced and consumed, which in turn affects its economics. From an economic standpoint, renewables can only be supplementary "band-aids" to help us overcome the enormous energy shortages we are facing when oil-fields are depleted. They can be very helpful in certain remote locations, but as multi-gigawatt sources of needed base-power for industrialized areas of the world we shall show that nuclear power generation is a lot more practical, less prone to cause environmental destruction, more economical, and much less "dangerous" than what false propaganda of anti-nuclear zealots wants us to believe. It is the central message of this book and will be discussed in detail later in Chapters 6–8.

Assertions have been made that all oil-derived petrols can be replaced by renewable bio-mass fuels such as bio-alcohol, bio-diesel, bio-hydrogen, etc., derived from sugarcane, corn, switchgrass, algae, etc., and that solar- and wind-farms can supply all needed electricity. That is, nuclear energy is not needed. We shall examine this proposition now in some detail. As discussed in Chapter 3, the estimated world-averaged energy consumption rate between 2005 and 2025 will be about 1.3 kW of equivalent electric energy per person, or 9.1 billion kW (= 9.1 TW) for 7 billion people.[1] A typical 100-W lightbulb, when turned on, continuously burns 100 J of electric energy per second. If in the next 2 decades each person consumes 1.3 kW of energy on average, he/she would continuously burn the equivalent of 13 electric lightbulbs. This energy consumption rate includes each person's share of electricity and motor fuel used in making foods and goods and their transport to market. It also covers fuel to drive to work and back, for making steel and aluminum used in cars, bridges, buildings, ships, airplanes, appliances, and for home lighting,

---

[1] In this chapter, we shall omit (e) in kW(e) for brevity.

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_4,

cooking, heating, cooling, etc. For comparison, refrigerators, heaters, and air-conditioners consume typically about 1 kW each, while driving a car takes 20–100 kW. Of course the latter energy consumptions are usually shared. The world-average usage of 1.3 kW per person (presently 0.77 kW) assumes that standards of living in China, India, Indonesia, and other countries will steadily improve in the next decades. Also it is assumed that energy conservation will be improved via better-insulated dwellings with solar-paneled roofs, and that energy will not be wasted in too many scorched-earth wars.

4.1 Sunshine-Produced Biomass and Biofuels

Conversion of biomass or organic wastes into energy-carrying synfuels by fermentation, digestion, and other techniques is only economically feasible and sustainable if the required processing energy is supplied by (nuclear) electricity or heat. In this case extraction of a biofuel (e.g. alcohol or fat) from biomass produces a portable synfuel whose inherent locked-up energy is made available upon combustion. But producing this biofuel was made possible by the expenditure of externally provided (nuclear) electricity or heat to cultivate plants and to extract their biofuel. Non-portable (nuclear) electricity or heat energy and sunlight (solar energy) is thus essentially converted into portable fuel energy in this case. However besides the need for (nuclear) electricity or heat, in order to replace all presently used petrol with biofuels, about one-third of all available lands in the world would have to be used for farming bio-fuel producing plants. This is feasible only in countries with vast thinly populated fertile lands such as Brazil or the USA, but may be impossible for densely populated Western Europe. If one dictates that no coal or uranium can be used to generate primary electricity, and only bio-fuel production is allowed, one finds that one needs four times all available land in the world to replace present petrofuel energy. Clearly this is a physically impossible proposition.

Solar radiation at the earth surface amounts to about 1.35 kW/m^2 or 5,463 kW/acre when sun-shine peaks. The overall efficiency of plants or trees to convert earth-incident solar energy into burnable carbonaceous chemical energy (alcohols, wood, etc.) is about 0.03 % for the best bio-fuel producers (Refs. VI-1, VI-2). This includes average diurnal, seasonal, and weather effects, as well as foliage intercept fractions, crop turn-over times, and plant photosynthesis efficiencies (plants use a lot of captured solar energy for pumping water). With 5,463 kW/acre of peak solar irradiation, plants might thus produce 1.6 kW/acre of potential bio-fuel. Assuming 6% for access roads to cultivate and harvest, one acre could yield 1.5 kW of bio-fuel energy, if crops are continuously replanted after harvesting. We are talking here about a continuous balance between solar energy delivery, conversion, and harvesting of bio-energy. One can accumulate bio-energy for years by growing timber for example, and consume it all in a few hours at 1,000 kW (a million Joules per second) per acre in a forest fire. But it takes a long time for re-growth before a repeat of such a high energy release rate is possible. Because of energy conservation (what goes out must come in), one can thus only extract 1.5 kW per acre of year-averaged bio-fuel energy. As mentioned in Chapter 1, the fossil fuels we burn up today in 1 year, were deposited by plants over millions of years in the past.

Brief 9. Acreage limitations for growing and harvesting bio-fuels to replace oil.[a]

	Needed acres for bio-fuel farming		
	Aided by Electricity[c] (*from Uranium or Coal*)	*Harvested by Biofuel only*[c] *(No Electricity)*	Available acres
USA			
Portable bio-fuels for transportation fleets[b]	1.15 billion[d] [0.62 billion[e]]	5.74 billion[d] [3.16 billion[e]]	*Total USA lands: 2.24 billion* *Total US arable lands: 1.3 billion* (1 billion in use for growing food + 0.3 billion non-food)
World			
Portable bio-fuels for transportation fleets[b]	5.75 billion[d] [2.4 billion[e]]	28.75 billion[d] [15.5 billion[e]]	*Total world lands: 37 billion* *Total arable lands: 8 billion* (7 billion food + 1 billion other)

[a] In 2006 the USA consumed 7.08×10^9 barrels/year (= 4.08×10^{10} GJ/year) of oil + 2.38×10^{13} ft^3/year (= 2.50×10^{10} GJ/year) of natgas, for a total of 6.58×10^{10} GJ/year of petro-fuels. Of this amount, about 4.5×10^{10} GJ/year is used for empowering transportation fleets. The world consumes approximately five times as much as the USA.

[b] Energy for transportation is about 40% of total energy consumption (electric power + transport + ⋯).

[c] Eighty percent of harvested bio-fuel energy is self-consumed for fertilizer manufacture, farm operations, alcohol distillation, etc.

[d] According to UN-sponsored studies, arable land yields at most 7 equivalent barrels of oil per acre annually (39.2 GJ/year) with an average bio-conversion efficiency of $\eta \sim 0.03\%$.

[e] Some bio-alcohol producers believe they can extract 12 equivalent barrels of oil energy per acre annually, thus assuming $\eta \sim 0.05\%$. Solar radiation at the earth surface is ~1.35 kW/m^2 or 5,436 kW/acre when sunshine peaks (1 acre = 4,046.87 m^2 = 0.4047 ha).

To replace all the world's petro-fuel and electric energy with synfuels and electricity derived *only* from bio-mass, will take about (9.1 billion kW)/(1.5 kW/acre) = 6 billion acres of arable land. To grow, harvest, and process bio-crops, one needs tractors, fertilizers, processing operations, etc., which all consume energy. Proponents of biofuel production claim this takes less than 90% of the alcohol energy produced by corn crops for example. Even if we assume that improvements can lower this number to 80%, bio-fuel production would then need five times more land, or 30 billion acres to generate a net of 9.1 billion kW of marketable portable bio-fuel since 36.4 billion kW has to be used to produce it. Since the world's total arable land is about 8 billion acres, this is four times more than what is available. The total surface area of the world's land mass is about 37 billion acres of which the USA occupies 2.24 billion acres, but about 20% of that surface is permanently frozen.

Clearly it is impossible to accommodate the world’s energy needs if one depends *only* on bio-mass. With the aid of nuclear electricity which can run alcohol distillation plants, fertilizer production, and the manufacture of farm equipment, five times less land is needed and “only” 0.6 billion acres of US lands are needed. In this case, bio-alcohol can be viewed as a synfuel produced jointly from nuclear electricity and sunshine as prime energy sources. Under that scenario, non-portable nuclear energy is converted into portable energy and the 80–90% energy penalty for harvesting and extraction is not critical. Globally, assuming 40% of total energy consumption requires portable fuels, one would need a formidable 2.4 billion acres or 30% of the world’s arable lands. Only in countries like the USA and Brazil with vast fertile land areas might such bio-fuel production be sustained, *provided sufficient nuclear electricity is also available*. More likely only 10% of arable land might be made available for bio-fuel farming because man also needs arable land for growing food. Brief 9 lists some of the estimated acreage limitations for bio-fuel farming.

Although bio-fuels like alcohol emit globe-warming carbon-dioxide upon combustion, there is no net addition of this gas to the environment since plants take up carbon-dioxide to make extractable carbon-based bio-fuels. Thus they are “carbon-neutral”. But as we showed, besides needing (nuclear) electricity to be sustainable, bio-fuel farming is limited by the availability of arable land. It is estimated that not more than about 10% of farm-lands might be converted to generating bio-fuels without threatening food crop cultivations. For this reason instead of using land, experiments are being conducted to harvest fast-growing algae in the oceans which can be processed to make bio-fuels. Such ocean bio-fuel farming will also require harvesting operations that require fuel. Though presented as a new technique, algae fuel farming was already studied in the 1950s (Ref. V-2), but only recently did it experience a renaissance. It is still somewhat uncertain how much sea surface is needed to produce sufficient quantities of extractable synfuels for fossil fuel replacement, and how much energy is needed for harvesting and processing the seaweed. Like bio-fuels from vegetation, without assistance of primary (nuclear) electricity or heat, biofuel energy extracted from seaweed may not be self-sustainable.

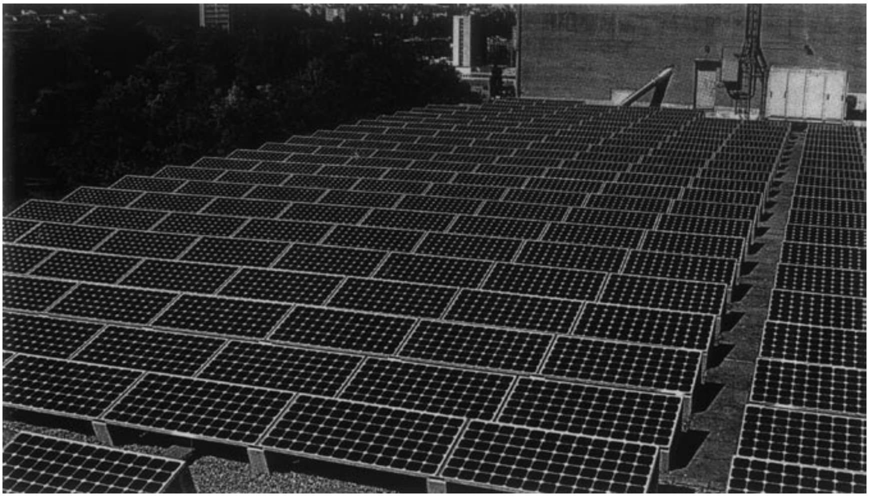
4.2 Direct Solar Energy Conversion

The development of solar cells to convert sunshine directly into electricity has been heavily subsidized for over 50 years, starting with the space program. Many prominent scientists like the well-known chemical physicist Farrington Daniels organized a number of conferences in the early 1950s on harvesting solar energy. Future energy shortages due to oil depletion were recognized and besides nuclear energy, many techniques for harnessing solar and wind power were reviewed in a 1954 world symposium in Phoenix, Arizona (Refs. V-1, V-2). Though much has been improved in the past half-century in terms of component performance, it is amazing how little the basic technical concepts for wind and solar power generation have actually changed since 1954. Our sun covers all of the earth's land-mass intermittently with about 120,000 TWe (tera-watt-electrical) of photon energy, but because the earth rotates (nights) and wobbles (seasons), the year-averaged energy absorbed by the lands is only about 35,000 TW. This enormous amount is far above the measly 15–20 TW we need to keep mankind happy. Of course such an observation is like saying there is more than enough water in all the oceans to quench the thirst of every man and beast a thousand times over.

The basic problem of utilizing solar radiation is of course its spatial dispersion and how much energy it costs to concentrate and store it to where man can use it effectively. It illustrates why the high density of man-controllable release of nuclear energy is so attractive in comparison. In thermodynamics one encounters a similar problem, called the "second law", which discloses that the amount of energy possessed by a given quantity of hot gas is much more valuable for doing work when it is at a high temperature than at a low temperature even though it holds the same amount of energy. One deals with this fact in thermodynamics by introducing the concept of entropy which can loosely be defined as indicating the degree of usefulness of a gas for doing work. Likewise, in assessing the usefulness of different energy sources, besides energy density E/V (energy per unit volume) and energy release rate or power $P = E/t$ (energy per unit time), one must consider also energy intensity P/A (energy flowing through area A per unit time). Energy concentrations and intensities released in nuclear fission are ten-million times higher than those produced in chemical combustion or solar irradiation. This is the basic reason why controllable nuclear energy is so useful and easy to manipulate for doing large amounts of desirable work.

As illustrated in Briefs 10 and 11, two general solar energy harvesting techniques are used today. One method involves solar energy concentration (SC) in which sunlight is focused by large concentrating mirrors to heat up a thermo-electric material or a heat-holding liquid (e.g. oil) in a pipe whose heat is exchanged with water that is vaporized and drives a turbine to generate electricity similar to that in a coal or nuclear power plant. In the other technique called photo-voltaic (PV) generation, solar photons excite electrons directly into the conduction band of a thin layer of doped semiconductor across a pn junction, allowing an electron current to flow through a load. Presently large arrays of PV solar panels using silicon (Si), cadmium telluride (CdTe), or copper indium/gallium diselenide (CIGS) semiconductors, are most popular for urban or desert installations. However advocates of SC systems claim that their approach is more practical than PVs since they can heat up an oily liquid that can hold the heat at a high temperature for 10 h during nightfall to continue providing electric energy when there is no sunshine. Earlier-studied thermo-electric schemes that utilize electric currents driven by thermal gradients in special materials seem to be largely abandoned today in favor of PV and SC fluid heating methods. While sunlight "fuel" is free, the SC capital and maintenance costs of large atmosphere-exposed focusing mirrors as well as the uncertainty of sunlight availability due to fog, rain, or snow, makes SC power farms generally less competitive than coal or nuclear power plants which use similar turbo-electric generators but occupy much less real estate and operate 24/7.

Brief 10 Solar concentration power system



Brief 11 Photo-voltaic solar-cell complex

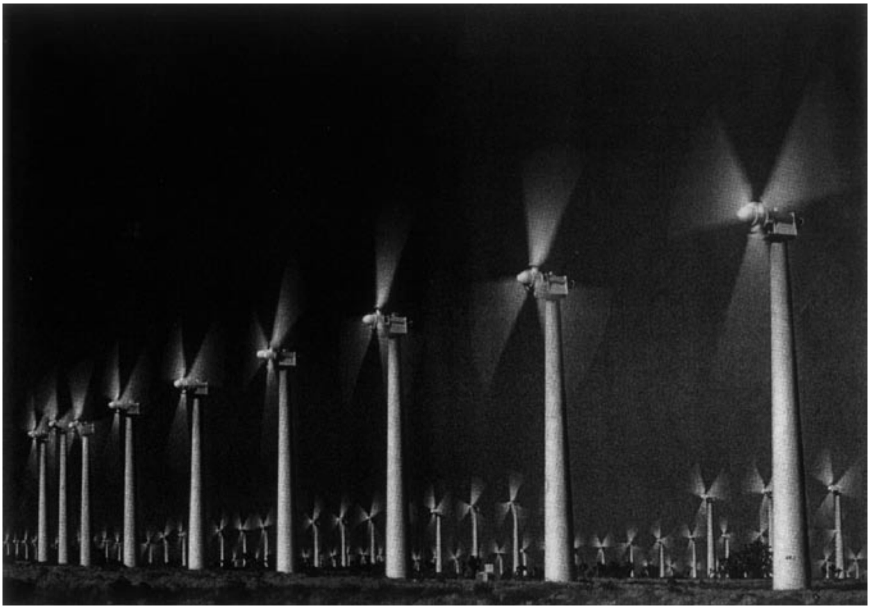
CdTe- and CIGS-based solar cells are reported to have photon conversion efficiencies of 10.6% and 19.9% respectively while single-crystal Si is quoted to be able to generate electricity with an efficiency up to 30%. However efficiency is not the only important parameter; the cost and ease of manufacture is also a big factor in commercial applications. Costly PV materials are only justified in special applications where costs are less critical. Presently the least expensive and most popular mass-produced PV solar cells are made of polycrystalline silicon. While direct photon-to-electricity efficiencies of fresh poly-Si cells have been measured to be 13–16%, the overall long-life efficiency is about 9.5% when losses from voltage up-conversions, atmospheric weathering, and energy transmission/storage are included. Then one can generate about 520 kW per acre of solar panels when sun-shine peaks. However because of diurnal (nights), seasonal, and weather fluctuations this value is reduced by 70% to a year-averaged 156 kW/acre. A further reduction of 15% must be allowed for access roads to install and maintain solar panels, energy storage batteries, and transmission lines. This yields finally a year-averaged 133 kW/acre (33 W/m^2). Construction of a large PV solar complex generating a million kW of electricity at a cost of about $10,000 per kW would thus require 7,500 acres of sunny desert land and $10 billion. To replace all present petro-fuel energy consumption and electric energy production in the world with solar-cell energy generation, would require (9.1 billion kW)/(133 kW/acre) = 68 million acres of sunny open land. To deliver 9.1 billion kW world-wide from solar cells then requires $91 trillion (2005 dollars) of capital investment and 68 million acres of accessible sunny desert. Should all future homes possess solar panels to provide self-sufficient domestic power (30% of total energy pie), $30 trillion can be passed on from the utilities to home-owners, who probably will have to pay double this amount ($60 trillion). Utilities must still invest $61 trillion in this case for PV solar farms placed on 40 million sunny acres to meet heavy industry, synfuel manufacturing, and plug-in automobile power demands. These figures represent only capital investment costs. Maintenance costs such as keeping solar panels clean and replacing damaged panels due to wind and dust storms are estimated to amount to $1,000/year per installed kW.

4.3 Wind Energy

Another popular “renewable” energy source is wind-power. Actually wind-power is also solar power, because it is solar irradiation that creates a temperature gradient in the atmosphere of a rotating earth which in turn produces wind currents. This solar irradiation fuels the rotating earth atmosphere which acts as a regenerative thermal engine with total kinetic energy on the order of 100,000 TW of thermal energy (~33,000 TWe). But only a portion in the lowest stratum, with an estimated 10 TWe is available for man’s use. This compares to 1 TW obtainable from hydro-power (Ref. V-1). As shown in Brief 12, today many wind-farms with scores of wind-turbines are dotting previously pristine land- and sea-scapes, each windmill producing 1–2 MW of electric power with average wind speeds. An approximate relation for wind-power is (Ref. V-1):

$$P(\mathrm{MW}) = 4\,\mathrm{x}10^{-9}\ D(\mathrm{ft})^2\ V(\mathrm{mi/h})^3 = 1\mathrm{x}10^{-8}\ D(\mathrm{m})^2\ V(\mathrm{km/h})^3 \qquad (4.1)$$

Thus for a windmill with a wind-intercept diameter D = 225 ft = 69 m and a wind speed of V = 20 miles/h = 32 km/h, one generates about 1.6 MW of electric power. Winds can be moving high up in the atmosphere, but generally deliver most power between 100 and 1,000 ft (30 and 300 m) from the ground depending on the local geography. Experimental studies in 1955 indicated that wind-mills rated for about 2 MW are most economic if they stand about 165 ft (50 m) high and have a blade-covered wind-intercept diameter of 225 ft (70 m) regardless of wind regime (Ref. V-1). Today (2009), modern 3 MW (nominal) wind-turbines stand about 270 ft (90 m) high from ground to turbine-hub, and have three 150 ft (50 m) long blades that turn optimally at about 8–15 revolutions per minute in winds of 15–25 miles/h (24–40 km/h). The blades can be pitched and the mill can be turned to face a wind for optimum performance. In storms of over 40 miles/h the windmill can be feathered to avoid damage. For a 20 miles/h (32 km/h) wind, about 3.3 MW can be generated theoretically according to Eq. 4.1. A 3 MW wind-turbine unit cost about $6 million and weighs about 275 t. If placed in a linear row perpendicular to the wind direction, 3-MW wind-turbines can be positioned about 450 ft (150 m) apart. For a wind-farm with a hundred turbines dispersed over a large windy desert or sea, an estimated 40 acres per turbine is needed to prevent excessive wind losses from interfering windmills.



Brief 12 Wind turbine farm

The economics of large solar stations and wind farms is plagued foremost by the intermittency of available source energy, but also by maintenance requirements, location restrictions, large-area problems, and opposition by naturalists. Whereas uranium- and coal-burning power plants can deliver so-called “base-load” energy continuously 24/7, solar and wind power must resort to energy storage systems to hoard energy for nighttime and wind-still periods if they are to be the exclusive providers of electricity. These systems can be in the form of electric storage batteries, high-charge-holding super-capacitors, hydrogen fuel produced by electrolysis of water, elevation of water to a high-lying pond whose energy is retrievable by water flow through a hydro-turbine, etc. Today (2008), on sunny and windy days, available power from “renewable” solar and wind sources are added to the electric grid on top of (adjustable) base-load power to fill in high-demand periods. But during nights and no-wind conditions, base-load power is the only provider of electricity. So far the renewables constitute only on the order of 1% of electric grid energy, but in some states like California, anxious lawmakers (without consulting hands-on energy engineers) are mandating that utilities increase this to 10–20% in the next 2 decades. It is doubtful that this high percentage can actually be achieved without wasting an enormous amount of capital that could be spent much more wisely on building nuclear power plants that provide pollution-free controllable base-load electricity 24/7.

Assuming that all the problems with renewables can be solved, it is estimated that wind-power if used exclusively, would require an investment of $51 trillion to deliver the needed 9.1 billion kW to the world. This would replace all petro-fuels and coal with wind-generated synfuels and electric power for plug-in and hybrid vehicles (Chapter 5). It requires 1,000,000 advanced 2 MW(e) wind turbines together with power distribution systems and modern electric storage systems when winds are not blowing hard enough (75% of the time). In contrast, to supply this global electricity need with nuclear heat or power from 1000 MWe reactors requires 9,100 nuclear reactors world-wide. Real estate for 9,100 reactors comes to 364,000 acres, assuming each 1,000 MW reactor takes 40 acres for buildings and cooling towers. They can be built anywhere away from earthquake faults. At $2.5 billion each, the 9,100 reactors would need $23 trillion of capital. It is not difficult to guess what utilities and capital investors prefer when choosing between $91 trillion for solar, $51 trillion for wind, and $23 trillion for the nuclear option. These cost figures are based on 2005 dollars which must be scaled by inflation factors for later years.

4.4 Geothermal, Hydro, and Ocean-Wave Power

In the 1980s, geothermal steam ran a power plant near some geysers in Cobb, Northern California. But steam pressure was gradually lost and the plant was shut down after 6 years. Such reservoirs of steam are evidently unpredictable and exhaustible like oil. Better geothermal schemes are being explored in France, Japan, and Australia. In the Cooper Basin of Queensland, Australia, anomalously hot underground fractured rock formations in the earth crust with a volume of about 1,000 km^3 have been found at a depth of 3–4 km. Water under pressure (~600 atm) is piped into these dry heat pockets or “hot-beds” and pressurized hot water at

T ~ 250°C is extracted and returned to the earth surface. This heat is exchanged in a second loop with a low-boiling-point fluid that vaporizes and drives a set of turbines to generate electric power (Ref. V-3). Water is continuously re-supplied to the underground hot-bed at the same rate at which it is removed. The scheme is similar to a nuclear Pressurized Water Reactor (Chapter 6) in which fissioning uranium heats circulating water pressurized at ~150 atm to ~280°C, whose heat is transferred to a secondary low-pressure water loop that produces steam for generating electricity. The dry Australian underground hot-beds are estimated to hold sufficient quantities of extractable heat (~160 million GJ/km^3) to run thirty 1,000 MW(e) electric power plants for 30 years. Eventually they will be exhausted however, so we listed geothermal hot-bed energy as item (1c) under non-renewable primary energy sources in Section 3.4.

One might think that heat from the earth's interior core and mantle could replenish the heat removed from underground hot-beds, but thermal conduction through solid rock is very slow. Without thermal insulation by rocks, most of the earth's interior heat would leak out much faster and cause much colder earth surface temperatures. Some 80% of heat escaping from the earth surface is generated by radioactivity in the mantle and crust. The other 20% is due to re-emitted solar heating which is balanced by incoming sunshine. Occasional volcanic eruptions are the only outlets of heat from the earth's mantle. The earth's crust goes down to 400 km below the earth surface while the mantle starts at 400 km down, reaching the earth's core at a depth of about 2,800 km (earth mean radius ≈ 6,370 km). Pressures in the crust increase to 200 atm per descending km and in the mantle temperatures and pressures are sufficient to keep rocks in a molten state. Clearly drilling into the mantle to extract heat is impossible as all drill bits would melt and holes would plug up.

Heat pockets in the earth crust at 2–8 km depth are a different story and have an interesting genesis. They are puddles of silicate melts which during earth's creation gelled within the earth crust at depths of 3–10 km from the surface. After the earth cooled, these silicate puddles became fractured rock but remained hot due to highly insulating rock cover (Ref. V-3). Some stayed dry but others filled later with water due to earth movements which under pressure feed natural hot springs and geysers on the earth surface through fissures. Some geologists have expressed concerns that deep drilling (more than 3 km) into hot rock deposits and the fracturing of rocks might set off earthquakes. In the geo-thermally active Geysers region of California where such drillings have taken place, it is reported that small drilling-induced earth tremors have indeed been observed.

Hydro-power is derived from the kinetic energy stored in bodies of water (lakes and rivers) that move due to earth gravity forces. It is used in hydro-electric plants where the flow of river water or a water-fall is passed through hydro-electric turbines that generate electric power. There is no direct application of hydro-power to provide portable propulsion for land vehicles, except for river-craft that move downstream with the river flow. Today most rivers with suitable conditions to generate hydro-electric power have been dammed, and new river sources are essentially exhausted. It is estimated that nature's water reservoirs store about 1,000 GWe of energy worldwide (Ref. V-1), of which perhaps 10% can be exploited for electric power generation and of which more than half has already been tapped.

Tidal ocean-wave energy has been examined for more than a century for generating power. While perhaps useful for special small-quantity applications, like wind-power, it is not always dependable. It is only marginally worthwhile to exploit even with recently proposed use of buoys outfitted with electricity-generating dynamos driven by bobbing pistons. While there is a lot of energy contained in the oceans, the main problem is again its distribution and dilution. For high-power applications it requires more energy for man to collect and concentrate than it yields.

4.5 Economic Comparisons

From the discussions above, it would appear that wind and solar might be able to replace present oil and coal consumption and provide us with equivalent amounts of electric energy if the energy that is collected over enormous land or sea areas can be gathered and distributed economically. However in addition to new long-distance power lines to connect to the grid, adequate temporary energy storage must also be provided during periods when there is no wind or sunshine. As calculated above and in Section 2.4, for the USA alone it would take an investment (in 2005 dollars) of $35 trillion for purely solar, $20 trillion for purely wind, or $9 trillion for purely nuclear power to replace 3.5 TW of energy generation when there is no more oil or natgas to burn and coal-burning is outlawed. Besides the capital-cost disincentives, the enormous land areas needed for solar and wind energy farms will cause enormous public resistance since they disturb local ecosystems and spoil many scenic landscapes, which would make such renewable energy collection installations very unpopular with naturalists.

Aside from capital costs, one must also consider maintenance and disposal costs. Solar cells require constant cleaning to remove dust or bird droppings, and must be replaced every 10–20 years due to erosion and deterioration from rain, hail, and sand storms. They are manufactured using silanes, arsenic, cadmium telluride, and/or copper-indium-diselenide. The toxic wastes generated in producing such solar cells for massive global use, dwarf the amount of nuclear fuel and waste for the nuclear option. For fickle wind-power generation, the maintenance of thousands of storm-damageable turbines, energy storage systems, and protective measures to avoid killing birds, seriously affects its economics. Once again, the secret why controlled nuclear power is much more economic is that it is a million times more concentrated than any non-nuclear scheme.

Chapter 5
Portable Energy and Propulsion Technologies

To provide locomotion for transport vehicles involves the availability of two inter-dependent components: (1) A portable fuel (stored chemical energy) or a portable energy source in the form of a battery (stored electrical or flywheel energy); and (2) an engine or motor that consumes stored portable energy and converts it into mechanical motion. Various portable fuels and energy storage devices have been developed in the last century, the champion fuel being petrol because of its low cost and availability, and the champion battery being the lead-acid device because of its ruggedness and recharge ability. Engines can be divided into three categories: (I) internal combustion engines (ICEs) fed by portable chemical fuels that can react with oxygen in the air, (II) motors driven by the electricity from chemical or mechanical storage batteries, and (III) fuel-cell engines (FCEs) fed by chemical fuels that react with atmospheric oxygen. ICEs in category (I) can convert the heat of fuel combustion into mechanical motion via piston action with an efficiency of 30–40%, while motors in category (II) can convert electricity from a storage battery via induction into mechanical motion of the wheels of an automobile via a gear-train with an efficiency of 85–95%. FCEs in category (III) utilize an electrochemical reaction between atmospheric oxygen and a fuel that takes place on special electrodes with an efficiency between 45% and 85%. The generated electricity then drives a motor as in (II). The quoted efficiencies are ratios of delivered energy of mechanical motion divided by energy extracted from a fuel or battery. Although FCEs are more efficient than ICEs, because of problems discussed below, the ICE has so far won out in the automotive field. It is presently the most developed device for propelling cars. Motors driven by batteries alone have also lost out against ICEs because of driving range limitations discussed below. In what follows, we first review portable fuels and energy holding batteries, and then discuss ICEs and FCEs.

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_5, © Springer Science+Business Media B.V. 2010

5.1 Review of Portable Fuels and Other Energy Carriers

Portable fuels and portable batteries can be grouped as follows:

(a) Natural non-renewable fuels:
  Oil (liquid hydrocarbons – C_mH_n)
  Compressed natgas (methane, ethane, propane, butane: CH_4, C_2H_6, C_3H_8, C_4H_{10})
  Coal (C)
(b) Manufactured energy carriers (synfuels and batteries):
  Hydrogen (H_2), from water (H_2O) + electricity or heat
  Ammonia (NH_3) and hydrazine (N_2H_4), from water (H_2O) + air (80% N_2) + electricity or heat
  Syn-petrols and methane ($C_mH_n(O_k)$, CH_4), from water (H_2O) + coal (C) + electricity or heat
  Methanol (CH_3OH), ethanol (C_2H_5OH), from biomass (e.g. corn) + sunshine + electricity
  Rechargeable electric storage batteries; rechargeable mechanical flywheel batteries; rechargeable super capacitors

As long as large quantities of energy can not be transmitted wirelessly (Tesla's dream), there will always be a need for portable energy sources. At present, portable fuels used in land or sea transportation and in aircraft propulsion come mostly from the non-renewable resources listed under (a), that is: Oil (petrol or diesel), Natural Gas (liquefied or compressed), and Coal. When these non-renewable resources are depleted, artificially manufactured energy sources must be developed which can be carried on-board vehicles to fuel engines or energize motors that propel the vehicles. Such portable energy can come in the form of a portable (synthetic) fuel that can be refilled periodically into an on-board fuel tank, or as an energy storage battery which is periodically recharged. In what follows we briefly examine past and present activities to develop portable synthetic fuels and rechargeable energy storage devices.

5.1.1 Portable Synfuels

The only practical solution to the out-of-oil problem is to manufacture portable fuels in which power-plant heat or electricity is converted (with some loss) and stored as chemical energy in an oxidizable compound. Such portable synfuels are most economic if they can react chemically with atmospheric oxygen (O_2) to produce heat or electricity and thence propulsion. Preferably they are synthesized from water (H_2O) and air (80% N_2; 20% O_2), both of which are abundantly available on earth. Hydrogen (H_2) synfuel would be advantageous since it can be made from water and returned into water when consumed, without polluting the atmosphere. It can be burnt in internal combustion engines (ICE) producing heat and propulsion, or consumed by a fuel-cell engine (FCE) to propel a car. A problem with gaseous H_2 is its high storage volume, the main reason why it is not widely used as a clean fuel for ICEs to replace "dirty" petrol.

Compact electrochemical fuel-cells have been developed that consume tank-supplied hydrogen (H_2) and air-supplied oxygen (O_2), which can make sufficient DC electricity at near-ambient temperatures to power a car (see Section 5.2.2). Electric motors to turn wheels with this electricity are well-developed today and hybrid fuel-cell-driven automobiles may be coming on the market after some basic problems are solved. Fuel-cell engines running on pure hydrogen, exhaust only water (H_2O). No nitric oxides (NO_x) nor carbon dioxide (CO_2) are emitted because they operate at lower temperatures than those of combustion engines. Thus fuel-cells are ideal car engines that do not pollute the environment. Interests of environmentalists and future-world planners have coincided here to promote this power source for (future) autos and trucks. As discussed in the next chapter, there are still problems to be solved for fuel-cells. One major problem is the fact that hydrogen gas is difficult to store compactly. Nevertheless hydrogen (H_2) is a potential universal synfuel, producible from water by electricity or heat (provided by nuclear, coal, or other prime energy source), since it can empower ICEs and FCEs without CO_2 air-pollution.

Besides hydrogen (H_2), other potential portable synthetic fuels which can be made from atmospheric nitrogen (N_2) and water (H_2O) as feeds, are hydrazine (N_2H_4) or ammonia (NH_3). Hydrazine is a liquid, and ammonia is liquid when compressed at a very modest pressure of 12 atm. Both have chemical energy stored in them comparable to petrol, and both produce heat in a combustion engine or can generate electricity via a fuel-cell when reacted with oxygen (O_2) from the air. Hydrazine is presently used as a rocket fuel, while liquefied ammonia is used as a fertilizer in agriculture. An experimental ammonia-burning ICE was successfully tested some time ago in The Netherlands at Delft University. More recently HEC (Hydrogen Engine Center), founded by entrepreneur Ted Hollinger in Iowa, is manufacturing and selling ammonia-fueled ICEs for tractors and farm equipment. If it is found difficult in the future to fly airplanes with pure hydrogen as fuel, a possible alternative might be to use hydrazine or ammonia as a fuel, if this can be done without significant air pollution. Should byproduct NO_x gases be present due to high-temperature combustion of hydrazine or ammonia, their conversion to O_2 and N_2 by catalytic devices used in many of today's automobiles must be considered. In colder fuel-cells, NO_x exhausts from hydrazine and ammonia fuels are virtually absent. That is FCEs yield essentially pure N_2 and H_2O as exhausts. The advantage of ammonia and hydrazine is that these synfuels are much easier to store than hydrogen. Ammonia is as stable as natgas, but hydrazine decomposes when slightly heated. The latter may be stabilized when hydrated and/or loosely bonded to a complex. Though pure hydrogen is preferred for running fuel-cells, ammonia and hydrazine can be catalytically decomposed to hydrogen and nitrogen on FCE electrodes by alloys of platinum, ruthenium, osmium, and iridium. Because of easier tank storage of ammonia, it may be preferred over hydrogen for automobile FCEs, even though the required catalytic decomposition of ammonia on FCE membranes is a complication that consumes extra energy. New high-temperature solid oxide fuel cells (SOFs) can use ammonia directly however (Refs. III-8 through III-11).

It was reported recently that nitrogen (N_2) can be compressed into a solid of pure trivalent N, storing lots of chemical energy. In an ICE device its decomposition could be detonated by an electric spark. The exhaust would be harmless N_2 already present in our atmosphere at 80%. Synthesizing this nitrogen compound requires 1,725°C and 10^6 atm of pressure however so it is doubtful it will ever be used as a portable synfuel.

Synthetic portable liquid hydrocarbons can be made from coal (C), water (H_2O), and electricity by the Fischer–Tropsch process, yielding man-made petrol-like compounds (C_mH_n and $C_mH_nO_k$). This was, and still is done in South-Africa at its SASOL plant which was built during WW-II by the US Kellogg company. Because of war-related blockades and perils of ocean-crossing petroleum transports, South-Africa ran short of petrol in WW-II, so synthetic SASOL petrol became economically attractive. Coal-derived SASOL synfuels, if massively consumed in combustion engines, do produce globe-warming carbon dioxide (CO_2) gas however. They are not carbon-neutral like bio-alcohols. In a future pollution-intolerant society the use of SASOL-produced petro-chemicals might therefore be restricted to non-automobile applications such as plastics manufacture. However during the interim period between the end of the petroleum era and the start of a uranium millennium, it may be necessary to make synthetic petroleum fuels by SASOL techniques to keep our long-haul transport fleets rolling, moving, and flying.

Extracting liquid alcohol (C_2H_5OH) and methanol (CH_3OH) from cultivated corn or other suitable plants or algae is another scheme to make hydrocarbon synfuels. Growing corn requires sunshine and electric power for fertilizer production and farm operations. Thus the combined prime energies of power-grid electricity and sunshine are converted into portable fuel. Since the same amount of CO_2 gas is returned to the biosphere in combustion as was taken in by plants or algae during photosynthesis, there is no net globe-warming biosphere pollution (unlike SASOL). Such biofuels are thus legitimate carbon-neutral synfuels even though they emit carbon-dioxide and require one-third of all lands to grow enough for the total replacement of petro-fuels.

As discussed in Section 4.1, unless (nuclear) electricity is available for agriculture operations and processing, there are insurmountable problems if one considers replacing petrol *only* with bio-alcohol in an out-of-oil economy. Energy budgets for farming, fermenting, distilling, manufacture of farm equipment, etc., show that the input energy to obtain alcohol from corn or sugarcane may exceed the energy present in the final alcohol product. Farming improvements might lower the input/output energy ratio to 80–90%, but it means that in a no-oil, no-nuclear, no-coal economy, 80–90% of agriculturally grown alcohol must be put back into its own operations. Then to power the world's transportation fleets, one would need four times all available land in the world for growing corn, which is of course impossible.

Hydrogen synfuel can be made by electrolysis of water using available grid electricity:

$$H_2O + \text{electricity} \rightarrow H_2 + \frac{1}{2}\,O_2, \qquad (5.1)$$

This scheme is reported to produce 7 ft^3 (15.36 g) of very pure H_2 at 2.25 V DC with an input of 1 kWh(e). Iron plates are used for the H_2 electrodes and nickel-plated steel for the oxygen electrodes (Ref. II-1). Assuming our standard energy equivalence (Brief 4) that 10 kg of H_2 can produce 0.72 GJe of electro-mechanical fuel-cell output energy, one finds that 1 kWh(e) = 0.0036 GJe of electric grid energy can be converted into portable H_2 for fuel-cell electricity generation with an efficiency of $[15.36 \times (0.72 \text{ GJe}/10^4)]/[3.6 \times 10^{-3} \text{ GJe}] = 0.307 = 30.7\%$. Assuming that grid electricity was generated from heat by a steam turbine at 33% efficiency, the overall conversion efficiency of making hydrogen fuel from latent uranium (or coal) energy is then 10%.

Instead of electrolysis, hydrogen can also be produced using fission heat directly in a "chemo-nuclear" reactor. This skips conversion of nuclear heat to electricity by a steam turbine. For example at 850°C sulfuric acid (H_2SO_4) breaks apart, and with iodine (I_2) it can generate H_2 as follows (Ref. II-10):

$$H_2SO_4 + \text{heat (850 °C)} \rightarrow O_2 + SO_2 + H_2O \tag{5.2a}$$

$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \tag{5.2b}$$

$$2HI + \text{heat (450°C)} \rightarrow I_2 + H_2 \tag{5.2c}$$

or overall:

$$H_2O + \text{heat} + \text{Catalysts} \rightarrow ½O_2 + H_2 \tag{5.2d}$$

This "sulfur-iodine" catalyzed scheme using nuclear reactor heat is under investigation, and may be compared with the older "steam-reforming" method of making H_2 (now undesirable because CO_2 is made):

$$2H_2O + C + \text{heat} \rightarrow 2H_2O(\text{steam}) + C \rightarrow CO_2 + 2H_2 \ (T \sim 975°C) \tag{5.3}$$

The efficiency of producing H_2 by (5.2) or (5.3) using (nuclear) heat has been estimated to be about 60%, meaning 1 GJ of (nuclear) heat can be converted to 0.6 GJ of H_2-carried chemical energy.

Before selecting H_2 production by either one of reactions (5.1), (5.2), or (5.3), it is prudent to consider the entire picture of a future "hydrogen economy". Some questions are: is it most economic to make hydrogen in large quantities at several large conversion plants and to distribute it through pipelines like today's natural gas for delivery to fueling stations; or is transport in the form of compressed or adsorbed hydrogen by tanker trucks better, as is done today with petrol? Or is it more efficient and practical to employ existing electric grid lines that already distribute power widely, to generate hydrogen by electrolyzing tap-water at city fuel stations equipped with electrolyzers. For fuel-cell usage, H_2 must be quite pure (Section 5.2.2). If contaminated by mercaptans for example, it must be passed through special scrubbers to remove them. Rather than piping H_2 to commercial fuel stations, hydrogen could also be distributed directly to homes using pipe-lines similar to natgas distributions. Then customers can directly fill their H_2 fuel tanks at home. The hydrogen might be adsorbed in an automobile fuel "bladder" (fuel tank of the future?). With a little heat, the bladder releases H_2 again to run the auto's fuel-cell. Alternatively, electrolysis of tap water (generating H_2), might be carried out in people's garages at night with grid electricity. Because "slippery" hydrogen effuses through many materials, and embrittles or attacks a number of metals, current natgas pipelines are unsuitable for distributing hydrogen. Thus new (larger) pipelines would have to be installed for the distribution of hydrogen. Another concern with home-provided or home-generated H_2 fuel would be safety, similar (but more stringent) to present-day home delivery of natgas.

Without considering energy expenditures for hydrogen gas distribution, the 60% efficiency of producing hydrogen by (5.2) or (5.3) using nuclear heat means that 1 GJ of latent uranium energy is converted into 0.6 GJ of hydrogen-held chemical energy. This in turn is converted to 0.33 GJ(e) of electro-mechanical energy in a H_2 fuel-cell at 55% efficiency. Since 1 GJ of nuclear heat can also be converted to 0.33 GJ(e) of electricity with steam turbines, portable H_2 produced via (5.2) or (5.3) followed by fuel-cell consumption gives the same overall conversion efficiency of 33%. It puts nuclear fission energy "under the hood of an automobile". In contrast, we found overall energy conversion (5.1) by electrolysis to be only 10% efficient. However additional costs for distributing H_2 from large chemo-nuclear reactor plants by new pipelines or tank-trucks must be added and compared with electric-grid electrolysis of H_2O in individual H_2-fueling stations to determine total H_2 fuel costs. As mentioned, the advantage of the latter scheme is that wide-spread distribution of electricity by power grids is already in place.

Because of the distribution and storage problems of gaseous hydrogen, after production with (nuclear) electricity as discussed above and before use as a portable fuel in a vehicle, one finds that to remain practical one must either liquefy it or compress it with nitrogen (air) to form liquid ammonia ("second" hydrogen). The latter is made by the Haber–Bosch process (Ref. II-11):

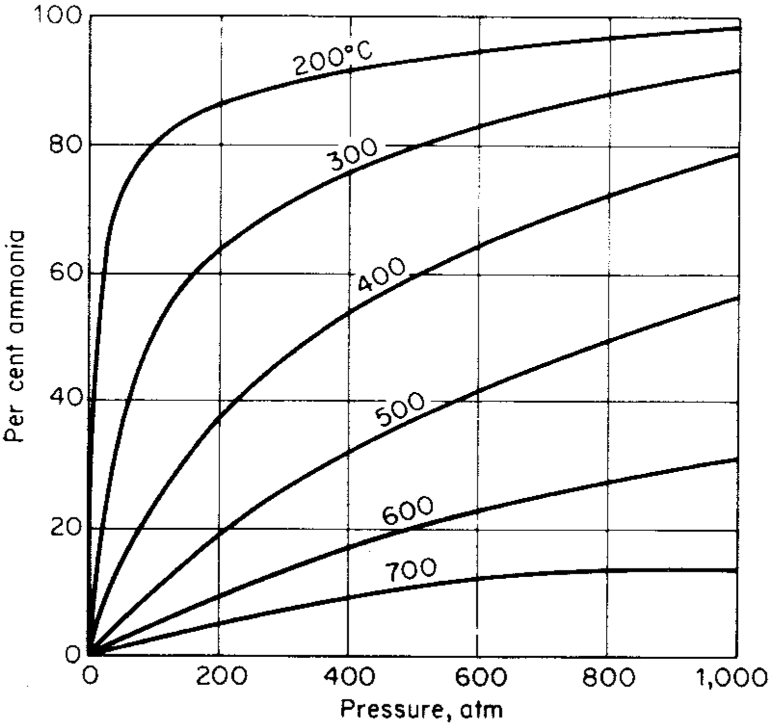
$$3H_2 + N_2 \rightleftarrows 2NH_3 \text{ (+ Fe catalyst)} \tag{5.4}$$

As shown in Brief 13, formation of ammonia (NH_3) in this reversible reaction is favored by high pressures at moderate temperatures. At 272 K (−0.5°C), ammonia is a liquid and at room temperature (300 K) it can be stored at a pressure of about 12 atm (Brief 14). This is much easier to handle than compressed H_2 gas at a pressure of 600 atm or liquid H_2 at 20 K for storage in an automobile fuel tank of acceptable dimensions for a 600 km driving range. Liquefying hydrogen to T = 20 K requires approximately 77,567 kJ/kg = 155 kJ/mole of H_2, while compressing it into liquid ammonia via the Haber–Bosch process costs about 4,475 kJ/kg = 80.5 kJ/mole of NH_3 in compressor energy.[1] Since one mole of NH_3 has 1.5 times more H atoms than one mole of H_2, comparable energies of compression are 76 kJ for liquefaction and 27 kJ for

---

[1] In chemistry a mole is defined as a quantity of 6.022×10^{23} molecules or atoms (Avogadro's number). This quantity weighs M grams, equal to the atomic weight M of the molecule or atom. Thus 1 mole of CO_2 molecules = 6.0247×10^{23} CO_2 molecules weighs 44 g (M = 44); 1 mole of U-235 atoms = 6.0247×10^{23} U-235 atoms weighs 235 g with M = 235.

ammonia synthesis per mole of H atoms. These values compare with ~700,000 kJ/kgH_2 or ~350 kJ/moleH_2 to manufacture hydrogen by electrolysis (Section 5.1.1). Clearly ammonia is less expensive as a portable hydrogen carrier than liquid hydrogen.



$$3\,H_2 + N_2 \rightarrow 2\,NH_3$$

(Hydrogen + Nitrogen → Ammonia)

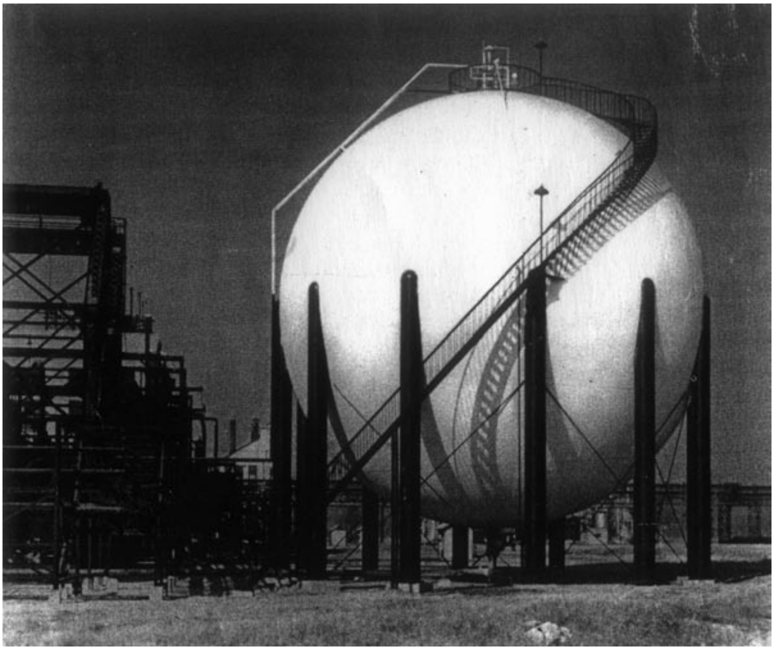
Brief 13 Ammonia synthesis yields using the Haber–Bosch process

Instead of "chemo-packing" hydrogen with nitrogen from air to make it more portable, one might consider reacting it with CO_2 from the air to form propane (C_3H_8), butane (C_4H_{10}), or methane (CH_4), by driving the following reversible gaseous reactions to the right (Ref. II-11):

$$10\,H_2 + 3\,CO_2 \rightarrow C_3H_8 + 6H_2O \text{ (+ Fe or other catalyst)} \quad (5.5)$$

or

$$2\,H_2 + CO_2 \rightarrow CH_4 + O_2 \text{ (+ Fe or other catalyst)} \quad (5.6)$$



Brief 14 Typical ammonia storage tank

Of these, reaction (5.5) is easier (exothermic) to carry out under pressure than (5.6) which requires some input energy (endothermic). Reaction (5.5) for propane and a similar one for butane produce portable alkanes known as LPG (Liquid Petroleum Gas) which at atmospheric pressure are liquid below 231.1 K (–42.1°C) and 273 K (–0.6°C) respectively. Like ammonia they can be kept liquid at room temperature (300 K) under a modest over-pressure between 5 and 10 atm. Methane on the other hand must be compressed to ~67 atm at room temperature or be liquefied at 111 K to be usable for automotive transport. Note that only 30% of the incoming hydrogen (H_2) in (5.5) is converted into propane. Reactions (5.5) and (5.6) are carbon neutral and product fuels are "green" since combustion of these fuels puts the same amount of CO_2 back into the atmosphere as was taken in during their manufacture.

While reaction (5.5) for synthesizing higher alkanes from hydrogen and atmospheric carbon dioxide might be technically feasible, compared to ammonia synthesis (5.4) the problem is that the concentration of carbon dioxide (CO_2) in the air is only 0.03% compared to 78% for nitrogen (N_2). This means one has to compress a lot of air to extract enough CO_2 before introducing it into the reaction vessel for reaction (5.5). It amounts to moving 2,600 times more air (requiring compression energy) than for extracting nitrogen from air to carry out reaction (5.4). Assuming the US has 100 nuclear power plants making petrol-replacing ammonia synfuel in 2050, a very coarse calculation shows that each plant would need to process about 3×10^6 L/s of air. At a pump-energy cost of 100 J/L this requires 300 MW (= 100 MWe) of air-processing power for each plant. If instead of ammonia, one would extract CO_2 from the air to make propane via (5.5), one would need 2,600 × 3 × 100 MWe = 780,000 MWe for air collection at each plant. This is impossible if each plant only generates between 1,000 and 3,000 MWe. Except from air, any other source of CO_2 would not be carbon neutral. Taking CO_2 (or C) from vegetation for (5.5) is not as efficient as extracting bio-alcohol from them. Which portable synfuel is most practical to mass-produce when oil is gone will depend not only on production costs of course, but also on engine performance, ease of synfuel distribution, and safety when used for public transportation vehicles. Note that distribution systems for both ammonia and propane are already in place: liquid anhydrous ammonia is widely used in agriculture, while liquid propane (and butane) is distributed globally as LPG (Liquefied Petroleum Gas). While propane manufacture from coal via the Fischer–Tropsch process may be viable and necessary for an interim period until enough prime nuclear power is installed, because of the paucity of atmospheric CO_2, it seems that only ammonia synfuel made via (5.4) is practical for the long term to replace petroleum fuels.

The list of feasible near- and far-future synthetic fuels or "synfuels" made with inputs of (nuclear) heat or electricity, water, air, and coal may be summarized as follows:

Hydrogen (H_2).
Ammonia (NH_3) and hydrazine (N_2H_4).
Syn-alkanes (C_mH_n), methane (CH_4), propane (C_3H_8), butane (C_4H_{10}).
Bioorganic Ethanol (C_2H_5OH), methanol (CH_3OH), biodiesel ($C_mH_nO_k$).
Syn-petrols ($C_mH_nO_k$), acetylene (C_2H_4), etc.

Brief 15 shows key combustion properties and fuel tank storage features (volume) of these synfuels some of which may be used in future public transportation.

From the analysis given earlier, for each GJ of heat expended in synfuel manufacture, between 0.1 and 0.6 GJ can be stored as portable chemical energy for the generation of electro-mechanical motion by an ICE or FCE. When consumed, hydrogen, ammonia, hydrazine, and bio-alcohols discussed above return the same chemical species used in their manufacture back to the biosphere. Their reaction chemistries in ICEs or FCEs reverse the synthesis steps and thus are "green". Only the coal-derived syn-petrols would add new globe-warming CO_2 to the atmosphere. The limitations on carbon-bearing biofuels is the enormous acreage needed for their cultivation, while making green butane and propane synfuels using atmospheric carbon dioxide is impractical because of the prohibitively low CO_2 concentration in the biosphere. This makes ammonia (and less so hydrogen) the most attractive synfuel for long-term replacement of petroleum fuels.

To satisfy world demand for making portable synfuels when oil is gone and to avoid global warming, one finds that only heat or electricity from uranium fission plants can economically produce the large quantities needed for extended periods (Chapter 3). Nuclear fission of uranium and thorium is able to support all synfuel production for more than 3,000 years for the entire world. Proposed "renewable" solar and wind energy sources can not provide sufficient capacity at a reasonable and affordable cost. Geothermal steam may be added to the world's supply of electric energy for a while. But it is only available at a few locations on earth in limited quantity, facing exhaustion after a few decades. Nuclear power plants on the other hand can be constructed anywhere and can provide heat energy for millennia at a 1,000

Brief 15. Fuel combustion properties and storage features.

Fuel	Heat of combustion (kJ/kg)	Vapor ignition temperature in air at 1 atm	Flammability range in air (mole %)	Density @ 25°C, 1 atm (kg/m^3)	Fuel tank with 2.2 GJ = 0.72 GJ(m) of Latent energy	
					Amount (kg)/(lb)	Volume (L)/(gal)
Gasoline (ℓ) (C_mH_n)	48,187	~500°C	1–8%	737.38	46/101	62.5/16.5
Alcohol (ℓ) (C_2H_5OH)	27,000	~600°C	3–19%	795.24	82/181	107/28.3
Ammonia(ℓ) (NH_3)	22,550	651°C	15–28%	682.8 (12 atm)	98/216	143/37.9
Propane(ℓ) (C_3H_8)	45,976	468°C	2.2–9.5%	500.5 (8.5 atm)	97/210	194/51.2
Butane(ℓ) (C_4H_{10})	45,339	430°C	1.8–8.4%	578.8 (3 atm)	49/107	85/23
Hydrogen(ℓ) (H_2)	125,000	580°C	4–77%	67.5	18/40	262/69
Methane (g) (CH_4)	50,144	537°C	5–15.4%	0.7174(g)	42/93	58,543(g) /15,466(g)
Hydrogen(g) (H_2)	125,000	580°C	4–77%	0.0899(g)	18 / 40	200,216(g) /52,893(g)

1. An average (2005) passenger car carrying 2.2 GJ of portable fuel in its tank can move approximately 600 km (= 373 miles).
2. Volumes in the last column are at 25°C and 1 atm except for liquid ammonia, propane, and butane which are compressed; 1 US gal = 3.785 L; 1 m^3 = 264.17 US gal; 1 kg = 2.2 lb; (ℓ) = liquid, (g) = gaseous.

times higher concentrations. In conclusion, most portable synfuels of the future will more than likely be synthesized by nuclear electricity or heat with air and water as feed. Some bio-alcohols may also be in the synfuel mix, while plastics and other hydrocarbon-based materials will be derived from coal using nuclear electricity.

Note finally that for a chemical rocket going into space where air is absent, it is necessary to provide two chemical reactants to produce heat and thrust. That is, both an oxidizer such as liquid oxygen or peroxide and a fuel like liquid hydrogen or hydrazine must be carried by a chemical rocket to propel it. On the other hand fission-heated nuclear rockets only need hydrogen. Auxiliary power systems on space vehicles likewise can not depend on atmospheric oxygen. Unless there is adequate exposure to the sun to energize some solar cells, nuclear decay heat is provided by a reactor-produced radioisotope like californium-252 (Cf-252).

5.1.2 Electric Storage Batteries

While electric-grid energy can not be conveniently carried along by a vehicle unless electricity-carrying guide-wires or rails contact it continuously as is done for trains, trams, and city buses equipped with contact blades, it is possible to deposit electric energy in portable storage batteries to power automobiles. Unfortunately energy/

weight ratios of the lightest known storage batteries are rather low, making it impractical for them to compete with present automobile combustion engines that are fueled with petrol. Only for special situations like wheelchairs, golf-carts, and short-distance (urban) vehicle transportation with 100 km (60 miles) ranges, are electric storage batteries useful.

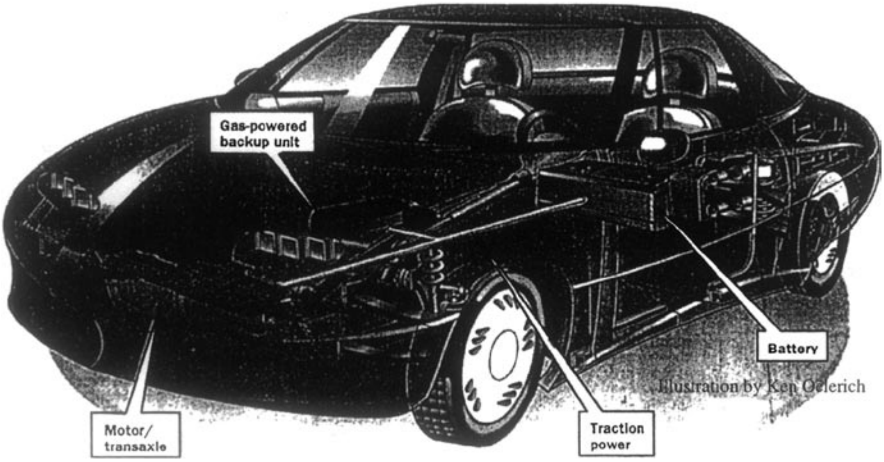
In 1995 the State of California demanded that the automobile industry produce some electric cars by 1998 to combat air pollution. So a number of electric cars powered by stacks of batteries were built. Batteries can store electric energy from the electric power grid and if they are rechargeable, they can serve as clean non-polluting portable energy carriers. The results over the past decade have not been promising however. The best purely electric models developed by GM, Chrysler, Nissan, and other car makers (Ford produced a hybrid later – see below) carry 200–500 kg of battery weight, and typically have a maximum range of 100 km (60 miles), while requiring 3–6 h of battery recharging time. Rechargeability features of existing (lead acid) batteries and their power and energy capacity per unit weight have been improved somewhat, but driving ranges for these electric cars are still far below those of modern petrol-fueled automobiles. Typically electric cars are operated at 300–330 V, with outputs of 250 W/kg fully charged dropping to 100 W/kg at 80% discharged, and capacities of 32 Wh(e)/kg for standard lead-acid units. For newer lighter glass-fiber reinforced lead-acid batteries, these numbers were improved to 500 W/kg (full) → 240 W/kg (80%) and 42 Wh(e)/kg. Later models using nickel metal hydride (NiMH) and zinc-bromine-based batteries claim 75 Wh(e)/kg and possible ranges of 250 km (156 miles), while new lithium polymer and lithium-manganese dioxide systems ($LiMnO_2$, $LiMn_2O_4$) have yields of 200 Wh(e)/kg and a potential 350 km (219 miles) range. The very latest (2009) lithium-manganese high-capacity battery developed at the Argonne National Lab now claims about 660 Wh(e)/kg or 2.4 MJ/kg at 4.3 V (average 3.7 V). Using our standard 0.7 GJ(e) = 200,000 Wh(e) to move a car 600 km (373 miles), the latest of these batteries with 660 Wh(e)/kg, would require 303 kg (667 lb) of minimum weight for such a range or about 450 kg (1,000 lb) packaged. This is equivalent to the weight of six human passengers! With possible maximum technically achievable improvements of future engine efficiencies such that only 0.5 GJ(e) can move a car 600 km, the needed packed lithium battery weight might be lowered to 320 kg (708 lb) equal to about four human passengers.

The difficulty with storage batteries is that nature has a more or less fixed electron density per unit mass for chemical compounds and the useful available energies from electrochemical interactions are only on the order of 1 eV.[2] Combustion yields 10–100 times more energy per unit weight of fuel than what is retrievable from a compound in an electrochemical reaction, although only one third of combustion heat can be converted into electro-mechanical energy. Typically a tankful of petrol for a medium-sized automobile contains 60 L (16 gal), and weighs 44.5 kg (98 lb) for a driving range of 600 km (373 miles). Substituting this fuel weight with 450 kg (1,000 lb) or even 320 kg (708 lb) of batteries is clearly unattractive as long as there is petrol or an alternative synfuel.

---

[2] The microscopic energy unit of eV (electron-volt) is most commonly used in physics for energy exchanges between single atoms and molecules. 1 eV = 1.6021×10^{-19} J.

While electric storage batteries can not compete with the internal combustion engine (ICE) in power per unit weight, in recently introduced "hybrid" cars, a combination of both has been achieved (see Brief 16). For long-distance driving the ICE runs the car, while in stop-and-go city driving a 100 kg (220 lb) electric storage battery kicks in and moves it. The ICE recharges the battery when it is low. By our estimates a 100 kg latest-model lithium car battery could take a car 187 km or 117 miles without recharging. A hybrid car still produces globe-warming CO_2 of course, but less than a conventional ICE automobile. FCEs also depend on electro-chemistry, but have the advantage that oxidant (O_2) is supplied by air and waste product water (H_2O) is exhausted to air. Their fuels are light and thus they give better driving ranges than electric storage batteries could provide on one charge. Besides lower weights, FCEs also don't require frequent recharging. For this reason development of "electric" cars have been focusing on fuel-cell engines (Section 5.2.2). The details of battery and fuel-cell physics can be found in Refs. III-1 and III-2.



Brief 16 Hybrid electric/ICE powered car

5.1.3 Flywheel Energy Storage (Mechanical Batteries)

Using induction coils, a possible portable energy storage scheme is to convert electric energy into mechanical energy of a high-speed rotating flywheel, and vice versa. This is sometimes referred to as a "mechanical battery" and is used on some city buses, for example in Switzerland. It has also been considered for automobiles. However to store sufficient rotational energy for moving a car 600 km (373 miles) before a recharge, requires more than 1,000 kg of flywheels. This is with assistance of fibers with the highest-known tensile-strength to hold spinning flywheels together.

An electro-dynamic flywheel device or "mechanical battery" is a non-polluting energy storage unit which could be charged up in everyone's garage by electricity from the power grid. In such a direct electricity-to-electricity energy transfer between utility power and a portable non-chemical electric storage device, there is no need for intermediate conversions to chemical or electrochemical storage systems. In the flywheel scheme, counter-rotating pairs of magnetically suspended discs or tori are spinning at 180,000 rpm in evacuated cylinders as shown in Brief 17. They are electromagnetically coupled to induction coils that can extract electric energy or, in reverse, can store electric coil energy as mechanical energy of rotation into the spinning discs. As with electric storage batteries, one finds that engine weight is again a problem maker. The quantity of rotational energy stored in a flywheel is given by:

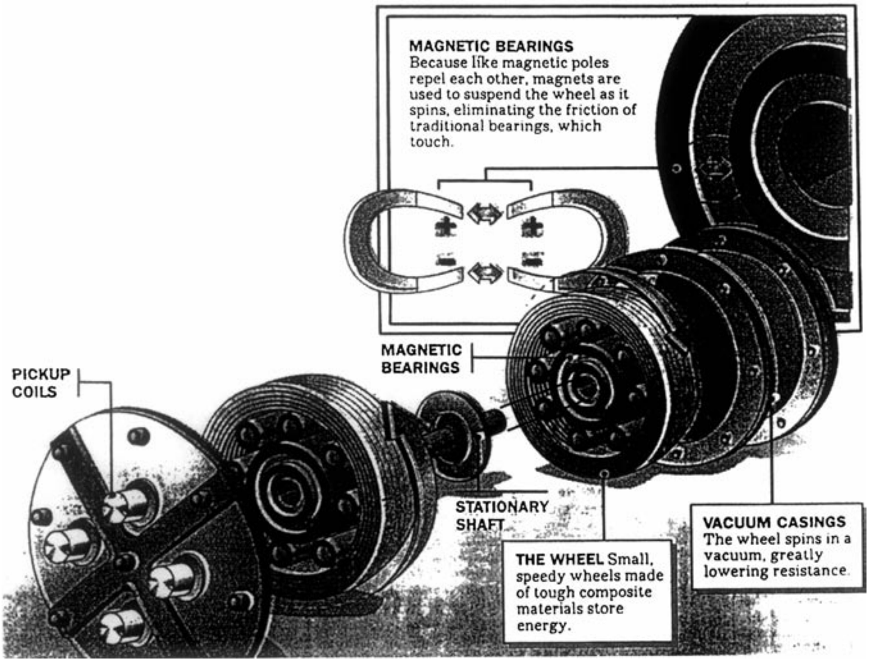
$$E = \frac{1}{2}\langle M\rangle(\Omega R)^2 = \frac{1}{2}\langle M\rangle V_a^2, \text{ Joules(e)} \tag{5.7}$$

Here Ω, V_a, and R are respectively the rotational velocity (rad/s), circumferential velocity (m/s), and outer radius (m), while $\langle M\rangle$ is the effective weighted mass (kg) of the rotating flywheel. For a torus-shaped (doughnut) flywheel with a thin body cross-section whose mass resides mostly at radius R, the mass $\langle M\rangle = M_{torus}$, while for a solid disc flywheel with distributed mass, $\langle M\rangle = ½\ M_{disc}$. From Eq. 5.7 it is clear that the highest tolerable circumferential velocity gives the highest stored flywheel energy. An analysis of centrifugal forces shows that the maximum tolerable value for V_a is:

$$V_m = (V_a)_{max} = (\Omega R)_{max} = (\sigma / \rho)^{½}\,\text{m/s} \tag{5.8}$$

Here σ is the tensile strength (N/m^2) and ρ is the density of the rotating material (kg/m^3). A fiber material which is believed to have the highest tensile strength is spider-silk. It was reported recently that spider-silk fiber molecules can be extracted from goat's milk. With a spider-silk fiber skin confining a heavy material, we estimate the maximum allowed V_m value is $V_m \approx 800$ m/s. If we assume our "standard" 0.72 GJe of energy is to be stored in a flywheel to achieve a 600 km (373 miles) range, one calculates from Eq. 5.7 with $E = 7 \times 10^8$ J(e) and $V_m \approx 800$ m/s, that $\langle M\rangle = M_{torus} = 2{,}180$ kg (4,818 lb)! This mass could be distributed over 48 tori at 46 kg per torus, who are spinning inside 24 evacuated cylindrical chambers, each containing two counter-rotating tori.

Spinning at 180,000 rpm $\approx 10^4$ rad/s and with $V_m = 800$ m/s, one finds from Eq. 5.8 that the discs or tori must have R = 0.08 m = 8 cm or an outer diameter of D = 2R = 16 cm. Such an outer diameter is reasonable for cylinders that must fit under the hood of an automobile. This result is independent of torus or disc mass. A lower rpm will increase the value of D if V_m is fixed. With a torus of 8 cm outer radius and a torus body cross-section of S cm^2, the torus body volume equals $Q_{torus} = 2\pi RS = 50.27\,S$ cm^3. Thus if each torus mass is 46 kg = 46,000 g, the density of the fiber-encapsulated material would have to be $\rho = 46{,}000/Q_{torus} = 915\,S$ g/cm^3. Using depleted uranium with $\rho = 18$ g/cm^3, one finds that S must equal S = 51 cm^2 for each torus. This could be achieved if the uranium torus bodies had a circular cross-section with body diameter $D_b = 8$ cm or a rectangular cross-section with a width of 3 cm and height of 17 cm. Instead of 2,180 kg (4,818 lb), a more reasonable total flywheel mass would be ⟨M⟩ = 400 kg (881 lb), giving a driving range of 107 km or 67 miles. Assuming again 48 tori, each now carrying 8.33 kg of depleted uranium, one finds S = 9.2 cm^2 in this case. This requires a torus body diameter of D_b = 3.42 cm if the cross-section is circular, or 2 × 4.6 cm for a rectangular cross-section. An 8.33 kg torus body is more convenient than a 46 kg torus body, but the driving range is of course only 107 km (67 miles) now.



Brief 17 Flywheel battery components

Development of flywheel-powered automobile engines clearly depends on the availability of high-tensile-strength fiber materials such as spider-silk which can withstand high stresses at high velocities V_m to prevent flywheel disintegration. It is unlikely that the weight problem can be overcome since it is improbable that a super-material exists which can double the highest estimate of V_m = 800 m/s. Satisfactory solutions must also be found to minimize damage produced in auto crashes, in which stored rotational energy is suddenly released and converted into random kinetic energy. Using adjacent counter-rotating discs can partially neutralize such released energies. In addition, energy absorbing or deflecting skirts to minimize damage in case of an accident need to be explored and tested. Fires from a bursting gas/petrol tank in today's auto crashes can of course release as much energy in the form of heat, and are just as destructive.

A Chrysler-sponsored experimental flywheel-powered automobile at the 1994 Los Angeles auto show had a reported twenty cylinders under the hood, each cylinder containing two counter-rotating discs spinning at 200,000 rpm. It was reported to develop 100 kW(e) = 134 hp of mechanical power at start-up and to have a range of some 320 km (200 miles). By the estimates given above, such a range would require about 1,000 kg (2,200 lb) of flywheel mass if $V_m = 800$ m/s. Instead of fully fly-wheel-powered cars, hybrid systems might be explored. Like electric hybrids, an ICE could in principle be used for long-distance driving and flywheels for short trips. But in summary, mechanical flywheel batteries do not offer much improvement over electric storage batteries even with use of the highest tensile-strength materials.

5.2 Vehicle Propulsion Engines

Besides well-developed electric motors empowered by electric or mechanical batteries, the three major prime movers which have been thoroughly investigated over the past 100 years, and which require portable combustible fuels are:

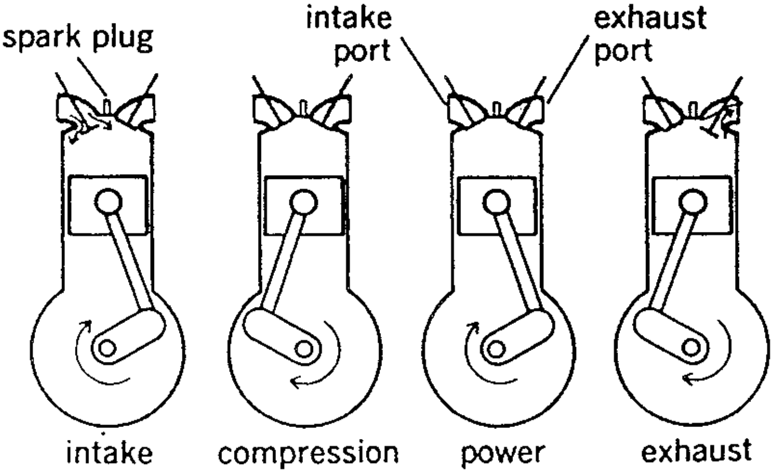
1. Internal combustion engines (ICEs)
2. Fuel cell engines (FCEs)
3. Steam engines

In what follows we shall briefly review these devices and examine their ability to consume future synfuels.

5.2.1 Internal Combustion Engines (ICEs)

The internal combustion engine (ICE) is the oldest device for propelling automobiles with portable petrol as energy source. It made its debut at the turn of the twentieth century. Coal-burning steam engines had preceded the ICE during the 1800s, so the concept of moving a piston back and forth guided by a cylinder using heated vapor or steam was not new. However coal was burnt separately to evaporate water in a boiler while in ICEs, burning fuel transfers heat directly to expanding gas and is incorporated in it. Although others had suggested it earlier, N.A. Otto is credited with building the first successful petrol-burning ICE in 1876, while G. Daimler first installed an ICE in an automobile in 1889 using suitable transmission gears to drive it.

In the ICE, a mixture of air and petrol is admitted and compressed in a cylinder provided with a moving reciprocating piston connected to a crankshaft that turns wheels or gears. As the piston compresses the mixture in the closed cylinder, the latter is ignited by a spark at the highest compression point just before the piston reverses its travel (see Brief 18). The heat of combustion then expands the gas which pushes the piston back in reverse which in turn rotates the crankshaft. After this work stroke, the expanded combustion gases are exhausted and a fresh mixture of air and petrol is injected to repeat the cycle. Many ingenious improvements to this basic concept were made during the 1900s, resulting in the sophisticated multi-cylinder automobile engines used today. The aircraft jet engine developed in the 1950s in England also burns a petrol derivative, aviation kerosene, which is mixed with air in a confined internal space and ignited. But instead of moving pistons, it utilizes expansion of the hot gases directly for propulsion.



Brief 18 Illustration of internal combustion engine four-stroke cycle

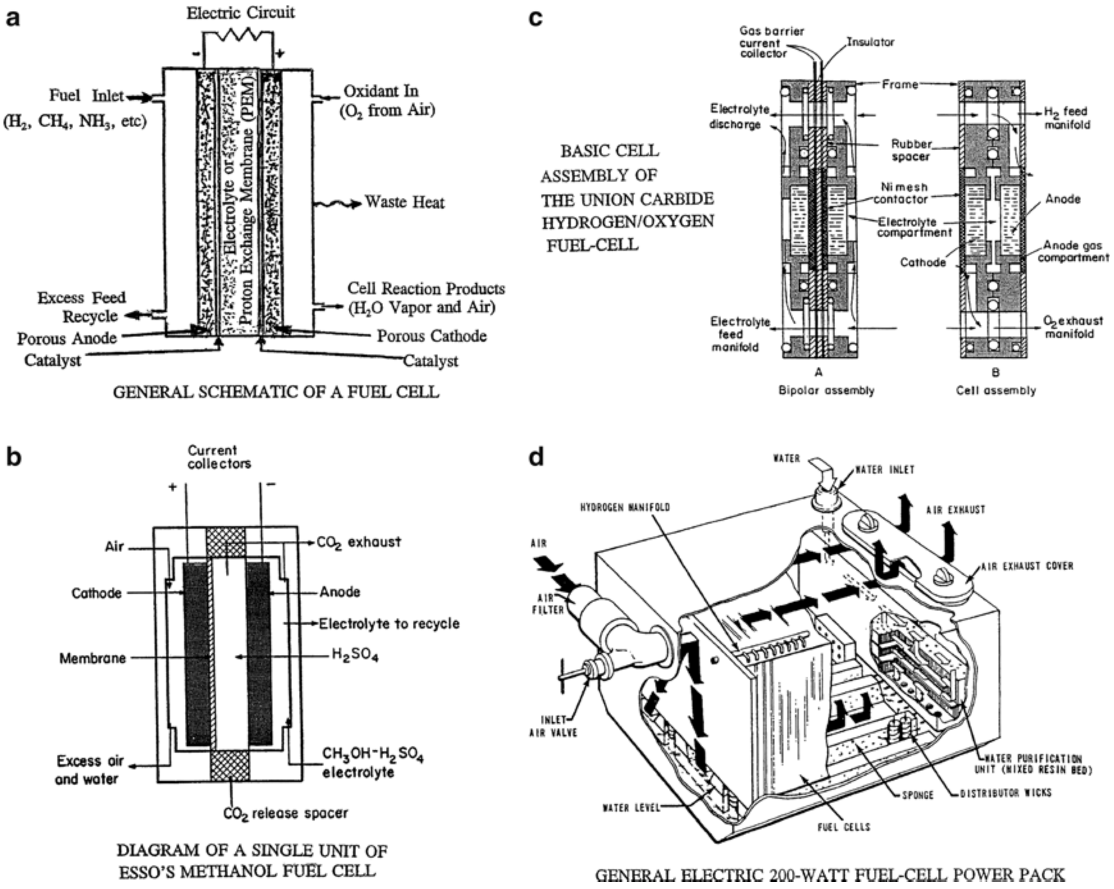
Three main types of refined oil are produced to fuel present-day ICEs, namely automobile petrol, diesel, and aviation fuel. Petrol-burning ICEs use spark-plugs to ignite combustion, while diesel-burning engines self-ignite when compression temperatures and pressures reach a certain point. The hydrocarbon composition of diesel fuel is therefore different from that of petrol. Both petrol and diesel are obtained from crude oil but from different refinery distillate fractions.

Although other means of locomotion will be developed when oil reserves are depleted, the ICE has been such a success during a whole century of development and usage that it probably will not be totally abandoned. While today's ICEs run on petrol or diesel there is no reason other oxygen-burning synfuels can not replace them to provide expansion heat. Alcohol (C_2H_5OH), ammonia (NH_3), hydrazine (N_2H_4), and pure hydrogen (H_2) all burn and react with oxygen (O_2) from air at certain ignition temperatures and mixing ratios. In fact alcohol and ammonia-burning ICEs have been built and tested, while hydrazine and hydrogen have fueled rocket engines for decades. Even though the US DOT (Dept of Transportation) has labeled ammonia as non-flammable, ammonia/air mixtures can be ignited at 780°C, burning with a yellow flame that yields nitrogen and water vapor. Mixtures of 16–25% ammonia gas in air can explode (Refs. II-12, III-3) if ignited. Of course existing ICEs must be modified, since each synfuel has a different ignition point and requires different high-temperature containment materials. All hydrocarbon and alcohol-fueled ICEs produce unwelcome globe-warming carbon dioxide (CO_2) gas besides water vapor (H_2O).However the CO_2 exhausts from bio-alcohols are balanced by atmospheric CO_2 absorbed during plant growth. In addition, regardless of the fuel, high temperatures in ICE's produce some NO_x gases since both nitrogen (N_2) and oxygen (O_2) reside in air intakes. At the high temperatures during combustion they can react with each other to form NO_x gases. For ammonia (NH_3) and hydrazine (N_2H_4) that are burnt in an ICE, NO_x byproducts might be somewhat higher. Nitrogen and water vapor can be the main exhausts however if NO_x-removing catalytic converters developed for petrol-burning automobiles are used in future synfuel-burning ICEs.

As discussed in Section 5.1.1, synfuels will have to be manufactured in large quantities using electric energy or heat supplied by nuclear and/or coal power plants when petroleum fuels are no longer available. For the large numbers of long-haul vehicles used in ground transportation all over the world, the use of non-polluting hydrogen- or ammonia-consuming engines appear to be the best solution to reduce future global warming when oil runs out. For aircraft propulsion where compact power systems are essential, it may be more efficient to use hydrazine-burning fuels and modified jet engines if handling and storing of hydrazine can be done safely and NO_x byproduct exhausts can be eliminated.

5.2.2 Electrochemical Fuel-Cell Engines (FCEs)

In a fuel-cell, chemical energy is directly converted into DC electric energy (see Brief 19a and Refs. III-1 and III-2). In automobile applications, the DC voltage of about 1 V per cell is boosted by a stack of cells in series to about 120–330 V to drive four electric motors placed on each wheel or to run one motor and engage a gear-train that moves the car. Electrically driven automobiles have been under development for many decades and several well-tested schemes are available. The first publication of experiments with H_2/O_2 fuel-cells was by Sir William Grove in 1839 in England. Later at the turn of the nineteenth century (1896), W.W. Jaques in the US and W. Ostwald in Germany, reported successful direct electricity generation with high-temperature (500°C) carbon/air fuel cells. However interest in direct carbon/air fuel-cell generation of electricity waned, when more robust coal-burning steam turbines showed successful conversion of heat to electricity at about the same time. Renewed efforts to produce electric power on a smaller scale with H_2/O_2 fuel-cells using modern materials, were started by Francis T. Bacon in 1933. After him, numerous other fuel-cell studies were undertaken by research teams all over the world. Several fuel-cell units with 2–20 kW(e) outputs were developed and used by NASA on Gemini, Apollo, and other spacecraft missions in the 1970s and thereafter. Brief 19b–19d show some early fuel-cell systems developed for NASA.



Brief 19 Typical fuel cell systems

The fuel-cell is similar to an electric battery except the active agents are gases, usually air or oxygen (O_2) as "oxidant" and hydrogen (H_2) as "fuel", each being continuously supplied to one of two electrodes separated by an electrolyte or proton exchange membrane (PEM). Solid PEM's are preferred today over liquid (corrosive) electrolytes used in earlier devices. The fuel-cell process is inherently more efficient than a chemical reaction in a combustion engine where heat is produced first and then converted into mechanical motion. The latter conversion has a typical efficiency of about 33% set by thermodynamics which rules heat conversions. Fuel cells are 45–85% efficient in practice, losses being ruled by the kinetics in electrodes and electrolytes or PEM's.

Hydrogen and oxygen gases when mixed would like to react and form water by the overall reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ (+ heat or electric energy)} \tag{5.9}$$

The reason is that the chemical binding of atoms in H_2O is stronger than that in H_2 and O_2. But at room temperature, an "energy barrier" prevents them from undergoing reaction (5.9). There are two man-engineered pathways by which H_2 and O_2 can overcome the barrier and react to form H_2O. One is by igniting combustion and the other via inducing electrochemical action. The energy barrier in reaction (5.9) arises from the fact that the two H atoms in H_2 and the two O atoms in O_2 molecules are strongly bonded to each other. They must be taken apart first before they can recombine into H_2O. Because the total binding energies of H and O in H_2O are larger than the sum of the bond-breaking energies of H_2 and O_2, the difference manifests itself as kinetic energy in the form of heated gas if ignited in an ICE, or as electron motion if catalyzed on electrodes in an FCE. In combustion, the heat increases the relative collision velocities of O_2 and H_2 molecules to the point that the bonds in H_2 and O_2 are broken, allowing for a re-arrangement of O and H atoms into H_2O. Kinetic energies required for prying O_2 and H_2 molecules apart into atoms and reforming them into H_2O molecules in collisions are on the order of 5 eV per molecule (see footnote 2). A gas mix of H_2 and O_2 will therefore not start to react measurably until an ignition temperature of about 580°C is established. Since liberated heat can keep the gas at 580°C, for example after igniting the reaction by an electric spark, reaction (5.9) becomes self-sustaining in an ICE.

In the electrochemical scheme, electrodes and electrolyte or a PEM are used to catalyze reaction (5.9) with liberation of electric energy. As shown in Brief 19a, H_2 gas is bubbled over a positive electrode called the "anode" which is in contact with an electrolyte or PEM (proton exchange membrane; proton = ionized H atom = H^+). The latter helps dissolve or dissociate H_2 to become ionized with energy expenditures of about 1 eV/molecule (= 1.6021×10^{-19} J/molecule):

$$H_2 + \text{Anode} \rightarrow \text{Anode:}H_2 \rightarrow 2H^+ + 2e^- \tag{5.10}$$

Process (5.10) can proceed at a much lower temperature (70–150°C) than what is required in combustion. To get electrons to flow in an external circuit, O_2 is fed to a negative electrode or "cathode" placed on the other side of the electrolyte or PEM, where incoming H^+ ions are recombined with oxygen atoms O and electrons:

$$\frac{1}{2}O_2 + \text{Cathode} \rightarrow \text{Cathode:O} \qquad \text{(adsorption)} \tag{5.11a}$$

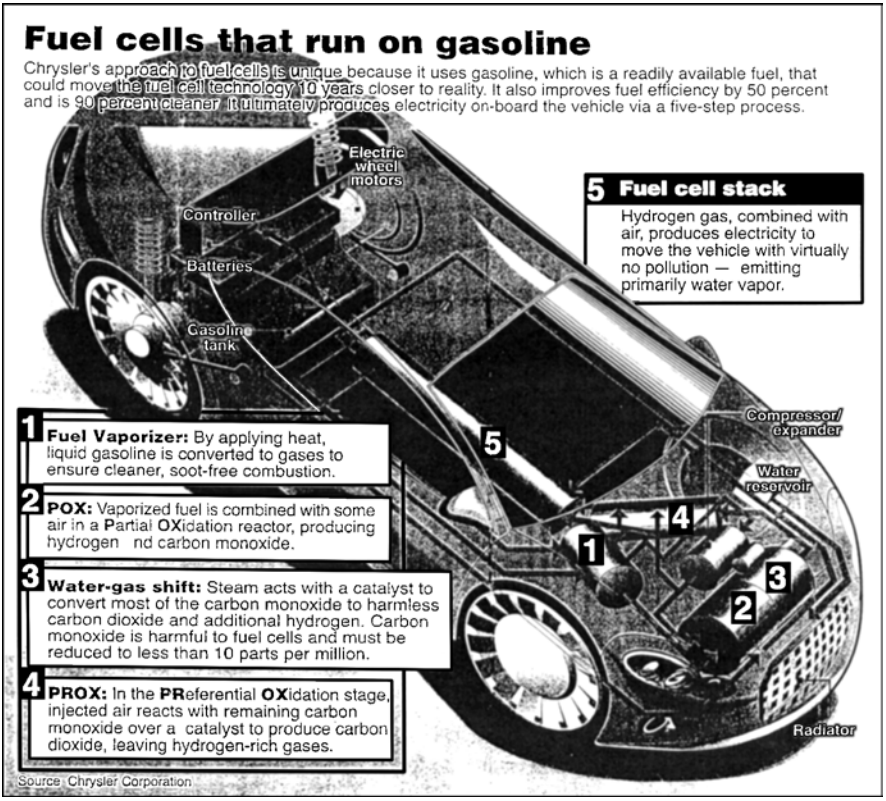
$$\text{Cathode:O} + 2H^+ + 2e^- \rightarrow H_2O \tag{5.11b}$$

Electrons liberated on the anode by (5.10) travel through the outside power-delivering circuit to the cathode to be reunited with H^+ ions, making neutral H_2O molecules via (5.11b) in accord with overall reaction (5.9). Protonization of H_2 by electrolytes or PEMs in (5.10) lowers the energy barrier in (5.9). If the freed electrons in (5.10) are allowed to flow through a conducting wire to be reunited with H^+ on the cathode via reaction (5.11b) to form H_2O, they promote an electric current in the wire. Chemical energy is thus converted directly and efficiently into kinetic energy of electron flow, i.e. electricity. A little heat helps increase the proton flow through the electrolyte or PEM and thereby increases the electric current. Presently, Dupont's Nafion is the most popular PEM in experimental fuel-cells, but new high-temperature fluoropolymer materials are under development to improve PEM performance.

Hydrogen (H_2) is presently available as a cryogenic liquid or pressurized gas. An experimental fuel-cell car with ~100 kWe (~130 hp) of power has been reported to have traveled 400 km (250 miles) on a 155 kg (342 lb) tank with 10 kg (22 lb) of liquid H_2. However liquid hydrogen is twice as expensive as gaseous hydrogen and various schemes are being investigated to compact it. Recent filament-wound high-pressure cylinders reportedly can hold 1 kg of H_2 each at 245 atm pressure. Each high-pressure fiber-glass cylinder weighs approximately 18 kg, has a storage volume of 50 L, and nominal outside dimensions of 25 D × 125 L cm. For a 10 kg H_2 supply on board a car to travel 600 km = 373 miles (Brief 4), one thus needs ten cylinders. These cylinders could be mounted overhead or at floor-level in a car in two rows of five. They would occupy about ten times the space of today's 60-L petrol fuel tanks whose dimensions are typically 25 × 40 × 60 cm.

An alternative solution for gaseous hydrogen storage are H_2-adsorbing porous "bladder" materials of light weight that compact H_2 in a volume a 1,000 times less than in its gaseous state. The adsorption energy for such storage must be moderate so that H_2 can be expelled from the bladder again with little heat, without destroying or incapacitating it. Bladder materials under investigation are clathrates, (mixed) metal hydrides like MgH_2, $LaNi_5H_6$, $NaBH_4$, $NaAlH_4$:Ti, and (mixed) amides such as $LiNH_2$, LiN_aH_b, or $(LiH)_m{:}(LiNH_2)_n$. Various H_2-adsorbing carbon and boro-nitride nano-tube configurations are also under investigation. A capacity of 8 wt% (kg hydrogen per kg bladder) with an adsorption energy of 15 MJ/kgH_2 or less is the goal. If 10 kg H_2 is the desired quantity (Brief 4) for one filling of a bladder fuel tank, such a fuel tank would weigh 125 kg without support structure. Presently the best materials still need improvements by a factor of 4 in weight as well as in adsorption performance to reach this goal. Note that hydrogen fuel storage costs extra energy, whether in bladder-heating to expel H_2 or in compressing/liquefying H_2 gas.

Instead of pure gaseous hydrogen (H_2), liquid petrol (C_mH_n), methanol (CH_3OH), and liquid ammonia (NH_3) at 12 atm or compressed (methane (CH_4) gas at 60 atm, can be used as fuel in automobile FCEs. These fuels can be catalytically decomposed ("cracked") with liberation of H_2 on the proton exchange membrane. Alloys of platinum, ruthenium, osmium, and iridium seem to give the best catalytic cracking performance. Although it adds complexity and cost to the FCE, it may be a more practical and safer solution to the hydrogen storage problem than the use of compressed hydrogen gas at 245 atm pressure or liquefied hydrogen at $T = 20$ K. Brief 20 shows an experimental car under development by Chrysler which uses a petrol-fed hydrogen-cracking fuel-cell engine. Such pioneers of the envisioned hydrogen age allow commercial development of fuel-cell technologies well before country-wide hydrogen (or ammonia) fueling stations and improved hydrogen storage techniques (or ammonia tanks) become available at a later date. Even though they still consume carbonaceous fuels and release CO_2, less air pollution (no NO_x) is generated by FCEs than by ICEs, because of the lower operating temperature of fuel cells. This should please both environmentalists and futurists. Ultimately instead of cracked petrol, non-polluting pure hydrogen or ammonia would be the most desirable green fuel after oil runs out.



Fuel cells that run on gasoline

Chrysler's approach to fuel cells is unique because it uses gasoline, which is a readily available fuel, that could move the fuel cell technology 10 years closer to reality. It also improves fuel efficiency by 50 percent and is 90 percent cleaner. It ultimately produces electricity on-board the vehicle via a five-step process.

5 Fuel cell stack
Hydrogen gas, combined with air, produces electricity to move the vehicle with virtually no pollution — emitting primarily water vapor.

1 Fuel Vaporizer: By applying heat, liquid gasoline is converted to gases to ensure cleaner, soot-free combustion.

2 POX: Vaporized fuel is combined with some air in a Partial OXidation reactor, producing hydrogen and carbon monoxide.

3 Water-gas shift: Steam acts with a catalyst to convert most of the carbon monoxide to harmless carbon dioxide and additional hydrogen. Carbon monoxide is harmful to fuel cells and must be reduced to less than 10 parts per million.

4 PROX: In the PReferential OXidation stage, injected air reacts with remaining carbon monoxide over a catalyst to produce carbon dioxide, leaving hydrogen-rich gases.

Source: Chrysler Corporation

Brief 20 Fuel-cell-powered hybrid car

Besides the hydrogen tank storage problem, a second problem that has plagued fuel-cell systems is the fouling of electrodes and PEM's with particles and other "poisons". To minimize this difficulty requires careful filtering of the fuel. Additional schemes to cleanse electrodes and PEM's may involve intermittent ultrasonic exposures, intermittent "flushing" with AC currents, or intermittent laser beam illuminations. It has been suggested this could be carried out at fueling stations or in car owner's garages when the fuel-cell engine is not running (e.g. at night). PEM's could also be made replaceable like the sparkplugs on IC engines if their cost is not too high.

While rechargeable batteries and plug-in vehicle will most likely replace present automobiles for short-haul (e.g. urban) driving less than 100 km, for long-haul transport (e.g. trucking), hydrogen- or ammonia-fueled FCEs may eventually replace ICEs if present developmental problems can be solved and their inherently higher efficiencies can be maintained. Future development programs and tests might also determine whether fuel-cells can provide sufficiently compact take-off power to match the power from today's jet engines of large commercial aircraft.

5.2.3 Steam Engines

For completeness, we mention one of the oldest automotive devices, namely the steam engine powered by burning portable coal lumps as fuel. A return to using coal-burning steam-powered locomotives and automobiles of the 1800s has been proposed to counter the no-oil peril we face. Several experimental steam automobiles using modern components were built and tested in the 1970s, but further development was abandoned. Instead of burning dusty air-polluting coal, one could burn a liquid carbon-carrying synfuel (e.g. alcohol) to generate steam and propulsion. However in that case it is more efficient to burn the synfuel directly in an internal combustion engine than to use steam as an intermediary. Of course if coal-burning is forbidden to avoid global warming, the re-introduction of coal-fired steam engines to propel our automobiles would not be an option at all.

Chapter 6
Coal and Nuclear Power Generation

6.1 Coal-Burning Power Plants

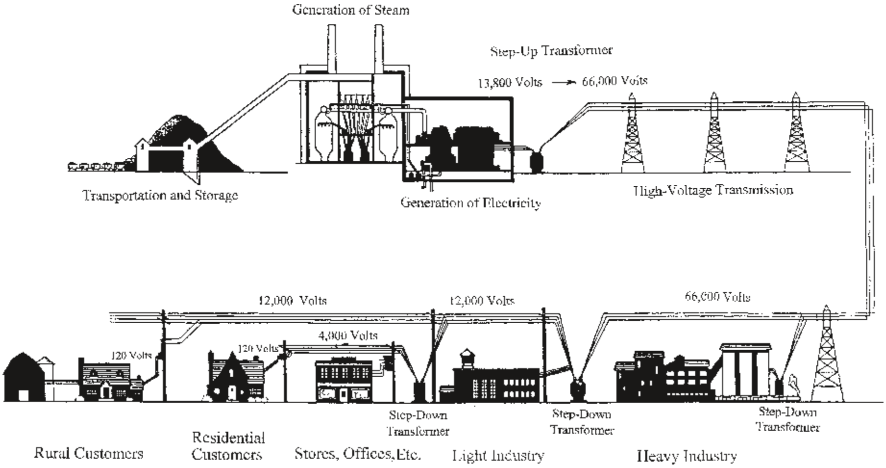
Historically the first electric power plants delivering large quantities of electric energy were hydro-electric. In 1895, Westinghouse built the first AC electric power generator in Niagara Falls by passing water flow from the Falls through a turbine that induced electric currents in copper windings. General Electric built high-power grid lines that took the 1.1 MWe of electricity to Buffalo, New York, where it lighted the city's streetlights and powered streetcars. The technical brains behind this were Nikola Tesla who worked with Westinghouse and Elihu Thomson who was a founder of General Electric. Tesla invented today's ubiquitous AC electric motor and had an uncanny intuition about how to generate and use electricity. He was a Serb born in Croatia and had studied electro-magnetism at universities in Austria, Tsjechoslovakia and Hungary before coming to America in 1884 (Section 3.3 and Brief 7).

Following the success in Niagara Falls, ambitious programs were started worldwide to dam up rivers and build hydro-electric power plants. Because suitable waterflow was not available everywhere, alternative coal-fired steam turbines invented by Parsons in 1884 were adapted next for electricity generation. High-pressure steam was used instead of water pressure to turn the blades of a turbine's rotor to induce electric currents. From the early 1900s till today, many coal-burning steam-driven electric power plants were built following this scheme. By 2005, 52% of all US electric power came from coal-fired power plants and of all energy consumption by man, about 50% is now in the form of electricity. This percentage is expected to increase to 60% by 2030 when large numbers of electric plug-in cars will be cruising our cities. Brief 21 illustrates the electricity generation and power distribution from a coal-burning power plant. Although electric power generation with coal has been a resounding success, the exhausts from such plants are globe-warming gaseous carbon dioxide (CO_2). Also entrained particles that carry unhealthy chemicals for all breathing creatures on our planet are emitted which seriously pollute our biosphere. While new exhaust filtering and underground sequestering of gaseous CO_2 is presently under intensive investigation, it appears that the replacement of coal plants

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_6,

with nuclear plants is the most sensible and least costly long-term way to satisfy man's demand for abundant electricity and avoidance of atmospheric pollution. Also when oil fields are depleted, coal becomes a very valuable commodity for making organic compounds (Section 9.2.6). Burning coal and dumping its combustion products into the atmosphere will be considered extremely foolish then, knowing that coal plants can be replaced quite affordably by green nuclear power plants.

A coal-fired power plant of 1,000 MWe output produces about 300,000 kg (660,000 lb) of ashes and cinders, and releases 11 million tons (22 billion lb) of globe-warming CO_2 gas into the atmosphere per year. In addition to gaseous CO_2, 55 million kg (120 million lb) of SO_x gases and 27 million kg (59 million lb) of NO_x gases, together with 240 kg (530 lb) of mercury and 409 kg (900 lb) of uranium are released annually into the air as entrained toxic materials. Because of the concern about global warming (Section 1.2) and air pollution, new laws have been passed which demand that coal-burning power plants restrict their CO_2 emissions and remove entrained toxics from their exhausts by 2010–2012. While the filtering of 90% of all particles from CO_2 effluent can be accomplished at a moderately added cost for electric generation, the removal of gaseous CO_2 is more difficult. Large experimental research programs are presently underway, financed by the US government and the coal industry, to scrub and bubble CO_2 through CO_2-absorbing fluids, or to "sequester" and store gaseous CO_2 in underground cavities or oil-depleted sandstone formations. Both operations, if viable, would add considerably to the cost of generating electricity from coal. While some sequestration advocates believe such underground "burials" could hold gaseous CO_2 for at least 100 years, others are not so sure. Also many existing coal plants are not near suitable underground porous rock formations so their CO_2 combustion exhausts would have to be pumped through pipelines to distant storage reservoirs. All this will make coal-derived electricity less competitive with nuclear generation, and has encouraged the renaissance of nuclear power even more.

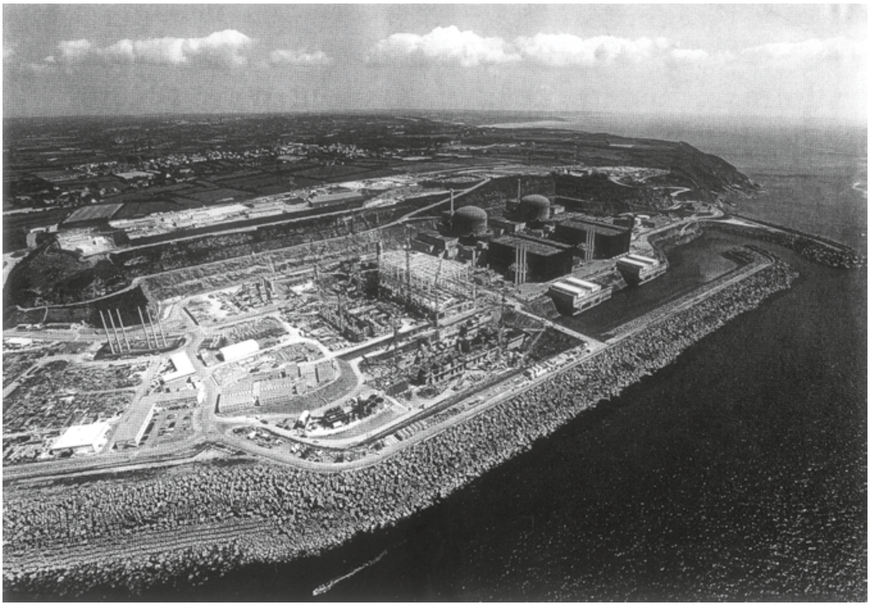


Brief 21 Electricity from coal – flowsheet

6.2 Nuclear Power Reactors

After the discovery and demonstration of uranium fission in WW-II, heat from nuclear fission of uranium in a nuclear reactor was immediately considered as a replacement for heat produced by burning coal. The same technique of generating high-pressure steam by heating water in a confined space is employed to drive the blades of an electricity generating steam turbine. The only difference between a coal and a nuclear power plant is in the heat generation system that produces steam. Everything beyond the coal furnaces in Brief 21 that produce steam, such as steam turbines, power-line insertion and control, cooling towers, etc., is essentially the same for coal and uranium power plants. Since the central theme of this book is nuclear power, in what follows we shall focus on major aspects of nuclear electricity generation. Where appropriate, comparisons will be made between nuclear and coal or other power generating schemes. Briefs 22 and 23 show two modern multi-gigawatt PWR (= Pressurized Water Reactor) nuclear plants, one in California and one in France cooled by ocean water. The Diablo Canyon plant in California has two PWR units, each producing approximately 1,130 MWe, while at Flamanville two PWR units are operating, each generating 1,330 MWe with a third unit of 1,600 MWe under construction.

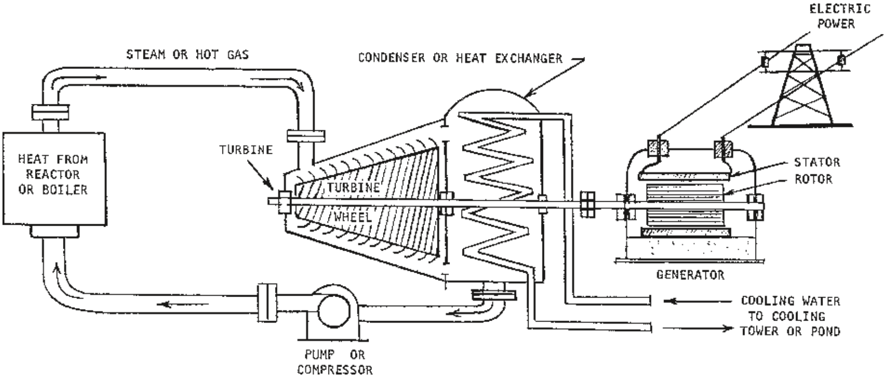
Brief 22 Diablo canyon nuclear power plant in California



Brief 23 Flamanville nuclear power plant in France

The first nuclear reactor was assembled in 1942 by Enrico Fermi and collaborators at the University of Chicago. Fermi who had left his native Italy for the US in 1939 when Mussolini’s fascists took over, was one of a few pioneers in the 1930s who tried to understand the workings of atomic nuclei by bombarding them with newly discovered neutrons (see Section 3.3 and Brief 8). After he learned in 1939 that his German colleagues Otto Hahn, Lise Meitner, and Fritz Strassman had shown that uranium could fission, he quickly started analyzing and measuring neutron multiplication by fissioning uranium and estimated what it would take to construct a “critical pile”, now called a “nuclear reactor”. He determined the minimum amount of uranium and moderator needed to activate self-sustained neutron-induced fissioning of uranium. The first reactor was designed and built in 1941 in Chicago according to Fermi’s calculations. Using rods of natural uranium dispersed through a pile of graphite bricks, a self-sustaining chain reaction was achieved on December 2, 1942, with a “critical mass” of uranium almost exactly as predicted by Fermi. Besides being a maverick in theoretical and experimental nuclear physics, Fermi had a social conscience. Like Leo Szilard and other colleagues, he disliked using nuclear fission for weapons. But he saw the urgency of developing a nuclear weapon in World War II before the Nazis did, to defeat their tyranny and to defend the democracies.

Although the first reactor and several others that followed were not designed to generate electric power, the principle of operation of all nuclear reactors is the same. When the uranium-235 nucleus fissions, 2.5 “fast” neutrons on average are liberated in addition to the two heavy fission fragments which carry most of the fission energy. As they slow down and stay in the solid material that encapsulates the uranium, the fission fragments heat it up. This heat is transferred by conduction to a coolant (gas, water, sodium or other liquid) that passes through the core. In a power reactor, the hot circulating coolant then heats up water through a heat exchanger in a secondary loop and turns that water into steam. The steam in turn drives a turbine to generate electric power as illustrated in Brief 24.



Brief 24 Electric power generation by a steam turbine

Neutrons have the same mass as protons but have no electric charge so they can move through and bounce around in a solid material as if they were a gas. The lifetime of a neutron is approximately 12 min, when it decays into a proton and beta particle. This lifetime is essentially forever as far as the fission process is concerned. After a “fast” neutron is slowed down (thermalized) by collisions in a good moderator material such as water or graphite, a thermalized neutron can be absorbed by a U-235 atom and cause it to fission, resulting in 2.5 new neutrons on average. After these are thermalized, the cycle is repeated and a chain reaction is started. While thermalizing, the gas-like neutrons “fly” and diffuse through the solid core which is a mixture of moderator and uranium fuel. Then if neutron thermalization is sufficiently promoted by a moderator, a reactor can be made to run continuously in a self-sustaining mode. Because of so-called “delayed” neutrons, reactors can be controlled safely at any desired level. The thermalizing neutrons provide some additional heat, but more than 90% of nuclear heating is delivered by fission fragments.

After Fermi’s initial success, a number of “research reactors” were constructed in the period 1945 through 1965 to further analyze and develop nuclear fission and its applications. Research reactors are still built and operated today to produce radioisotopes used in nuclear medicine for diagnostics and therapeutics (combating cancer), as well as to provide tracers for biotechnology research. In this case it is not the heat energy but the newly formed radioactive isotopes that are of interest.

The first uranium-fission power plant that generated electricity for a small community (Arco, Idaho) was operated in 1955 at the Idaho reactor testing station, now INL (= Idaho National Laboratory). Many electric power reactors have been built since then and today 104 reactors provide power for 21% of the US electric grid. In France, 59 nuclear reactors provide 87% of its electricity needs. The total number of operating power reactors worldwide in 2004 was 438, with more under construction (mostly in Asia). In addition, the USA and Russia operate a hundred or so naval propulsion reactors.

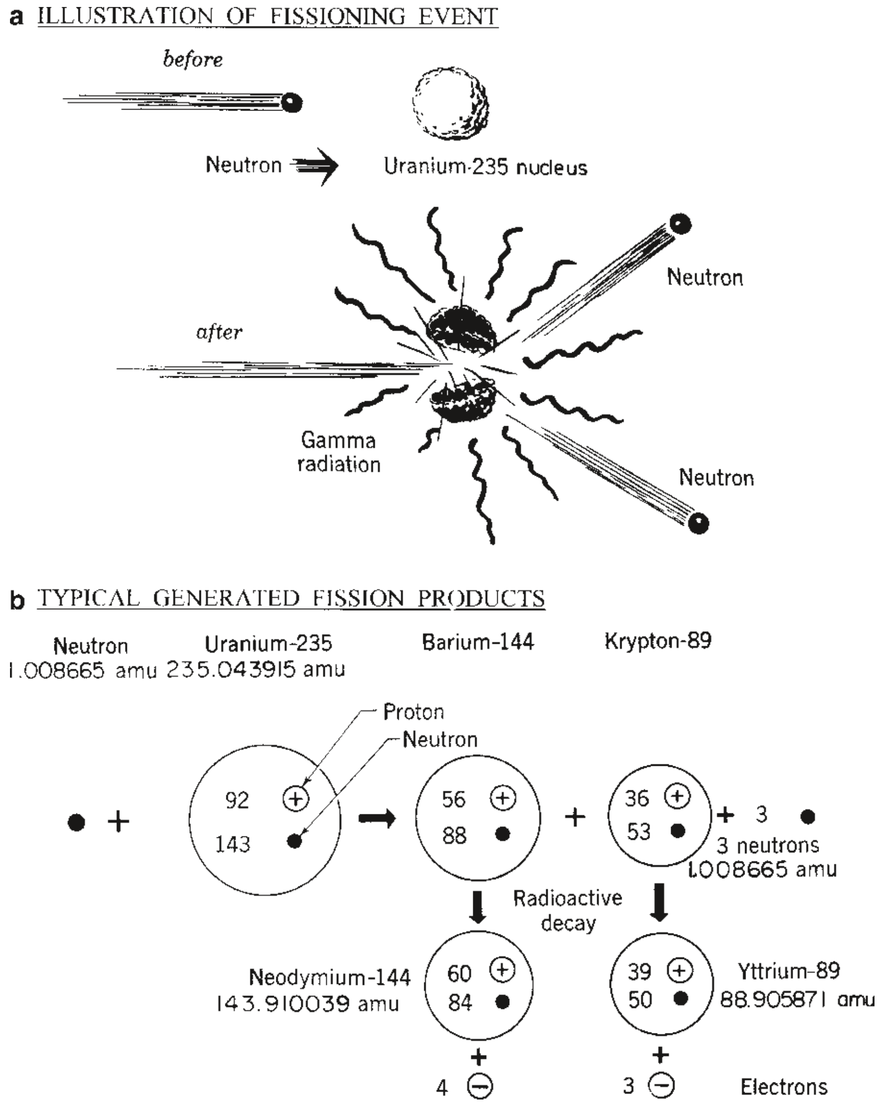
The average age of the world's power reactors is about 25 years. Many are having their operating lives extended for another 20 years after completing 30 years of their design life. Two reactor core meltdown accidents have occurred since 1955; one in Russia (Chernobyl) with a total of 45 fatalities, and one in the US (Three-Mile-Island or TMI) with no loss of human life. These accidents are discussed further in Section 7.3. The Chernobyl and TMI accidents caused a complete re-evaluation of reactor safety procedures (mostly human factors) and expansion of accident prevention techniques, originally believed to be adequate before these mishaps took place. Today, an accidental reactor core meltdown is as unlikely as a meteor hitting the Washington monument. Even if this happens, reactor containment vessels worldwide are designed to hold all nuclear debris. If a reactor overheats, the chain reaction is automatically stopped and the reactor shuts itself down.

6.2.1 *Basic Physics, Design, and Operation of a Reactor*

The basic process in a nuclear reactor is the splitting of nuclei of uranium atoms by self-multiplying neutrons resulting in the liberation of heat. Physicists and chemists write this process in shorthand as:

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow \mathrm{FP1} + \mathrm{FP2} + 2.5\ \mathrm{n}\ (+\ 196\ \mathrm{MeV}) \qquad (6.1)$$

Here FP1 and FP2 are the two products from the split ^{235}U nucleus. They are new atoms with charge numbers $Z_1 + Z_2 = Z_U - \Delta = 92 - \Delta$ and masses $M_1+M_2 = M_U+1$. Here Z is the number of protons in a nucleus which equals 92 for uranium (see footnote 3 in Section 3.3) and Δ is the proton deficiency after fission. There is a statistical distribution in possible product masses in uranium fission so we write FP1 and FP2 to describe them. A specific pair of products might for example be Barium-144 with $Z_1 = 56$ for FP1 and Krypton-89 with $Z_2 = 36$ for FP2 with release of three new neutrons. These isotopes decay respectively to Neodymium-144 with $Z_{1f} = 60$ and emission of 4 betas, and Yttrium-89 with $Z_{2f} = 39$ and emission of 3 betas (Refs. II-8, II-17). Brief 25 illustrates the basic fission process.



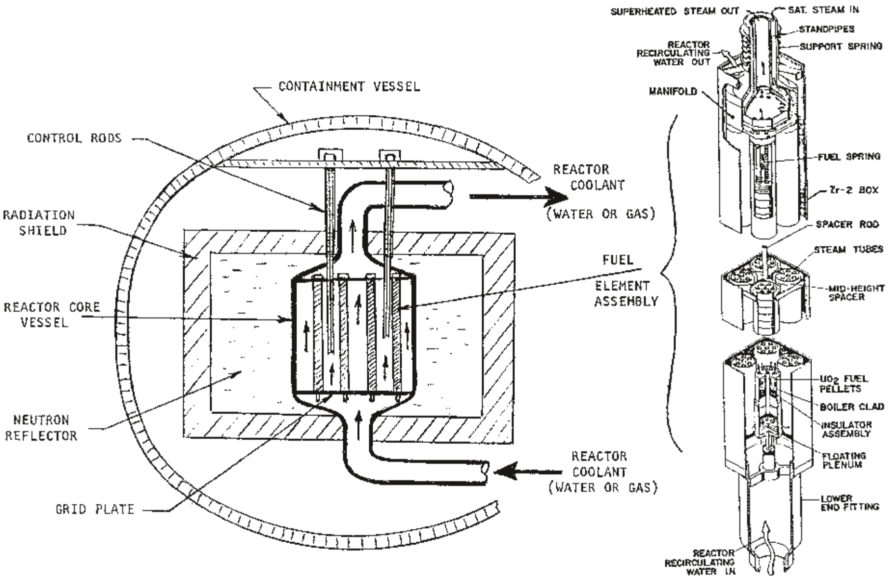
a ILLUSTRATION OF FISSIONING EVENT

b TYPICAL GENERATED FISSION PRODUCTS

Brief 25 Illustration of U-235 nuclear fission process. (**a**) Illustration of fissioning event, (**b**) Typical generated fission products

The average energy release of 196 MeV given in parentheses in (6.1) is distributed over kinetic energy of the recoiling fission fragments and internal nuclear excitation energy in the fragments. Energy is given here in atomic energy units of MeV (Million electron-Volt; 1 MeV = 1.6021 × 10^{-13} J; see footnote 2 of Chapter 5). Of the 196 MeV, about 165 MeV is liberated as kinetic energy of the recoiling fission fragments and the balance of about 30 MeV is distributed over post-fission emitted particles. Most of the 30 MeV of initial excitation energy is almost instantly released after the fission event in the form of emissions of gammas, neutrons, betas, positrons, and neutrinos, all carrying energies on the order of an MeV. Gammas are high-energy photons, betas are high-energy (negative) electrons, positrons are high-energy positive electrons, and fission neutrinos are essentially massless neutral particles, all with energies in the 10 keV to 10 MeV range (see also footnotes 3 of Chapter 3 and 2 of Chapter 5). Some fission product pairs release only 2 and others 3 neutrons, but on average 2.5 neutrons are released for every one that creates a fission event as indicated in reaction (6.1). Fission products FP1 and FP2 do not fission again but decay with further emissions of betas, positrons, gammas, and neutrinos that change them into other elements accompanied by additional "decay heat". The fission fragments are lodged in the solid fuel elements and later removed as radioactive waste during spent fuel processing. The energy release per U-235 fission which is mostly kinetic energy of FP1 and FP2 is converted into heat in the solid lattice as they slow down. This heat is in turn transferred to the reactor coolant. Since 1 g of U-235 contains 2.56×10^{21} U-235 atoms, 1 g of uranium fuel yields 80 GJ = 22.3 MWh = 0.93 MW-day of heat, or 0.31 MWe-day assuming that conversion of heat into turbine electricity is 33%.

The "core" in a reactor comprises 20–200 fuel elements, the exact number depending on the reactor power that is wanted. Each element or assembly has bundles of fuel "rods" which are zirconium tubes filled with uranium oxide pellets between which water can flow to remove liberated fission heat. The fuel elements are typically 2–5 m (6–15 ft) long with square 10 × 10 cm (4 × 4 in.) cross-sections. Positioning pins at the top and bottom anchor them in so-called "grid plates". An array of such fuel elements forms a roughly cylindrical core with a diameter of 2–5 m and a height of 2.5–6 m as illustrated in Brief 26. The precise dimensions depend on the power one wants to extract from the reactor.



Brief 26 Schematic of major nuclear reactor components

Pressurized water at about 150 atm is made to flow through the core removing fission heat generated in the uranium oxide and acting also as neutron “moderator”. The moderator decelerates all new neutrons originally born with very high kinetic energies in fission events. Moderators are desirable since neutron absorption by fissionable U-235 or Pu-239 by reaction (6.1) is much enhanced (100–1,000 times) for thermalized neutrons compared to that for high-energy or “fast” neutrons. In a Pressurized Water Reactor (PWR), water under pressure is heated to about 350°C and passed from the core to a heat exchanger where its heat is transferred to a secondary low-pressure water loop. In this second loop, water becomes steam and is fed to a turbine. The expanding steam then generates electricity as shown in Brief 26. In BWR’s (= Boiling Water Reactor), core-heated water/moderator is evaporated directly into high-pressure steam to drive a steam turbine, thereby avoiding a second loop. Both designs have pros and cons. More details of the physics and engineering design of nuclear reactors may be found in Refs. II-2 through II-8, II-17, and II-18.

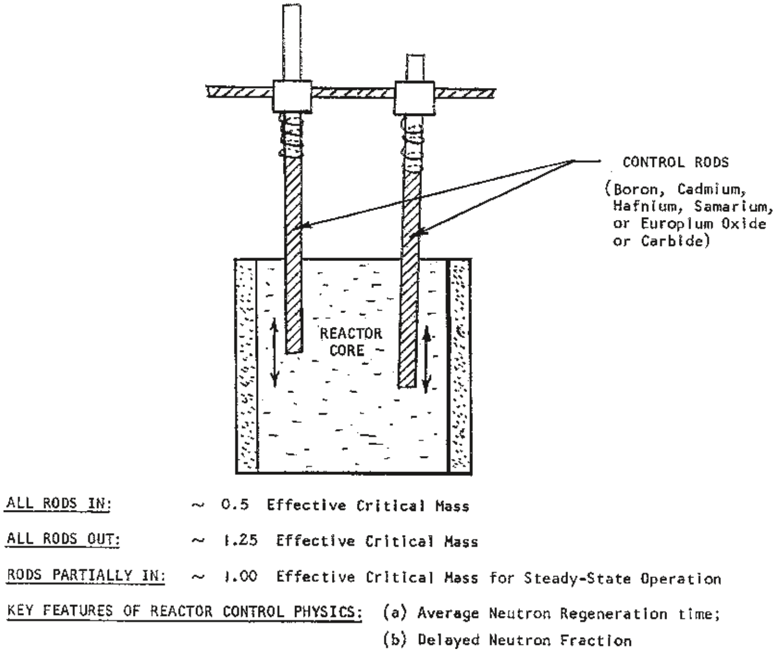
Instead of water, some reactors use gas as a coolant which drives a gas turbine instead of a steam turbine. Otherwise electricity generation is the same. If gas is used instead of water, moderator materials like graphite or beryllium are often used in fuel elements to effect efficient neutron thermalization. Typical coolant gases are helium, nitrogen, and carbon dioxide. Still another reactor version developed in Canada is the heavy-water-moderated and -cooled CANDU reactor. This reactor uses D_2O instead of H_2O which has a lower neutron-robbing absorption cross-section. Using D_2O moderator allows fissioning to occur with natural uranium (0.7% U-235; 99.3% U-238) instead of enriched (3% U-235) uranium needed in normal-water (H_2O) cooled reactors. A CANDU reactor needs lots of deuterium (D) which is extracted from natural water. Deuterium or heavy hydrogen ($D = {}^2H$) occurs in concentrations of only 0.015% (D/H) in nature. Considerable amounts of energy are therefore required to extract it from ordinary water, using distillation or hydrogen-sulfide exchange processes (Ref. II-17). Canada has many hydroelectric power plants and water so it can do this with least expense during periods when electric demand is low, which is usually around midnight. In 2005, the world had 44 operating CANDU reactors, compared to 260 PWR’s, 93 BWR’s, 26 gas-cooled, 13 graphite-moderated light-water-cooled, and two fast-breeder reactors.

Surrounding the core of a reactor, there is usually additional water acting as a neutron reflector. The reflector in turn is surrounded by a “gamma shield” that attenuates and stops most gammas emitted from the core. The entire reactor assembly is finally positioned in a containment vessel (Brief 26). As its name implies, the purpose of the containment vessel is to retain all fission products in the event of a core meltdown, a strong earthquake, or other accidents like an airplane crashing on the reactor. The neutron reflector is very important and serves to minimize the loss of neutrons from the reactor and to maximize the neutron economy. Even though each fission of U-235 produces 2.5 neutrons on average for each one that induces fission, there are losses due to neutron absorption by materials of construction such as steel, and due to escapes of neutrons from the reactor core region. The 1.5 neutrons that are left, while not needed to maintain the chain reaction, must be conserved as much as possible. Low-neutron-absorbing zirconium metal is therefore used to hold uranium fuel pellets. In breeder reactors, absorption by uranium-238 of 1 of the 1.5 "left-over" neutrons is required to make new plutonium fuel. Neutron escapes are considerably reduced by a core-surrounding neutron reflector. While a neutron can live for as long as 20 min before it decays into a proton and beta particle, in a reactor core loaded with fissionables, its life is approximately 20 μs for thermal reactors, and 0.4 μs in fast breeders (Ref. II-18).

If too many neutrons escape from a reactor core, it is not possible to maintain a chain reaction. This can happen if not enough neutron slowing-down material (= moderator) is present and/or if there is no reflector. There is a minimum critical volume and associated critical mass below which a neutron chain reaction can not be maintained because the surface area surrounding the volume is too large and the neutron escape too high. When a reactor is operating at steady state, the neutrons produced by fission and neutrons lost by absorption or escape are exactly balanced. A small increase in temperature will expand the surface area for neutron escape and lowers neutron fission rates to the point that the chain reaction is curtailed. Thus a nuclear reactor is inherently self-controlling and can only get overheated or melt down if a man removes the control rods (see below). Together with the "delayed neutron" effect, this allows stable and safe reactor operations. Only with extreme operator negligence or deliberate sabotage in which control rods are forcibly removed, could a reactor meltdown be initiated when excessive generation of heat is not carried away fast enough by the coolant. Even this event is mitigated in today's reactors by sensors that in case of an abnormal excursion activate controls to engage an independent emergency core-cooling system (ECCS), which in emergencies allows soluble neutron-absorbing compounds to be added to the coolant, thereby suppressing neutron multiplication.

To have a reactor operate at steady state with a constant rate of heat generation, the neutron population in a reactor is controlled by manipulating "control rods". These rods contain strongly neutron-absorbing materials like boron, samarium, europium, or other rare-earth containing compounds (Brief 27). Usually there are a minimum of four control rods which when completely inserted in the reactor core, make it impossible for the reactor to start or maintain a chain reaction. The control rods are pushed into the core with springs. To pull them out, electromagnets must first be energized after which a motor drive can slowly move them upwards out of the core to a desired preset level. If there is any disturbance, the currents in the electromagnets are interrupted and the springs push the rods back into the core in milliseconds. Current breaking is called a "scram" and is usually initiated by the reactor operator. However in case excessive heat develops, or if cladding on a fuel element leaks, or if an earthquake strikes, the reactor scram is automatically activated by special sensors. Any one of such situations can cause an automatic non-operator-initiated scram.

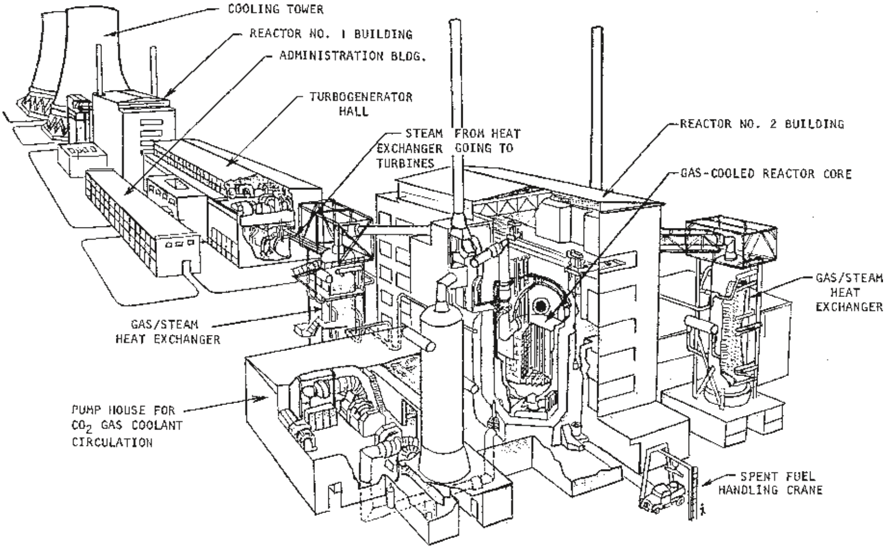
In addition to control rods, some research reactors also have an emergency "neutron-poison fuse". This is a small rod with a high neutron absorbing material which is spring-injected into the core when a thin metal wire that keeps the fuse out of the core, melts and breaks under excessive heating. When this "fuse" drops in the core, neutron multiplication stops and the reactor is sub-critical.



Brief 27 Illustration of reactor control rod operations

To start a reactor, one control rod is first slowly pulled out of the core by a motor activated with a switch under control of the reactor operator. As he pulls out the first rod, the operator watches a control panel to make sure no excessive neutron multiplication occurs. A small neutron source such as a polonium-beryllium nugget, is present in the core whose neutron emissions are detected by neutron counters like a boron-fluoride gas-filled tube. As a control rod is pulled out of the core, the subcritical multiplication of neutrons emitted by the independent source is measured and the amount of “reactivity” or “worth” is determined. Reactivity is a measure of how close a reactor is to criticality. After the first rod is removed, the second rod is pulled out slowly next. Finally after the third rod is pulled up, the reactor becomes “critical”, that is it starts to increase the neutron population in the core by self-multiplication. The position of this rod is then adjusted and held when a desired amount of fission heat is generated steadily. A fourth rod called the “shim rod” and possibly additional ones, stay in the core and are used for long-term corrections of the core’s reactivity. With time, fissionable U-235 in the core slowly “burns up” and the reactor’s critical mass or “reactivity” drops. Keeping it operating requires refueling it every 1.5–2 years. To compensate for loss of reactivity as the fuel is burned up, shim rods are gradually pulled out of the reactor core. We assumed four control rods here as in a small research reactor. Actually power reactors have banks of ten or more removable control rods distributed throughout the core to even out neutron flux distributions and thus fission heating, but the operating principle is the same.

Most modern U-235 burning reactors generate approximately 1,000 MWe (3,000 MW heat), with older units ranging between 300 and 1,200 MWe. The new fast breeder reactors (Section 6.3.2) typically generate between 300 and 600 MWe. Two or three fast reactor units are planned for each generating site to give a total of 600–1,800 MWe of capacity 24/7. This compares with 2 MWe for the maximum capacity of large modern windmills with a year-averaged 0.5 MWe. Brief 28 shows the layout of a typical nuclear power plant cooled with gaseous carbon dioxide (CO_2) as primary (contained) coolant, designed and built in Great Britain in the 1950s through 1970s. In general one has a reactor hall where reactor heat is produced and transferred to a coolant which in turn transfers its heat to water that turns into steam through heat exchangers in a secondary loop. The hot steam is passed onto the turbo-generator hall where it produces electricity by driving turbines. Low pressure ("exhausted") steam is condensed into liquid water in a condenser in the generator hall from where it is recycled back to the reactor room to pick up heat and be changed into steam again. The condenser which liquefies exhausted steam is cooled by a final loop of cooling water which is not the same as steam cycle water. This final cooling water takes the "dump" or "waste" heat from the condenser to a cooling tower or pond.



Brief 28 Typical layout of a nuclear power plant

Cooling towers are usually the most conspicuous feature of inland power plants whether nuclear, coal, or natgas-fired. They are not unique to nuclear plants as many assume. Hot secondary cooling water coming from the turbine hall condensers is dropped from the top of a cooling tower downwards through large stacks of air-vented trays, thereby cooling this water through evaporative cooling. In some earlier power plants, water from a river was used to cool condensers and the heated water was directly returned to the river without use of a cooling tower. With larger power plants some fish were found to die due to excessive temperatures in the river near the point where condenser exhaust water was returned to the river, labeled “thermal pollution”. Today most power plants use cooling towers and/or a cooling pond before returning water to a river, sea, or ocean. Actually fish have been found to thrive and are attracted to lukewarm water from a power plant. As mentioned, steam-to-electricity conversion of a power plant is the same for a nuclear, coal-fired, or natgas-burning plant, and the above-described water-cooling operations apply to all.

Before government approval is given to build a nuclear power plant, a “hazards analysis and environmental impact report” must be prepared and submitted by the reactor construction company to the Nuclear Regulatory Commission (NRC). This report is carefully examined by the NRC and takes 1–2 years. It insures that all required safety features are incorporated in the reactor design before it is approved. After construction, NRC representatives inspect the reactor for compliance.

6.2.2 Breeders and Mixed Fuel Reactors

Because only 0.7% of natural uranium is directly fissionable U-235, and 99.3% is the less fissionable U-238 isotope, large amounts of uranium would be wasted unless the U-238 is converted to fissionable Pu-239 by the breeding reaction U-238 + n → Pu-239 + 2β. This breeding reaction in which a neutron is absorbed (but not producing fission) takes place whether intended or not in every power reactor that uses say 3% enriched U-235 (reactor-grade) uranium, since the remaining 97% U-238 is always present to absorb some neutrons. The “fissile” isotopes are U-233, U-235, Pu-239, and Pu-241, which after absorption of a thermalized neutron break apart, while the so-called “fertile” isotopes are Th-232, U-238, and (Pu-240), which after absorption of a neutron become fissionable isotopes U-233, Pu-239, and (Pu-241). The fertile isotopes in parentheses are not directly obtainable from earth-mined uranium or thorium and occur only in reactors after sequential neutron absorptions. For commercial power production, only the isotopes not in parentheses are important. Fertile isotopes can actually also fission after absorption of a fast neutron but with a much lower probability than after absorption of a thermal neutron after which they become fissile.

Uranium reserves on earth are not unlimited and would be exhausted in some 40–50 years if only U-235 with a natural abundance of 0.7 %, were to be burned up (Brief 6). However by converting U-238 to Pu-239 in breeder reactors, nuclear uranium reserves can provide energy for a period that is 144 times longer than what would be available from burning U-235 alone since the ratio U-238/U-235 = 144. Because of losses, the actual practical multiplying factor is 60–100, so that uranium reserves can provide nuclear energy for at least 2,400–3,000 years if breeder reactors are utilized. Clearly, operating breeder reactors are critical to long-term nuclear energy programs (Refs. I-31, II-18, II-23).

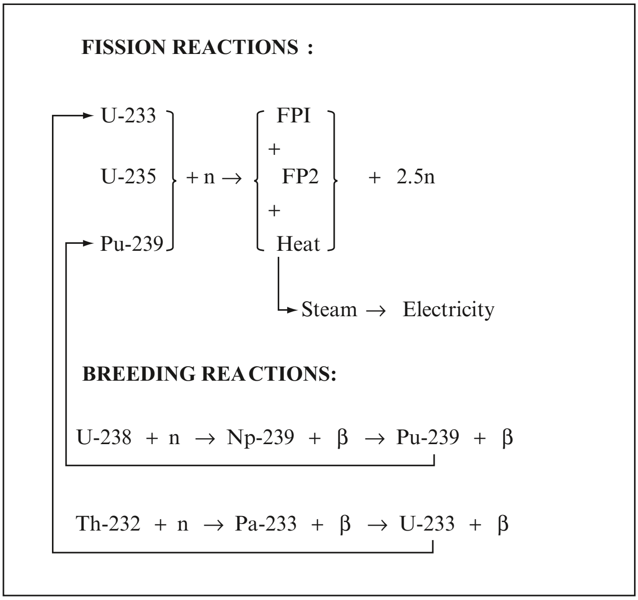
The optimum situation for a breeder-based fission energy economy occurs if one can breed one new fissionable Pu-239 atom from U-238 for each atom that is fissioned, that is a breeding ratio of 1 or more. This means that of the average 2.5 fresh neutrons produced in a U-235 or Pu-239 thermal fission event, 1 new neutron must always be subsequently absorbed by a U-238 atom to maintain breeding. Since 1 new neutron is also required to maintain the fission chain reaction, one can afford to loose only 0.5 neutron per fission for core escapes or absorptions by construction materials and coolant. To design a nuclear reactor such that only 0.5 neutron per fission is lost requires materials of construction and coolants with low neutron absorption cross-sections. For example ordinary water (H_2O) can not be used as coolant because it contains ordinary hydrogen (H). While H is the best (= lightest) moderator material for slowing down neutrons in burners, it also absorbs neutrons just a little too strongly. One must instead use coolants with very low neutron absorption cross-sections such as heavy water (D_2O), helium gas, liquid sodium (Na; melting point = 97.5°C), or bismuth (Bi; MP = 271°C).

Actually, the 2.5 neutron per fission by thermal neutrons is very marginal to allow breeding. Fortunately one can obtain three neutrons per fission for Pu-239 (bred from U-238) if the neutrons that are born with about 1 MeV of kinetic energy are not thermalized to 0.025 eV but kept energetic or "fast" above about 0.1 MeV. The best breeder reactor that can convert U-238 to Pu-239 as it burns the Pu-239 to produce heat and electricity is therefore a fast breeder. The uranium/plutonium fissioning process is then shifted from a thermal fission reaction using thermalized neutrons as occurs in today's burner or "thermal" reactors, to a fast fission reaction that employs fast (not slowed-down) neutrons to maintain the chain reaction. The core coolant can then not be H_2O but must be liquid Na or Bi. Instead of pure Na or Bi, eutectics with lower melting points like Na/K (sodium/potassium) and Bi/Pb (bismuth/lead) have been used as coolants in experimental fast breeders. Although fast fission lacks some of the convenient time delays of slowed-down thermal neutrons, the broadening of fission cross-sections at higher temperature (Doppler Effect) and mechanical design (e.g. fast neutron reflectors) can make the operation of a fast-fission breeder reactor just as safe as that of thermal-fission "burners", where a "burner" reactor is defined as having a breeding ratio less than one. In summary, control techniques, construction materials, and primary coolants are chosen differently for breeders than for burners, but generally the same operating principles apply (Refs. II-18, II-23).

Most power reactors that have been built to date are thermal U-235 burners since they are less expensive to build and operate (by about 10%) over fast breeders. Only three pilot breeder reactors are presently operational, one in France, one in Japan, and one in Russia, each generating about 300 MWe of electric power. India has a thorium breeder under construction. The USA once was in the lead and had a successful breeder reactor development program, the Experimental Breeder Reactor-II (EBR-II; Refs. I-31, II-23). However previous government administrations unwisely mothballed it, looking only at the short term. In the next 20 years, it is imperative to phase in more breeders and less burners lest we leave our children with electric energy shortages in mid-century. France, Japan, and Russia have taken the lead now and are acquiring important long-term operational experience with breeders. Most presently operating burner reactors are called Generation-I (GEN-I), while future breeders are referred to as Generation-IV (GEN-IV) reactors. Gen-II reactors are advanced burners which can tolerate higher "burn-ups" of U-235 fuel than GEN-I units and thus have longer refueling intervals of 2–3 years, while GEN-III reactors burn "mixed-oxide fuels" (MOX fuels) composed of mixtures of enriched uranium and reprocessed plutonium. GEN-III reactors do not quite achieve a breeding ration of 1 but they do approach it by burning reprocessed plutonium-239 together with enriched uranium. While GEN-I, GEN-II, and GEN-III reactors need to be refueled every 1.5–3 years, GEN-IV breeders can operate for a decade before their fuels need to be reprocessed and re-conditioned to remove some excessive neutron-poisoning fission products.

The comments about thermal burner reactor operations apply equally to fast breeder reactors. The main difference between breeders and burners is that sodium coolant replaces water. Also if one switched to saving fertile U-238 and use breeders, one must have re-processing and fuel purification in the fuel cycle. This adds extra costs when compared with present burner operations that use only "once-through" enriched uranium and discard plutonium- and U-238-rich burnt-up fuel as "waste". But the plus side of a nuclear breeder economy is millennia of energy availability and less frequent refueling of reactors, once per 10–20 years. Also most generated plutonium will be continuously burnt up and does not accumulate, so the threat for diverting plutonium for use in weapons is lessened. Strict accounting of all out-of-reactors plutonium like banks do with money, is necessary of course, but quite feasible. The world has no choice if it wants to avoid serious shortages of energy by the middle of this century. Governments should assist electric power industries with development and financing of essential plutonium reprocessing technologies, as well as with security measures against plutonium misuse. Fuel element fabrication, reprocessing and (laser) enrichment of isotopes and species should be integrated. Because plutonium handling adds extra costs and breeder reactors are newer, utilities have been slow to finance and introduce them on their own.

Besides breeding U-238 to make fissionable plutonium, there is one other element, thorium-232, that can be bred to make fissionable U-233 by neutron absorption: Th-232 + n → U-233 + 2β. Experimental reactors using thermally bred U-233 have been built and operated. This breeder cycle can be added to future U-238-breeding schemes when they become important. Estimated reserves of thorium in India, Brazil, and elsewhere, indicate that breeders using thorium can provide at least an extra 3,000 years of electric energy to the world. Brief 29 summarizes all possible nuclear fission and breeding reactions that can support neutron chain reactions, using the available uranium and thorium resources on our planet. Because U-233 is not directly available from mines and must be bred from thorium, the Th-232/U-233 power production scheme, like U-238/Pu-239 power generation, requires fuel re-processing to eliminate build-ups of "neutron poisons" (isotopes that rob neutrons and depress the neutron population causing sub-criticality). Details of neutron physics and nuclear engineering for optimizing a breeder reactor requires considerable analysis and lengthy computer calculations (Refs. II-18, II-23) which we can not enter into here. For U-238/Pu-239 breeder reactors, measurements show that it is necessary to allow mostly fast neutrons to wander around in the core rather than thermal ones, if a breeding ratio exceeding 1 is to be maintained. For the Th-232/U-233 scheme on the other hand thermal neutrons can be used. Both breeder techniques require fuel reprocessing which adds 10–20% to reactor fueling costs. Calculations of neutron utilization show that to maintain breeding ratios higher than 1 in an operating reactor, the average neutron energies born at a few MeV (see footnote 2 of Chapter 5) must stay above 0.1 MeV (no thermalization) for Pu-239 but can be thermal (0.025 eV) for U-233 (produced from Th-232) fuels. Neutron-"stealing" absorptions are too high at average thermal energies for U-235 and Pu-239 (but not for U-233) to allow breeding ratios above 1, and only a "fast" neutron spectrum above 0.1 MeV can maintain breeding and fissioning continuously.



Brief 29 Nuclear fission and breeding reactions

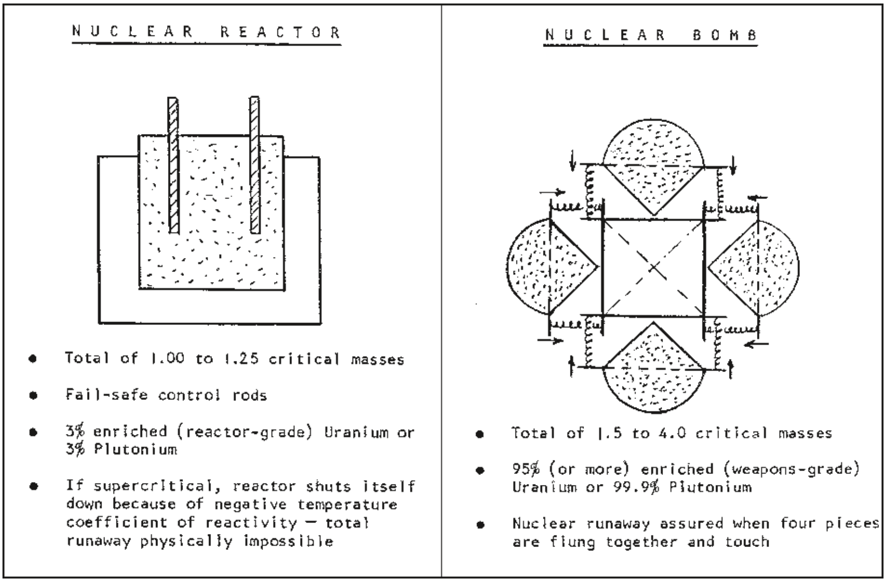
Concerns have been expressed that during reprocessing, weapons-grade Pu-239 or U-233 might become available that could be diverted for making weapons. Future reprocessing has therefore been designed to only promote optimization of reactor-burning fuel compositions that are not usable for weaponry. The latter requires very pure (95%+) Pu-239, U-233, or U-235. Some isotopes can be left in reprocessed fuel that make it unsuitable for nuclear weapons but still allow reactor operations.

While Th-232/U-233 breeders can be operated using heavy water (D_2O) as moderator and coolant (used in CANDU reactors), in the three presently operated

U-238/Pu-239 breeders, one uses liquid sodium as coolant to maintain a fast neutron spectrum. A high-temperature fast breeder reactor using helium coolant is also being investigated by General Atomics in the USA, while a sodium-cooled “traveling-wave” breeder concept is being studied by TerraPower, LLC. In the latter, neutron populations peak in a fast-breeder section but slowly move between a non-thermal fast-neutron region and a thermal-neutron region of the reactor core. This arrangement tries to combine the best of thermal and fast neutron effects on the fissioning and heat production of uranium. GE-Hitachi has designed a sodium-cooled fast reactor called the PRISM-S reactor for the coming GEN-IV era that incorporates know-how learned from the EBR-II program (Ref. II-23). Westinghouse-Toshiba is promoting a water-cooled and moderated AP-1000 GEN-III BWR (Boiling Water Reactor) reactors that can use mixed (reprocessed) as well as presently standard nuclear fuels (Brief 22), while the French company AREVA is selling GEN-III PWR (Pressurized Water Reactor) reactors worldwide that can also use present or mixed fuels (Brief 23). While most of these reactors generate on the order of 1,000 MWe of electricity, a newcomer in the field is Hyperion which is promoting a small 27 MWe (70 MW-thermal) modular breeder reactor that will run about 8–10 years without the need for refueling. It can be shipped in one piece for example to remote mines, tar-field developments, water treatment plants, sewage facilities, wind farms, and military operations to provide steady base-load electricity or heat. After 10 years it is shipped back to Hyperion’s factory for rejuvenation. Babcock and Wilcox (B&W) is also re-entering the nuclear power market with a modular reactor unit, the details of which are still sketchy. A number of companies in Japan, S. Korea, Russia, India, and China are likewise designing new GEN-III and GEN-IV reactors to accommodate the expected resurgence of worldwide nuclear power development in the next decades.

6.2.3 Nuclear Reactors Versus Nuclear Bombs

There is a mistaken popular belief that a nuclear power reactor is nothing but a controlled nuclear bomb. Nothing is farther from the truth. Although both make use of the nuclear fission process, there are major differences in their construction and modus operandi. As illustrated in Brief 28, a nuclear reactor with about 1.2 critical masses of uranium or plutonium fuel has its excess critical mass (0.2) nullified by the presence of neutron-absorbing control rods. On the other hand a nuclear bomb has no control rods and between 2 and 4 critical masses of pure nuclear fuel (no moderator), which are kept apart before it is detonated. When flung together, these mass components make a super-critical assembly, causing an uncontrolled exponentially increasing multiplication of neutrons and fissions. The sudden release of an immense amount of heat then results in a fireball and explosion. Brief 30 illustrates the difference between a nuclear power reactor and a nuclear bomb.



- Total of 1.00 to 1.25 critical masses
- Fail-safe control rods
- 3% enriched (reactor-grade) Uranium or 3% Plutonium
- If supercritical, reactor shuts itself down because of negative temperature coefficient of reactivity — total runaway physically impossible

- Total of 1.5 to 4.0 critical masses
- 95% (or more) enriched (weapons-grade) Uranium or 99.9% Plutonium
- Nuclear runaway assured when four pieces are flung together and touch

Brief 30 Differences between a nuclear reactor and a nuclear bomb

Steadily running nuclear reactors, whether thermal or epi-thermal, employ neutrons which have a "slowing-down time", that facilitates reactor control. Even in fast breeder reactors fast-neutron reflectors impart delays in neutron regeneration lifetimes, which aid reactor control implementation. In addition there is a "delayed neutron emission" phenomenon that assists in the control of all reactors (thermal, epithermal, and fast) which provides added safety against any run-away neutron multiplications. The design of electromechanical control rod drives is such that rods can only be withdrawn slowly from the reactor core and only one after the other. This prevents sudden excursions and allows alarms to be set off in time to interfere with undesirable rod movements and/or to induce a scram. Even in the event someone would pull all control rods fully out of the core in an act of sabotage, the initial excess heat generated by such a reactivity increase causes a decrease in the coolant/moderator inventory because of the coolant's decrease in density with increasing temperature. Less moderator means less neutron slow-downs which makes the reactor sub-critical. In addition, fission rates decrease at higher temperatures and thermal expansion of core and reflector increases neutron escapes. The result is that the reactor ceases to continue the neutron chain reaction. This effect is referred to as a "negative temperature coefficient of reactivity". All modern gas- or water-cooled and -moderated power reactors exhibit this feature, but Chernobyl did not.

After shutting itself down, a reactor core is sub-critical but can still produce decay heat for a while which is removed by continued coolant flow. Should this normal flow be interrupted, nearly all reactors have an "emergency core-cooling system" (ECCS) that kicks in to cool the core down. If both normal and ECCS coolant flows fail to perform, the core can still get overheated without uranium fission and melt itself down due to after-heat from nuclear decay. While some steam will be generated and some core components may melt or evaporate, the containment vessel, a thick steel and concrete pressure vessel that surrounds the reactor, is designed to retain all vapors and molten materials if this happens. No explosion in the sense of a bomb blast can ever occur, even in a meltdown.

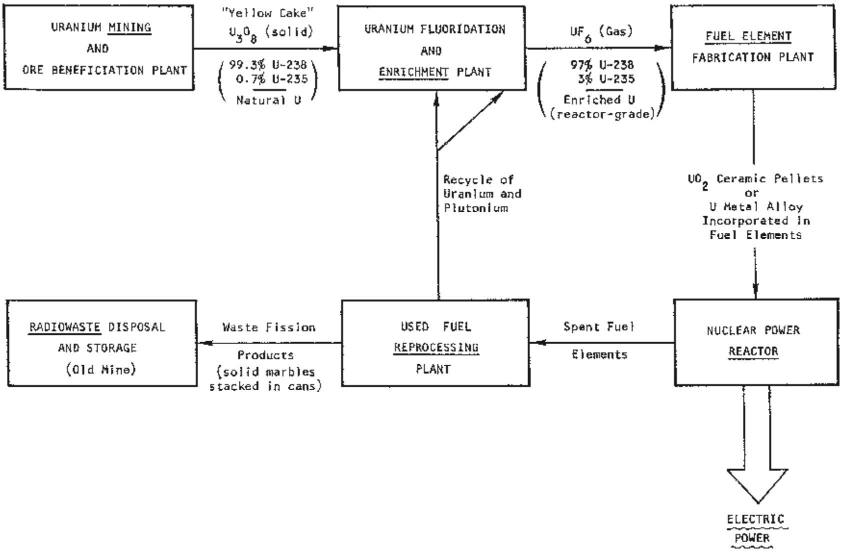
Some time ago, alarmists in the news media reported that any freshman college student could design and build a nuclear bomb. These stories are difficult to reconcile with the fact that countries who actually have built and tested a nuclear weapon, like the USA, Russia, Great Britain, France, China, India, Pakistan, Israel, and South-Africa, spent three or more years and billions of dollars to get to that point. Sketching out a principle or a design on a piece of paper is not quite the same as building, procuring, and constructing equipment necessary for testing or use of a nuclear weapon. The same can be said about building a rocket to fly to the moon, which any college student can outline in pencil but not carry out.

The uranium fuel used in nuclear power reactors usually has a U-235 enrichment of about 3%, whereas for nuclear bombs one needs U-235 enrichments of 96% or better if one wants an effective weapon. Thus there is a big difference in reactor-grade fissionable fuel and weapons-grade material. To increase the enrichment of reactor-grade fuel to weapons-grade fuel would require an expensive billion-dollar uranium enrichment plant which is discussed in Section 8.2. Only the countries mentioned above have developed stockpiles of nuclear weapons after spending many years and billions of dollars on them. However under the global NPT (Non-Proliferation Treaty) accords the number of nuclear weapons must be gradually reduced and ultimately totally banned. Further discussions about nuclear-weapons states and the NPT are given in Section 8.3 (see also Ref. II-22).

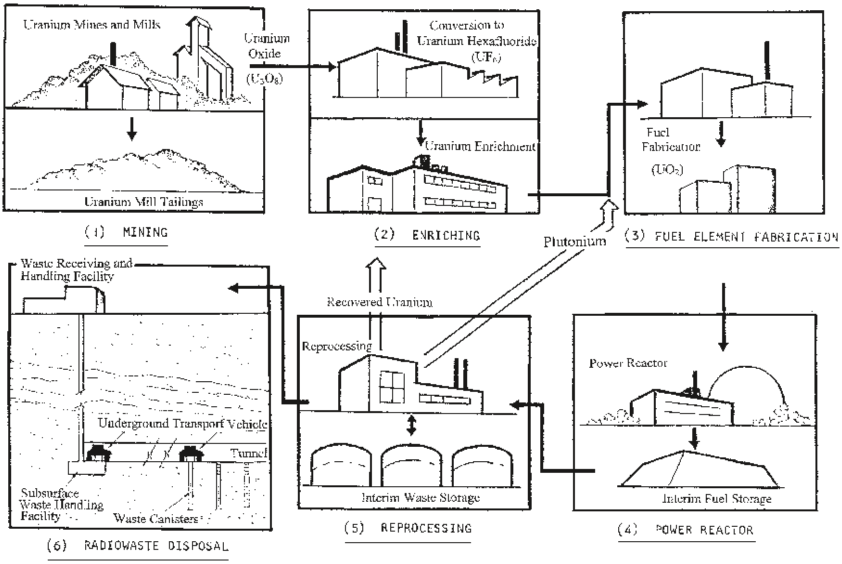
It is fortunate that building nuclear weapons is enormously expensive and virtually impossible to carry out for a small group of terrorists. Even if they stole weapons-grade Uranium-235 or plutonium from an enrichment or reprocessing plant (Section 8.3), it would cost a terrorist gang many hundreds of millions of dollars of sophisticated equipment and a sizable work force that included some highly educated scientists to construct a useful nuclear bomb. Such an activity could hardly escape the attention of an effective global intelligence agency. It would be simpler for terrorists to steal an already manufactured nuclear weapon (still very difficult – Chapter 8) or use chemical or biological weapons to achieve their nefarious goals. Besides fuel purity (absence of neutron-multiplication-delaying species) it takes a lot more physics and engineering know-how to cause most pure U-235 or Pu-239 to fission in sub-microseconds than just throwing two near-critical masses of U-235 or Pu-239 together (Ref. II-22).

6.3 The Uranium Fuel Cycle and Its Environmental Impact

Uranium mining, enrichment, fuel fabrication, reprocessing, and radio-waste disposal make up the elements of what is called the “Uranium Fuel Cycle”, which we shall briefly examine in what follows. Briefs 31 and 32 illustrate the sequence of processes that uranium must undergo before it is ready as a reactor fuel. Since the beginning of the atomic age which started during WW-II, great care was taken to safeguard and insure the accountability of all processed uranium. Strict security, environmental caution, and safety measures were applied early in all phases of mining, refining, and handling of uranium. Security and safety disciplines instituted since WW-II, far exceed those in other industries such as coal mining and oil refining. That is, security, safety, and environmental awareness were promoted early on because of the duplicity of uranium's applications, namely nuclear weapons and beneficial controllable electric power generation.



Brief 31 Schematic of the uranium fuel cycle



Brief 32 Illustration of the uranium fuel cycle

Uranium ore has been found in may parts of the world such as Colorado, USA, Canada's Northwest Territories, South-Africa, Congo, Russia, and Australia. After digging it out of the earth, often on the surface, uranium-bearing ore is crushed and leached with nitric acid in a "beneficiation" process which is usually close to the mine. The final product yields a mixture of uranium oxides called "yellow cake" with chemical composition U_3O_8. The U_3O_8 yellow cake contains natural uranium with 99.3% of U-238 and 0.7% of U-235 isotopes.

As mentioned, for a water-cooled nuclear reactor, it is necessary to increase the U-235 isotope concentration in uranium from 0.7% to about 3.5%. Research reactors generally use fuels with 20% U-235 but for production of some special medical isotopes higher neutron fluxes are required and higher concentrations (~85%) of U-235 are needed. For nuclear weapons a concentration of 95% U-235 or better is necessary. Special operations are therefore necessary to increase the natural concentration of fissionable U-235 from 0.7% to higher levels. This operation, called uranium "enrichment" is discussed in Section 6.3.1. The uranium enrichment process usually requires gaseous uranium hexafluoride (UF_6) as feed which must first be prepared from the U_3O_8 yellow cake by chemical conversion reactions. Thus as shown in Briefs 31 and 32, prior to entering an enrichment plant, U_3O_8 yellow cake is fed to a chemical conversion plant which produces gaseous UF_6. The UF_6 is then shipped to the enrichment plant in special autoclaves as a solid sublimate. At this point the uranium is still all natural (as found in nature) and only mildly radioactive.

After the U-235 isotope in UF_6 is enriched, it is sent from the enrichment facility to a fuel element fabricator which converts it back to solid UO_2 pellets, metallic uranium, or other uranium compound. Fuel elements incorporate the enriched uranium oxide (or other compound) as pellets that fill zirconium tubes or they use metal-clad uranium plates. One fuel element is generally composed of a bundle of tubes or a number of plates between which coolant can flow to carry off fission heat and to perform its function as a neutron thermalizing moderator (Brief 26). Fuel elements are typically 2–4 m (6–12 ft) long with a 10 × 10 to 20 × 20 cm square cross-section. After shipment to a reactor, fuel elements are inserted and anchored to top and bottom "grid plates" in a cylinder-like array which constitutes the reactor core. For a 1,000 MWe PWR nuclear reactor, the startup mass is approximately 80 t of 3.5% enriched uranium of which approximately 20 t is refueled every 1.5 years.

Following 2 years of operation, the fissionable U-235 in a fuel element is exhausted and the fuel element is removed from the reactor core and hung in a swimming-pool for a few months to allow dissipation of initially high levels of decay heat and gamma radiation. Used fuel elements are next shipped to a reprocessing plant in shielded crash-proof casks, to separate fission products from reusable uranium. It is important here to fully understand the difference between "spent" or "used" fuel, "fissium", and true nuclear "waste". After 1.5–2 years in an operating reactor, used fuel elements contain both products of fission (fissium) as well as unused fertile and fissile uranium, plutonium, or thorium. These need to be separated from fissium during a so-called "reprocessing" operation every 1.5–2 years, before they can be recycled and used for further consumption in a nuclear reactor. The unused fertile and fissile uranic species in a spent fuel element are quite valuable and in present burner reactors constitute over 90% of un-fissioned uranium material. They can be "re-conditioned" as nuclear fuel for a fast breeder reactor and recycled many times after removal of neutron-poisoning fission products that built up which inhibit a chain reaction. A starting amount of 3% U-235-enriched uranium fuel can empower a nuclear reactor 60–100 times longer before all fuel is converted into fissium, if operated in the fast breeder mode that converts U-238 into plutonium. During the 1980s and 1990s, opponents of nuclear power who wanted to see its demise tried to limit the use of uranium to once-through reactor operations and tried to have fuel reprocessing prohibited, claiming it was too expensive and risky, and would facilitate weapons proliferation because of the presence of plutonium. They infiltrated the US government, pushing through laws and regulations that labeled all once-through "spent" reactor fuel as "waste" which was to be discarded and stored in underground repositories. Such action would limit the use of nuclear power from the world's uranium resources to 40 years instead 3,000 years and would fill the Yucca mountain repository in about 50 years instead of 500 years with tons of still useable uranium and plutonium fuel instead of pure fissium or radio-waste.

The latest maneuver by anti-nuclear zealots in the US is to claim that the transport of casks with spent fuel elements through the USA poses great risks to the population. These are just plain fabrications. Shipments by truck or railroad can be carried out in an entirely safe manner and constitutes less of a hazard than the routine shipments of some hazardous chemicals. Used-fuel casks have been designed and tested to stay intact in a head-on collision between a cask-carrying truck and a full-speed train. Even in case they are penetrated by an armor-piercing mortar, little radioactive material could escape since fission products and unconsumed fuels are embedded in solid material. A statistical analysis of nuclear waste shipments from all one hundred US nuclear reactors taken to the Yucca repository in Nevada, predicts maximally two deaths per century attributable to radioactivity in worst-case cask transport accidents. This risk is 50,000 times less than the estimated deaths caused by coal transports. Radioactive fission products (fissium) can not undergo further fission; only enriched uranium or reprocessed fuel could if placed in a reactor of critical size. Fissium itself can only produce some heat and gamma radiation from slow nuclear decay of some isotopes.

In a used-fuel reprocessing plant, the canning or cladding on fuel elements and fuel tubes is removed by cutting machines and the fuel is dissolved in nitric acid. The uranium, thorium, and plutonium fractions are then separated from the fission product fractions by chemical separation techniques and subsequently recycled for re-use (Briefs 31 and 32; Ref. II-22). Some special fission products are also removed for use in nuclear medicine and for isotope power generators used on space vehicles. The remaining unusable fission products are true radioactive waste, abbreviated “radio-waste”, which are concentrated and vitrified into solid marbles that are placed in waste repository canisters. These canisters are finally transferred to underground vaults in a nuclear waste repository such as Yucca Mountain. Next we review uranium enrichment, reprocessing, and radio-waste disposal operations in more detail.

6.3.1 Uranium Enrichment

Although ordinary hydrogen (H) present in water (H_2O) is the best (= lightest) thermalizing agent to slow down neutrons, it unfortunately also absorbs a neutron every now and then instead of decelerating it. This happens to such an extent that a reactor using ordinary H_2O as moderator (= neutron thermalizer) as well as a coolant, must employ uranium that is enriched from 0.7% (natural) to 3% in U-235 to allow neutron chain reactions. Only with the next best neutron thermalizer, deuterium ($D = {}^2H$) which is present in heavy water (D_2O), is it possible to use natural uranium with 0.7% U-235 to operate a reactor with D_2O as moderator and coolant. Very pure graphite (C) as moderator and helium gas as coolant can also operate a reactor with natural 0.7% uranium. Since ordinary water is universally available and abundant as moderator and coolant, most power reactors today use 3–4% U-235 enriched uranium (“reactor-grade” uranium) obtained from the old WW-II diffusion plants, or from more economic centrifuge enrichment facilities built after WW-II.

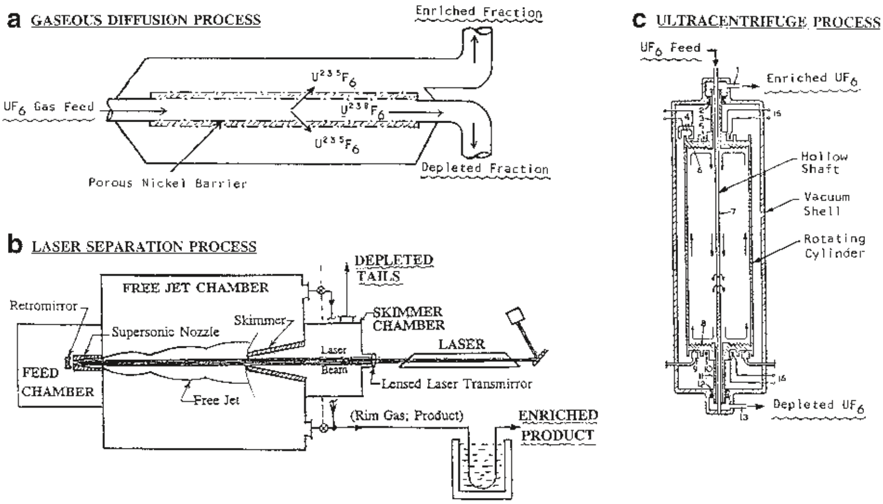
As mentioned, for nuclear weapons one needs “weapons-grade” 95% or higher U-235-enriched uranium, so during WW-II when the United States feared that Hitler might develop a nuclear fission weapon before it did, a crash program was launched to build a uranium isotope separation plant of a magnitude and cost unprecedented in history. Under the command of army general Leslie Groves, a gaseous diffusion enrichment plant and an electromagnetic separation plant were designed and built in parallel. They were almost 100 times larger and more costly than any other chemical plant ever built before anywhere in the world, and for which only scanty laboratory process data were available. Because one was not sure which process, electromagnetic or diffusion, would give the quickest results, one plant of each kind was designed and constructed simultaneously. There was less than one week’s worth of natural uranium feed available for processing when construction of these two plants was started and many components were invented and researched along the way.

The electromagnetic separation plant at Oak Ridge, Tennessee was put together between February 1943 and November 1943 and immediately started enriching small quantities of uranium. It produced kilograms of highly enriched uranium used in the first two exploded US atomic bombs. The third and last WW-II bomb used plutonium extracted from graphite-moderated reactors hurriedly built at Hanford after Fermi's success with the experimental reactor pile in Chicago in December 1942. The Oak Ridge diffusion (DIF) plant took a little over 2 years to complete but was found more economic for large-scale enrichments than the high-vacuum electromagnetic "calutron" method. In normal (non-war) times it would have taken 10 years to design and build these two enrichment plants. After WW-II ended in 1945, the first power reactors obtained their 3% enriched uranium fuel from the diffusion plant while the calutrons were (and still are) diverted to separate small quantities of medical and research isotopes.

The WW-II construction of the Oak Ridge uranium enrichment plants in Tennessee combined American ingenuity, organizational skill, brains, and a unity of purpose which will probably never be equaled again in US history. It remains as a unique once-in-a-hundred-years engineering achievement. Otto Hahn and Werner Heisenberg, who had worked on nuclear fission in Hitler's Germany and who were captured and taken to England in late 1944 for questioning, would at first not believe the Hiroshima and Nagasaki nuclear bomb drops in August 1945 when informed of these events during their confinement. In their estimation it was impossible for any nation to have separated enough of the low-abundance U-235 isotope for a bomb within a period of 3–4 years.

In the diffusion method (Brief 33a), gaseous UF_6 is pumped through long pipes with porous walls possessing microscopic holes through which slightly lighter $^{235}UF_6$ can slip a little faster than slightly heavier $^{238}UF_6$. Thus the gas coming through the porous walls is a fraction more enriched in $^{235}UF_6$. By repeated recycling of the UF_6 gas through compressors in hundreds of stages, the U-235 fraction is gradually increased, the number of stages being determined by the desired final U-235 enrichment. In the electromagnetic or "calutron" isotope separation method, uranium atoms are ionized and when passing through an electromagnetic field, heavier ions (U-238) follow a slightly different path than lighter (U-235) ions so they can be focussed at two different collection points. However this only works at very low pressures (a millionth of an atmosphere) and hence calutron throughputs are very low. They also require a lot more energy and cost per separated U-235 atom than in the diffusion case.

Following the WW-II development of the gaseous diffusion process (DIF) for uranium enrichment, two other competitive methods have come to the fore, namely ultracentrifuge (UCF) enrichment and laser isotope separation (LIS). Brief 33 sketches these isotope separation schemes which all use gaseous uranium hexafluoride. The latest LIS scheme is still in the development stage, but promises to reduce present uranium enrichment costs by a factor of 3. The fully developed UCF method is currently favored over the DIF scheme since it consumes much less energy. Today Europe, Russia, and China all have operating UCF plants, while the US is replacing its old DIF plants from WW-II with a UCF enrichment facility. Commercial enrichment companies providing reactor-grade uranium for power plants are AREVA (France), URENCO (England, Germany, Netherlands), and USEC (USA). Enrichment services for power reactors are also available in Russia, China, India, and Japan.



Brief 33 Isotope enrichment schemes for gaseous uranium hexafluoride. (**a**) Gaseous diffusion process, (**b**) Laser separation process, (**c**) Ultracentrifuge process

In the UCF technique, gaseous UF_6 is swirled around at very high speeds, causing the heavier $^{238}\mathrm{UF}_6$ to accumulate closer to the outside wall of the centrifuge and circulating downwards, while lighter $^{235}\mathrm{UF}_6$ concentrates more inwards toward the center of the rotating cylinder and circulates upwards. By continuous removal of the upper and lower gas streams and by recycling through many centrifuge stages, enrichment of $^{235}\mathrm{UF}_6$ is achieved.

In molecular laser isotope separation (MLIS), a supersonic free jet of UF_6 mixed with a carrier gas such as xenon, is coaxially or transversely illuminated by an infrared laser beam as it expands from a nozzle into a low-pressure chamber. Gaseous $^{235}\mathrm{UF}_6$ in the jet is selectively excited by tuned laser photons, the selectivity being possible because of a shift between the absorption spectra of $^{235}\mathrm{UF}_6$ and $^{238}\mathrm{UF}_6$. Laser excitation of $^{235}\mathrm{UF}_6$ suppresses it from forming dimers downstream as the jet cools down, and also promotes its migration out of the jet core. Non-excited $^{238}\mathrm{UF}_6$ molecules on the other hand form UF_6:Xe dimers with xenon atoms as the jet cools itself by supersonic adiabatic expansion. Since the dimers carrying mostly U-238 stay closer to the central core of the jet flow, while $^{235}\mathrm{UF}_6$ monomers fly out of the jet, the two streams can be separated by intercept of the free jet flow with a skimmer that sucks up the core of the jet but excludes the rim gases, which are pumped out separately.

The DIF technique requires hundreds of stages to enrich 0.7% U-235-enriched UF_6 to 3%, while a UCF plant can do this in tens of steps and MLIS in two to three stages. Brief 33 illustrates DIF, UCF, and MLIS unit separators. Besides a desirable high enrichment factor per stage which determines the number of stages, high throughput factors are also important. In the DIF enrichment process, operations are carried out at near-atmospheric pressures resulting in high throughputs, while in UCF and MLIS, gas pressures are less than a hundredth of an atmosphere. However the flow through an MLIS separator is supersonic, that is 1,000 × the subsonic flow speeds in DIF and UCF units. For UCF enrichment, the throughput per separator is much less than in DIF operations, so more UCF separator units must be put in parallel for a given total throughput. In general therefore, the capital cost of a UCF plant is higher or comparable to that of a DIF plant, but operating costs which comprises mostly electricity consumption, are much less. For MLIS, throughputs depend on nozzle throat dimensions and pumping capacities. Clearly, enrichment factors, operating pressures, energy consumption, and costs of capital equipment and their maintenance are among the main factors determining the economics of an enrichment technique.

Besides the currently explored condensation-repression MLIS technique, another LIS scheme called AVLIS (Atomic Vapor LIS) was investigated in the 1970s, first by the AVCO Research Labs in Cambridge, Massachusetts, and later at the Lawrence Livermore Laboratory (LLL) in California. AVLIS laser-irradiates and processes hot corrosive uranium metal vapor instead of cold molecular UF_6 used in MLIS schemes. It requires an electron beam to evaporate metallic uranium in a high-temperature vacuum furnace. Three rapid sequential laser pulses selectively excite and ionize U-235 in the uranium vapor as it is vaporized from a molten uranium puddle in a crucible in the vacuum chamber. The vapor moves upwards past oppositely charged vertically placed collection plates, which deflect and collect the ionized U-235, while neutral U-238 passes on and is condensed/collected on the ceiling of the irradiation/vacuum chamber. While operation of a pilot unit in the 1980s successfully demonstrated the technical feasibility of AVLIS, it has now been moth-balled in favor of a more economic and more reliable UCF plant being readied by USEC for 2010 to replace its aging DIF plants. USEC is an acronym for United States Enrichment Corporation, the successor of the former US AEC/DOE uranium enrichment operations.

6.3.2 Fuel Re-processing

In a spent-fuel reprocessing plant, fission products are separated from the remaining uranium and from neutron-bred plutonium. Great precautions are taken in such plants to prevent accumulated plutonium from falling into the wrong hands. Purified separated plutonium, like highly enriched uranium, can be used for making nuclear weapons. Opponents of nuclear energy have used this argument to advocate that spent nuclear fuel not be reprocessed for fear that terrorist might break into a reprocessing plant and divert purified plutonium for making bombs. However without reprocessing, nuclear power generation would in effect die out in 50 years after all U-235 is burnt up, which is the real objective of the anti-nuclear lobby. The original plutonium present in a spent-fuel element has some isotopic components that make it unsuitable for use in thermal "burner" reactors, else newly formed plutonium could be directly burnt up in the latter. Fast breeder reactors can utilize plutonium once it is separated from neutron-absorbing fission products. As mentioned, by converting U-238 in Pu-239-burning fast breeder reactors, the generation of nuclear power can be extended to 3,000 years instead of 50 years. While fuel for effective nuclear weapons requires high-purity Pu-239 and absence of strong fast-neutron-absorbing and delayed-neutron-emitting isotopes, fast reactor fuels can actually profit from some of those isotopes. Thus complete separation of pure Pu-239 is not needed in the fast breeder fuel cycle. That is during extraction and re-constitution of uranic fuels for fast breeder reactors in a reprocessing plant it is possible to avoid having ultra-pure Pu-239. This feature should alleviate concerns that weapons-grade plutonium might be stolen or diverted from reprocessing facilities. Of course "dirty" plutonium might still be stolen but if the thieves wanted to use it for making an effective weapon, they would need to build a very expensive plutonium purification plant first. One could detonate dirty Pu-239 or U-235 by throwing two or more near-critical masses together, but the resulting explosion would not cause the same horrific blast obtainable with pure materials. Only a small percentage of the nuclear fuel would fission if neutrons are not present throughout the material within nanoseconds. Considering all the difficulties of stealing and weaponizing Pu-239, the transparent demands by anti-nuclear zealots that reprocessing be banned is absurd. If acted upon, it would only hinder and delay urgently needed expansion of nuclear power to cope with serious energy shortages in the near future.

When spent fuel elements enter a reprocessing plant, they are first cut open in a special room by remotely operated mechanical "slaves" and manipulator arms. The contents are dropped in nitric acid solution which forms various chemical salt solutions with the uranium, plutonium, and lower-mass fission products such as molybdenum, promethium, cerium, etc. The salts containing uranium and plutonium and some transuranics are then removed first from the mixture by chemical exchange with Tributyl Phosphate (TBP) solvent, fractionation, or other chemical extraction process. Valuable uranium, plutonium and some transuranics are finally retrieved for recycling into reactor fuels (Ref. II-17).

The remaining salt solutions containing fission products (called "fissium") are treated further to retrieve valuable radioisotopes used in nuclear medicine and other applications. After this extraction, the final mixture of fission products that is left is true radioactive "waste" (radio-waste) and has no commercial value. It is mixed with glass, heated and vitrified into solid glass-like marbles. These marbles are then dropped into canisters which are shipped to a radio-waste repository such as Yucca Mountain.

Based on the fact that 1 g of U-235 when fissioned releases ~100 MW-days of heat energy, the yearly amount of fissium produced by a typical 1,000 MWe nuclear power reactor is about 400 kg (880 lb). After extraction of usable radioisotopes and vitrification, this amount of solid radio-waste can be hauled away in one railroad car or truck. In comparison, 300,000 kg (660,000 lb) of ashes and cinders are produced annually by a coal-fired power plant of 1,000 MWe output. In addition it releases 11 million tons (22 billion lb) of globe-warming CO_2 gas into the atmosphere as well as 55 million kg (120 million lb) of SO_x gases and 27 million kg (59 million lb) of NO_x gases together with 240 kg (530 lb) of mercury and 409 kg (900 lb) of uranium as entrained toxic materials. In contrast, no gases are emitted into the atmosphere by nuclear reactors. They are absolutely non-polluting and should be applauded by environmentalists for this feature. Summarizing, fission products from nuclear reactors are: (a) solid; (b) very modest in quantity; (c) valuable (in part) for nuclear medicine and biotechnology research; and (d) residual non-usable radio-waste can be easily and safely contained for disposal. In contrast aside from globe-warming CO_2 gas, the waste products from oil-, natgas-, and coal-burning power plants are

(a) voluminous; (b) gas-laden particulate matter; (c) loaded with entrained toxic elements and; (d) costly to separate from the main gaseous CO_2 exhaust.

As more breeder reactors will take over from burners, two future scenarios are possible for fuel reprocessing operations. In one US-DOE proposal called the GNEP (Global Nuclear Energy Partnership) initiative, a few internationally financed and operated reprocessing facilities would be built at a dozen or so locations around the world where any NPT country can have its nuclear fuel reprocessed and can obtain fissionable fuels for its nuclear power plants. This concept would minimize the possibility that some country might decide to re-direct a reprocessing facility on its territory which was built for serving civilian nuclear power generation, into making weapons-grade fuel for its military instead. International GNEP facilities could incorporate fuel element fabrication and (laser) isotope enrichment as well. Reprocessed re-conditioned fuel could then provide fresh new fuel elements for delivery to any nuclear fast-breeder or burner power plant in the world to replace used fuel when needed. Inclusion of isotope and species enrichments at international GNEP fuel fabrication sites allows optimization of reactor fuel compositions. More than half of all countries in the UN have already signed on for GNEP, but within the USA the usual anti-nuclear crowds disapprove and some nuclear safeguards specialists appear to dislike GNEP because they had not thought of it themselves. Kazakhstan, which has uranium mines and harbored nuclear testing grounds and enrichment operations when it was part of the former Soviet Union, has offered to be host to a future integrated GNEP facility in the middle-East. Operations at international GNEP fuel facilities would be monitored by the IAEA (International Atomic Energy Agency; Section 8.3) to insure that reprocessed fuels go only directly into breeder reactor fuel elements and are not suitable for use in weaponry. After extraction of useful radioisotopes from fissium which was separated from re-usable fissile and fertile uranics, left-over radioactive waste at a GNEP reprocessing plant would be shipped and stored at a few international repositories where it would decay to harmless radiation levels in a few decades.

The shipments of used and fresh nuclear fuel elements to and from international processing facilities can be done quite safely using thoroughly tested casks that can withstand transportation crashes. Simulated collisions of a cask-carrying truck with a fast train and 100 ft drop-tests of casks show that such fuel casks can be built without expulsion of a fuel element in an accident. Reactor fuel re-loading at a 1,000 MWe (= 3,000 MW heat) plant once every year requires only ten or so trucks to deliver casks with fresh fuel assemblies. The same number can return with spent-fuel assemblies. The much higher packing density of nuclear energy over that of coal or fossil fuels shows its advantage again here. The 3,000 MW-years (= 95 million GJ) of heat energy packed in the nuclei of about 120 kg (260 lb) of U-235 in a 1,000 MWe plant occupies a volume of only 65 L (17 gal). This compares with 95 million GJ of chemical heat energy contained in 4.2 million tons of coal, requiring some 42,000 railroad cars for its transport to fuel a 1,000 MWe coal plant for 1 year. The 120 kg of 3.5% U-235 burnt in a reactor, giving 3,000 MW-years of thermal energy, is accompanied by U-238 and by structural materials that must hold a fuel element together (Brief 26). This makes the total weight of the fuel-elements in the reactor core about 200 times larger. Typically the total fabricated weight of fuel elements capable of providing

95 million GJ in a reactor is about 24,000 kg. Because of void space in fuel elements to let coolant pass through and to vent noble gases, the volume occupied by the fuel elements in a 1,000 MWe reactor is about 24,000 L (= 24 m^3). This weight and volume could be transported by two trucks, but after shielding and packing into casks, and for reasons of safety and security, ten trucks might be used for fuel cask transportation. In conclusion, the annual transport of fresh and spent casketed fuel elements for a 1,000 MWe nuclear reactor can be carried out by ten or so trucks, compared to 42,000 railroad cars of coal to fuel a coal-fired 1,000 MWe power plant. Clearly fuel weights and volumes in reprocessing are quite small and manageable, and much less than the general public has been made to believe from alarmist newspaper articles.

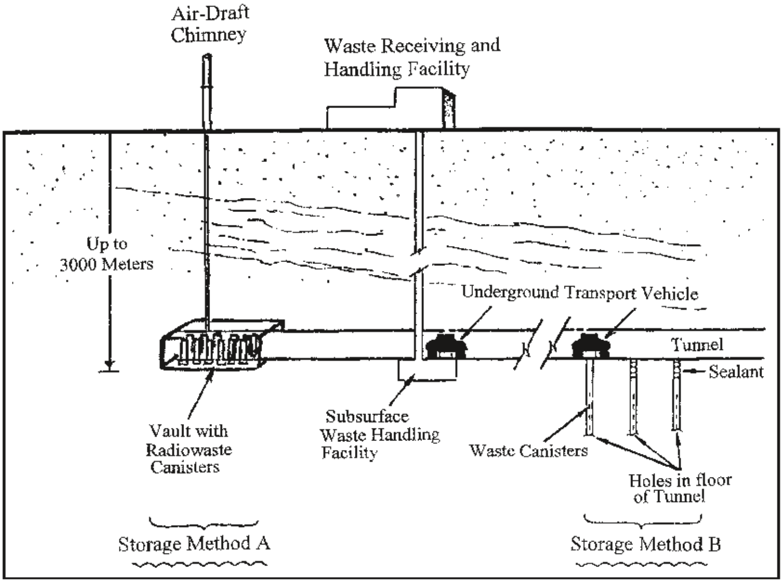
In another reprocessing scenario, each reactor or group of reactors would reprocess its own used fuel on its own reactor site and also include on-site fuel element fabrication. This approach was carried out in the development of the US EBR-II breeder reactor program (also called the IFR = Integral Fast Reactor), where fuel fabrication, fuel reprocessing, and IFR operations were carried out on one site in Idaho. With smaller laser enrichment system footprints it would also be feasible to carry out any needed isotope and species enrichments on-site as well. All fabrication, reprocessing, and enrichment operations as well as multi-giga-watt nuclear power generation could be carried out on about one hundred acres (40 ha), thereby eliminating transport of fresh and used fuel elements to and from reactor sites. In the US, the years-long legal proceedings to obtain approval for operating a nuclear facility at a particular site would then also be minimized. On the other hand compared to the international GNEP concept, this approach would lose the cost advantage of economies of scale. It would also be more costly for the IAEA to monitor 2,000 sites worldwide each with combined reprocessing, fuel fabrication, enrichment, and power generation activities, instead of only a dozen sites harboring the first three of these proliferation-sensitive operations on a larger scale.

6.3.3 Final Disposal of Radio-Waste

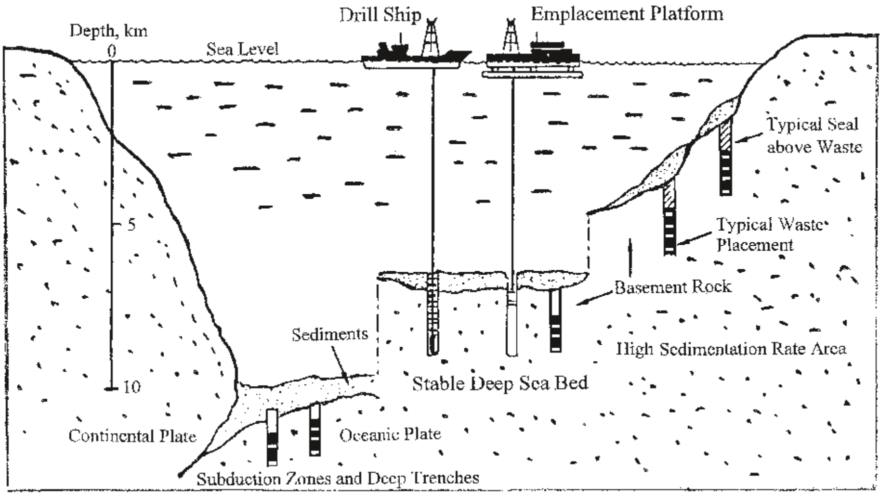
As mentioned, useless fission-product radio-waste can be vitrified into solid marbles and placed in steel canisters for final disposal. The canisters may typically be 20 cm (8 in.) in diameter and 2–3 m (6–9 ft) long. Canister walls are typically made of 6.5 mm (1/4 in.) thick nickel-alloy steel. Only evanescent gamma and x-ray radiation (no particles) could escape from such a canister. Each canister might originally pack about three million curies of radioactivity which generates about 2 kW of decay heat, equivalent to the power consumed by 20 light-bulbs. After shipment to a nuclear waste repository site the canisters are taken to underground vaults as shown in Brief 34. They are cooled there by circulation of filtered air drawn through chimneys and air ducts. Alternatively the canisters can be set into holes in the vault and be cooled by thermal conduction to the soil.

Previous studies of radio-waste disposal have included canister storage in 10-m (30-foot) deep water basins with water providing shielding and cooling by natural convection. Placement of radio-waste canisters on a basaltic deep-ocean floor was also considered (Brief 34). However more easily accessed land-based underground storage in abandoned mines or similar excavations are favored now. Use of gamma radiation from radio-waste canisters may become of interest for food preservation and sterilization of medical supplies (this is being researched) and warm air from decay heat cooling might be used for hot-house plant cultivations. Under a breeder reactor regime, it is estimated that three abandoned mines, after conversion into vaults, can handle the radio-waste from 900 nuclear power plants for a 1,000 years before they are filled.

a SALT-BED MINE RADIOWASTE STORAGE



b SEA-BED UNDERWATER RADIOWASTE STORAGE



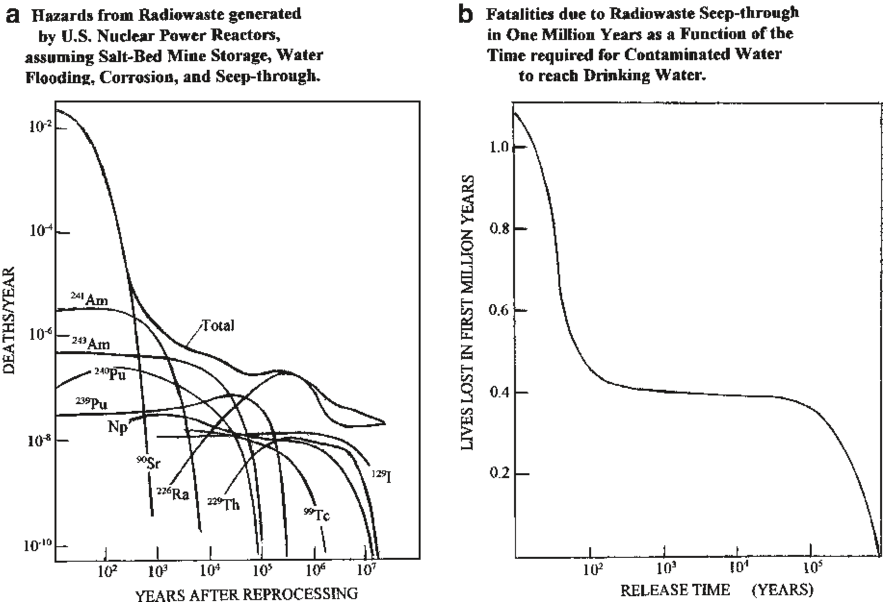
Brief 34 Radiowaste disposal schemes. (**a**) Salt-bed-mine radio waste storage, (**b**) Underwater sea-bed radio-waste storage

Suggestions to send radio-waste into space and into the sun have been made, but such proposed schemes are very costly and totally unnecessary. Fears that man-made vaults filled with radio-waste constitute a long-term hazard for future generations are more emotional than real, if one considers that uranium and other natural radioactive ore bodies already exist on earth and have been there for millions of years. They are no less of a hazard to man than artificial ones. The amount of radio-waste produced is much less than many man-made hazardous materials that are routinely used. For example the annual amount of arsenic trioxide imported into the US for use in agriculture, is ten times larger than the annual reactor radio-waste that is produced by all US reactors. Arsenic trioxide is more toxic than decaying radio-waste and is stored above ground as opposed to underground radio-waste storage.

As time passes, radioactive waste products decay to stable non-radioactive elements, the shorter-lived species first and longer-lived ones last. Long-lived plutonium is a very valuable fuel and is removed as completely as practical from spent-fuel material in a processing plant. However a small amount, less than one half percent, may remain as a trace in the final fission product radio-waste and will get stored with it. Anti-nuclear critics state that because of the 24,000 year half-life of plutonium present in trace amounts in radio-waste, a 500,000 year biological hazard is created. This statement sounds ominous but lacks substance when one considers the fact thousands of tons of biologically hazardous materials like cyanides, nitrosamines, mercury, arsenic trioxide, etc. have been and will be on earth for ever since their lifetimes are infinite. Yet we manage to handle and live with such materials even without having them locked away in deep underground vaults.

Critics also continue to bring up the fact that a liquid radio-waste storage tank hurriedly constructed during WW-II on the nuclear complex at Hanford in Washington State leaked and had contaminated the surrounding soil. The successful decontamination of this old WW-II storage tank required some effort, but the degree of soil penetration was actually less than what was calculated in some hazards analysis reports. In the first few years of the nuclear age, the amount of radio-waste produced by nuclear facilities was small so one used the principle of infinite dilution instead of concentration to get rid of unwanted radioactive wastes. The dumping of small amounts of radioactive liquid solutions in the ocean which is already naturally radioactive to a small extent, causes rapid dispersion and disappearance of any trace of enhanced radioactivity within tens of minutes. It is like adding a few grains of sand to the Sahara desert. The early practice was to dilute and dissolve weakly radioactive wastes into liquid solutions, and to store them in large tanks for later disposal at sea. With power reactors coming on line, the handling of larger quantities of more highly radioactive waste was switched from one extreme to another: concentration instead of dilution. Interim storage of radioactive liquid solutions still occurs at some processing plants to allow removal of useful medical radioisotopes and decay of short-lived species, before concentration and vitrification of useless longer-life radio-waste is undertaken.

Engineers see absolutely no difficulty with the secure storage of radio-wastes underground in deep mines, in salt-bed formations, or similar excavations. Salt-beds are known to be geologically stable for millions of years. Fears have been expressed by critics that water flooding of such underground storage vaults (however unlikely) might cause nearby drinking water supplies to become contaminated and cause cancer deaths. Brief 35 shows possible long-term hazards associated with radio-waste storage as calculated by professor Bernard Cohen of the University of Pittsburgh under a worst-case scenario. He assumed stored radio-waste vaults could unexpectedly be inundated with (ground) water. Assuming that the canisters would rust through and that water with radioactive contaminants would seep into the ground, he estimated its possible arrival at a nearby well used for drinking water, as the radioactive species spread through the soil by diffusion.



Brief 35 Long-term hazards of radiowaste storage in salt-bed mines. (**a**) Hazards from radiowaste generated by U.S. nuclear power reactors, assuming salt-bed mine storage, water flooding, corrosion, and seep-through, (**b**) Fatalities due to radiowaste seep-through in one million years as a function of the time required for contaminated water to reach drinking water

Cohen's charts in Brief 35 show that possible fatalities due to drinking contaminated water are virtually negligible even if one assumes the "linear extrapolation theory" of induced cancers. Actually the linear cancer induction theory has been proven to be incorrect and mild amounts of radiation can in fact be beneficial (Ref. II-16). Also it is quite unlikely that flooding and rusting of canisters would go unnoticed by future sentinels of a radio-waste repository. If signs of canister rusting should occur, future generations would probably re-jacket the canisters if they found them to pose a hazard. Maintenance of a disposal site is fairly trivial, and requires only monitoring and periodic patrolling. If water would somehow enter the vaults, it can be pumped out. But even if nothing was done, Cohen's calculations show that possible hazards to man are miniscule.

Concern has also been expressed about the possibility that terrorists might try to acquire radio-waste material for use in a so-called “dirty” but non-nuclear bomb. Any terrorist gang who would want to break into a radio-waste repository to steal canisters of radioactive waste for some evil purpose would have to bring a truck, winch, and special engagement equipment to retrieve any. Even if a gang was able to subdue the repository guards by guns or in a gunfight, they would mostly expose themselves to radiation and could do little harm to anyone else, should they succeed with such a heist. Damage from the explosion of a “dirty” bomb comprises mostly mechanical blast effects. Radioactive materials are easily detected and a dirty bomb blast area is readily decontaminated with so-called “rad-waste” solvents. Anyone not killed by the bomb’s concussion but covered with radioactive dust can and should take a quick bath, shower, or swim to wash off radioactive particles. Gamma radiation exposure from radioactive dust is evanescent and does not stick as some seem to believe. If the terrorist’s goals are to poison people, there are many poisonous chemicals available that would be more effective than radio-waste. In short, stealing radio-waste canisters is as pointless as recovering an old WW-II army tank from the bottom of the ocean for use in an armed robbery.

The waste from the uranium fuel cycle has been solidly explored and engineered for several decades. After lengthy studies of possible sites to avoid earthquake faults, water-table infiltration, etc, the US DOE (Department of Energy) selected, designed, and built a billion-dollar repository for the storage of high-level nuclear waste in the Nevada desert at Yucca Mountain, approved by the US House and Senate. The main problem with getting DOE’s Yucca Mountain repository into service now has been the unreasonable opposition by anti-nuclear activists who keep court litigations going by interjecting trumped-up transportation safety concerns and other delaying tactics. Originally Yucca was to have opened in the year 2000. But because of the delays, nuclear power plant operators have resorted to temporary storage of fuel elements in swimming pools until Yucca will start to accept and process them or an alternative GNEP-like operation is put in its place. While the practice of temporary swimming-pool storage and cool-down can be carried out safely from a radioactivity management point-of-view, and is checked out and approved by the NRC (Nuclear Regulatory Commission), it would appear more prudent to have all final reactor radio-waste stored ultimately at one well-protected site instead of at a hundred reactor sites all around the country.

6.4 Nuclear Fusion

In contrast to nuclear fission which involves the heaviest known elements, in nuclear fusion a merging of two of the lightest elements occurs in which energy is released. Nuclear fusion was investigated long before fission by astrophysicists who tried to explain what caused the stars and our sun to emit so much energy for so long. From spectral and other observations it was known that hydrogen (H) and helium (He) had to be involved and that nuclear reactions had to produce the billion-year-long emissions from these nuclear furnaces. Some early physicists who studied nuclear fusion between 1915 and 1939 were A.S. Eddington, J. Perrin, W.D. Harkins, E.D. Wilson, R. d'E. Atkinson, F.G. Houtermans, C.F. von Weizsäcker, H. Bethe, G. Gamov, and E. Teller. S. Chandrasekhar (Ref. II-24), who was/is a renowned astrophysicist himself, quotes these authors as the major fusion pioneers. Stellar fusion reactions take place at extremely high temperatures of millions of degrees where all elements exist as ions stripped from their outer electrons. This state of matter is called a "plasma", and plasma physics plays an integral role in fusion physics. Thus in describing nuclear fusion events, one uses symbols $H = {}^1H$ (proton), $D = {}^2H$ (deuteron), $T = {}^3H$ (triton) to respectively describe the hydrogen nucleus consisting of one proton of atomic mass 1 with unit positive charge, the deuterium nucleus comprising one proton and one neutron with total atomic mass 2 and unit positive charge, and the tritium nucleus with one proton and two neutrons having total atomic mass 3 and unit positive charge. The symbols ${}^3He$ and ${}^4He$ are used to indicate helium atoms stripped of their two electrons with respectively a helium nucleus containing two protons and one neutron with total atomic mass 3, and a helium nucleus with two protons and two neutrons yielding an atomic mass of 4. The ${}^4He$ ion is identical to an alpha particle identified in early radioactive decay research by Madame Curie and others. With two neutrons and two protons, the alpha particle (i.e. a ${}^4He$ ion), is the most stable nuclear particle emitted by decaying radioactive elements besides a neutron n or proton $p \equiv {}^1H$.

To imitate solar fusion reactions on earth, it is necessary to confine a plasma with ionized species at temperatures of 10,000,000 K. This can and has been done by placing it in a strong magnetic field where positive and negative ions are constrained to travel helical paths around magnetic lines of force. By proper shaping of this field, charged nuclei can be confined for enough time to undergo fusion reactions. From unraveling fusion physics in the sun, and from improved data obtained with Cockroft and Walton accelerators in the 1930s, it was deduced in the 1940s that the following two nuclear fusion reactions are easiest to ignite at the lowest temperatures:

$$ {}^2D + {}^3T \rightarrow {}^4He + {}^1n + 17.6\ \text{MeV} \tag{6.2} $$

and:

$$ {}^6Li + {}^1n \rightarrow {}^4He + {}^3T + 4.8\ \text{MeV} \tag{6.3} $$

or overall:

$$ {}^6Li + {}^2D \rightarrow 2\ {}^4He + 22.4\ \text{MeV} \tag{6.4} $$

Another possible fusion reaction with two different outcomes of almost equal probability is:

$$ {}^2D + {}^2D \rightarrow {}^3H\ (0.96\ \text{MeV}) + {}^1H\ (2.88\ \text{MeV}) \tag{6.5a} $$

$$ {}^2D + {}^2D \rightarrow {}^3He\ (0.80\ \text{MeV}) + {}^1n\ (2.5\ \text{MeV}) \tag{6.5b} $$

Released energies are in atomic units: 1 MeV = 1 Million electron-Volt = 1.6021 × 10^{-13} J. Reaction (6.5) requires higher ignition temperatures but may be active once fusion is initiated in a plasma.

Although intense research and development of controlled nuclear fusion has been conducted for the last 60 years, instabilities in electromagnetic confinement are formidable obstacles and exploratory costs are enormous (Ref. I-35). Alternative methods to ignite the above reactions using pulsed focused beams of laser photons or particles that strike pellets of fusionable ingredients (called Inertial Confinement Fusion) are also being explored. The latest multinational collaborative effort is ITER (International Thermonuclear Experimental Reactor) which one hopes will demonstrate at least “break-even” nuclear fusion. It was expected to be ready for experiments in 2008, but construction on a finally agreed-upon site at Cadarache in Southern France will not start till 2010 and completion is expected to take at least 2 more years. Compared to nuclear fission, many believe nuclear fusion can not compete economically for some time (at least 50 years), even if one can extract electric power from a device such as ITER. Since uranium fission can provide man with needed energy for millennia, chances are good that the technology needed for controlled nuclear fusion will have been conquered in that period of time well before the world’s uranium and thorium reserves are exhausted.

Some mistakenly believe that nuclear fusion will not produce radioactive waste. Reaction (6.2) shows that fusion produces neutrons, and even though it is hoped that most will be captured by reaction (6.3), a good fraction will be absorbed by confinement materials of construction whose nuclei will thereby be transmuted and become radioactive. Also the size of a fusion power-producing reactor will of necessity be much larger than that of a fission reactor, so there is a large exposed area for neutron activation.

The main attraction of nuclear fusion is that there is an abundant supply of deuterium on earth. Even though deuterium’s abundance is only D/H = 0.00015, the world’s oceans hold approximately 100 trillion tons of deuterium, and a similar amount is estimated for ^{6}Li with natural abundance ^{6}Li/(^{7}Li + ^{6}Li) = 0.075. Of course energy required for isotope separation of D and ^{6}Li must be less than the potential fuel energy in the isotopes. As in the case of U-235, because of the large amounts of energy released in nuclear processes, energies required for separation of isotopes are generally less than 0.1% of the harvested nuclear energy. Another item not to be ignored is the gathering cost, that is the energy needed to pump tons of (sea-)water to a point where one can remove 1 kg of deuterium from 60 tons of water with an isotope separator. With the extraction of deuterium from 1% of all the oceans, one calculates that one trillion tons of deuterium and lithium could provide the world with 10^{21} GJ of fusion energy. With a stabilized total world consumption of 10^{12} GJ/year, this supply could provide the world’s energy needs for a billion (10^{9}) years, which happens to be about the remaining life of our sun.

While “Hot Fusion” induced by high-energy nuclei was the main focus from 1945 till 1989, in 1989 M. Fleischman and S.J. Pons at the University of Utah claimed to have discovered so-called “Cold Fusion”. In an electrochemical cell, where hydrogen is produced by electrolysis of water (Eq. 6.1), they believed to have observed the emission of nuclear fusion products. They used heavy water (D_2O)

which generates D^+ ions, the same species as in fusion, and employed a palladium electrode presumably generating reactions (6.5) on/in the palladium electrode surface. Because of the exponential "Gamov factor" which gives the probability for two positive ions to penetrate the nuclear repulsion barrier between them, such a reaction is almost impossible at room temperature. It requires temperatures of 10,000,000 K for the D's to penetrate the mutual repulsive barrier and undergo fusion.

A different fusion reaction between deuterium ions on a solid electrode (omitting the + charge signs) might be:

$$\mathrm{D + D{:}electrode} \rightarrow {}^4\mathrm{He}\ (23.8\ \mathrm{MeV}) + \mathrm{electrode} \tag{6.6}$$

This reaction might explain why neutron emission rates reported by Pons and Fleischman were far below what one would expect on the basis of reaction (6.5b). Extremely energetic alpha-particles (^{4}He) possessing 23.8 MeV by reaction (6.6) can generate neutron emissions in secondary nuclear interactions with intensities much less than what one expects if the primary reaction (6.5b) was involved. Unfortunately Pons and Fleischman (PF) did not measure possible ^{4}He or ^{3}He productions. The reaction:

$$\mathrm{D + D + Third\ Body} \rightarrow {}^4\mathrm{He} + \mathrm{Third\ Body} + 23.8\ \mathrm{MeV} \tag{6.7}$$

has been observed to occur in stellar plasmas at a rate one thousandth (10^{-3}) of that for reactions (6.5a) and (6.5b). The main reason for the low probability of (6.7) is that the laws of physics demand simultaneous conservation of momentum and energy in a two-particle encounter such as D + D. If only one outgoing particle is formed, this law would be violated. Only in the presence of a third body which can carry off balancing energy and momentum as in (6.7), is the reaction possible. In a gaseous stellar plasma, one out of a thousand two-body collision events takes place in the presence of a simultaneously colliding third body, which allows reaction (6.7) to proceed. If a D + D reaction took place on an electrode wall by (6.6) as in the PF experiments, the wall can act as the required third body provided it can interact resonantly with the D's and ^{4}He's at the nuclear level. An explanation would still have to be found however to explain nuclear repulsive barrier penetrations at low temperatures on a palladium or other electrode surface.

Many who tried to duplicate the 1989 Pons–Fleischman experiments failed to get the same results, except for a few who claimed to have also seen some nuclear emissions (neutrons, ^{3}He, and ^{4}He) and release of excess heat. Most of these emissions occurred in occasional spurts during extended week-long D_2O electrolyzing runs. Numerous theories have been proffered to explain a possible nuclear process, while just as many have been proposed to give a non-nuclear chemical explanation of these observations. Presently the majority of nuclear physicists are skeptical and believe that spurious observations of "cold fusion" are due to nuclear background interactions such as cosmic rays, or because of inaccurate and/or inadequate measuring instruments. To date no absolute scientific proof acceptable to most physicists has been provided yet for PF-like cold fusion phenomena. Nevertheless cold fusion research is still being pursued by believers (Ref. I-35).

Chapter 7
Safety Considerations in Nuclear Operations

While some aspects of reactor safety procedures were already discussed in Section 6.1, here we give a more general review of safety measures that have been instituted for reactor and nuclear fuel handling operations. We start with discussing the nature of nuclear radiation and its effects on man and bio-matter. Next we consider radiation dose measurements and tolerable exposure levels, followed by a review of radiation protection measures and safety assurance in reactor operations. Finally, some typical mishaps in reactor operations and fuel handling are discussed and a review is given of serious nuclear accidents that have occurred since the beginning (1945) of the nuclear age, including the Three-Mile-Island (TMI) and Chernobyl reactor meltdowns in 1979 and 1986.

7.1 Nature of Nuclear Radiation

The major nuclear emissions in an operating reactor consist of alphas, betas, gammas, and neutrons. Alphas are highly energetic helium ions ($^{4}He^{+}$), while betas are nothing but very high-energy electrons. Like fission fragments, alphas and betas slow down and are completely stopped after a few millimeters (0.04 in.) of travel in solids, and after 2–6 m (6–18 ft) in most gases at atmospheric pressure. In a running reactor, these particles convert their kinetic energy into heat in the fuel element's solid matrix as they slow down. It is impossible for fission fragments, betas, or alphas to fly out of the reactor core, through the neutron reflector, and out through the gamma shield.

Gammas are the only emitted radiation species that can pass through the core and reflector of a reactor (Brief 23). For this reason a special gamma shield is placed around the reactor core and reflector to stop them. Gammas are massless evanescent high-energy photons like x-rays and light. The typical 1 MeV gammas emitted in fissions can travel through 150 cm (60 in.) of water or 10 cm (4 in.) of lead before they are attenuated 100-fold. Although they have no mass, gammas do have energies which generally lie between 0.1 and 10 MeV. This compares with visible light whose photons have energies between 1.9 and 3.6 eV approximately,

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_7,

that is one million times less than gammas. All photons, gammas, x-rays, and light vanish once they have been absorbed by matter or flown away into space. Their identity ceases and they do not stick because they are *evanescent*. The heavier the shield material is, the smaller the gamma's stopping length is. Typical lead shields are 20 cm (8 in.) thick, while less costly heavy concrete reactor shields are 1–2 m (3–6 ft) thick. The exact shield thickness is determined by the criterion that the radiation dose level at the outside of the reactor shield must be 2.5 mr/h or less (Section 7.3).

Neutrons have approximately the same mass as positively charged protons or hydrogen nuclei (the lightest of all elements) except they have no charge and are neutral. Neutrons can therefore fly through a solid material as if they were a gas. In uranium fission, neutrons have at first very high velocities when they are born, but as they diffuse through the reactor core they collide and slow down. The lighter the atoms that neutrons collide with, the more quickly the neutrons are thermalized. Since thermal neutrons promote fission better than fast ones, a neutron thermalizing material or "moderator" such as water is dispersed through the core which otherwise contains primarily fissionable uranium or plutonium and fuel-holding materials. Water is also a good reflector of neutrons. A neutron reflector comprised of water, when placed around the core, insures that most neutrons escaping from the core are reflected back into the core. To stop any remaining neutrons that might pass through the reflector, some extra boron (or other high neutron-absorbing compound) is often mixed in with or added to the outer gamma shield to bring neutron levels down to acceptable safe levels outside this shield. The advantage of using water as moderator in the core is that it can also function as the reactor coolant.

Nuclear radiation emitted by fissioning uranium and radioactive fission products in a reactor can not travel very far, and their intensity drops off with the square of the distance from the reactor, aside from being attenuated by the reflector and shielding. However radiation from so-called "fall-out" often mentioned in connection with nuclear explosions, has a much farther reach. Nuclear fall-out consists of airborne particles or dust of pulverized radioactive fission products released as a cloud into the air from a nuclear bomb explosion or a Chernobyl-like fire from a reactor without a containment vessel (Section 7.6). Such a cloud is carried downstream by the wind and can "rain" on a populated area causing widespread radioactive contamination. In this case the radiation sources are in the radioactive dust particles taken far from their originally contained place of birth.

The fall-out of radioactive particulate matter, if not inhaled or ingested, can be rendered harmless by people covered with it by washing it off. A quick shower or swim is recommended in this case. Of course it is even better to get out of the path of a fall-out cloud if one is warned by radio where it is going. It is extremely unlikely that any individual would receive an acute lethal gamma burn from fallout that covered him. Fall-out particles are clusters of mostly metal-oxides of radioactive fission products of uranium mixed with oxides of structural fuel element materials such as zirconium, steel, aluminum, and silicon. Since alpha and beta particles are stopped by a millimeter or so in most solids, dust particles provide some self-shielding, while betas that reach a person's skin are stopped in the skin and can not reach internal organs. Only gammas emitted by the fall-out can provide a whole-body radiation burn with some body penetration, if a person is totally covered with fall-out.

If fall-out is inhaled and absorbed by the lungs or enters the digestive tract by eating or drinking it, a more serious situation can occur. There are three main "bad actors" among the various radioactive daughter products of uranium fission which can be selectively absorbed by and lodged in human organs. As listed in Brief 36, these are iodine-131 and -129, strontium-90, and cesiun-137. Fortunately iodine-131 which collects in the thyroid decays relatively fast. On the other hand, iodine-129 (like the K-40 in our blood) lasts "forever", but delivers a very low dose because of its long life. Sr-90 and Cs-137 can last a long time unless metabolized or driven out before lodging in body parts. Short-lived radioactive species present in fall-out decay away to stable elements, and if inhaled or ingested are usually eliminated by the body in a day.

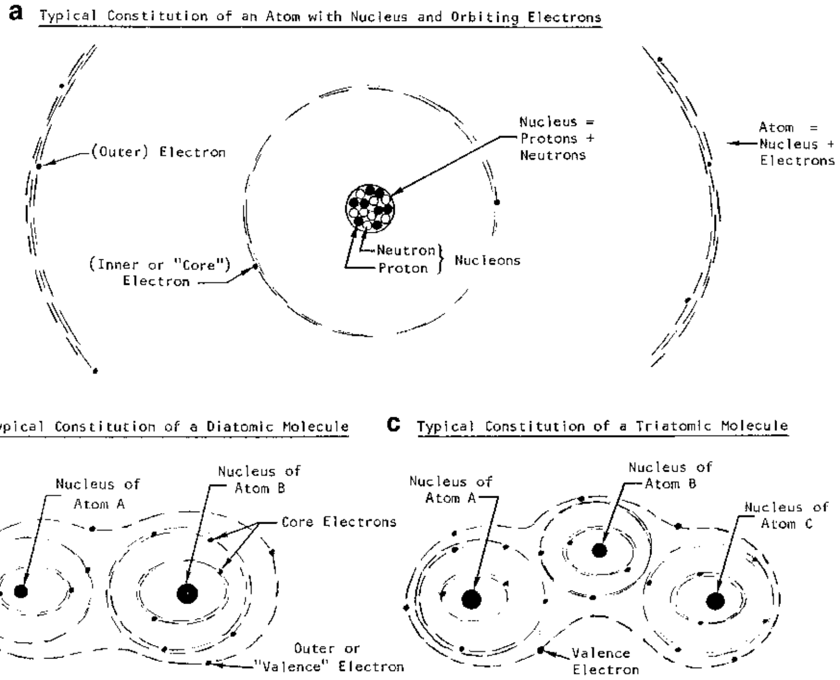
Brief 36. "Bad" radioisotopes for humans and mammals.

I-129 with a half-life of 17 million years → thyroid (very low level)
I-131 with a half-life of 8 days → thyroid
Sr-90 with a half-life of 28 years → bones
Cs-137 with a half-life of 30 years → cells

In summary, gamma radiation emanating from an operating reactor is evanescent. It does not "stick" as some mistakenly seem to believe. Only fall-out dust from a nuclear explosion can "stick" to a person's skin. It can be washed off if not inhaled or ingested. If someone inadvertently walks through fall-out rain, he/she should breath through a wetted handkerchief or gas-mask if available, to prevent dust inhalation.

7.2 Biological Effects of Nuclear Radiation

Many people are unaware that nuclear radiation is also emitted by nature and is all around us. It comes from the heavens (cosmic radiation) and from naturally radioactive minerals on the earth surface that emit it. Life on earth has evolved in this radiation climate for eons, and all bio-organisms have learned to tolerate or make use of it. When a gamma, x-ray, or ultraviolet photon strikes a bio-organic molecule in skin or in an internal organ, it will knock off an electron. That is it "ionizes" the biomolecule. Biomolecules like DNA (Desoxyribo Nucleic Acid) and RNA (Ribo Nucleic Acid) are very large atomic species complexes, containing thousands of atoms and electrons per molecule. Brief 37 illustrates the electron clouds around an atom and a simple molecule. The response to removal of an electron from a large biomolecule is that the electron cloud surrounding it will quickly refill the gap, while the loose electron after some migration, reattaches itself to another large biomolecule with thousands of electrons. Because of the immense "sea" of electrons around biomolecules, one displaced electron usually produces hardly any effect.



Brief 37 Make-up of a nucleus, atom, and molecule. (**a**) Typical constitution of an atom with nucleus and orbiting electrons, (**b**) Typical constitution of a diatomic molecule, (**c**) Typical constitution of a triatomic molecule

Because man's body contains a lot of water, most other entities besides biomolecules that a gamma encounters in traversing through tissue are water (H_2O) molecules. Ionization of water usually results in the formation of a hydroxyl radical (OH) or hydrogen peroxide (H_2O_2). These molecules can attack a biomolecule and "denature" (= kill) it. However many water ionization events result in a return of the liberated electron to the ionized water molecule without causing secondary destructions.

The above processes take place continuously on our skin when we expose ourselves to sunlight, which consists of ultraviolet (UV) and visible photons. The only difference between a UV and a gamma photon is that a UV photon can only remove one electron from a molecule, while a gamma photon can knock off many electrons from different atoms along its path, the distance between knock-off points being usually quite large (millimeters to centimeters). Thus a gamma photon can produce 10–1,000 distributed ionizations (= electron knock-offs) in traversing human tissue. One might conclude from this that a gamma burn is more dangerous than a solar UV burn, but in reality the number of UV photons from the sun that bombard our skin is a billion times larger than the number of gammas that hit and pass through us from a typical gamma source. Clearly, one has to take into account both the number of photons per second (i.e. the flux), as well as the ionization strength of each photon. Tolerable radiation exposures are discussed in Section 7.3 together with units commonly used for measuring radiation dosage.

Like gammas, strikes by high-energy betas or alpha particles also cause ionization, and thus electron stripping. However compared to gamma-produced ionizations, the ionization tracks of alphas and betas leave a much higher concentration of effected biomolecules, that is the electrons knocked off by alphas and betas are much more closely spaced. This also means that alphas and betas propagate only a millimeter or so, and are completely stopped by the human skin if one deals with an outside source. The effect is not much different from what a person would receive by a UV sunburn.

Internal organ exposure to alphas and betas is possible only if a radioactive particle that emits alphas or betas is inhaled, swallowed, or injected. In this case one finds that damage of biomolecules by betas and alphas can be more severe since ionizations are closely spaced. For heavy alphas it is necessary to assume a relative biological effectiveness (RBE) factor of RBE $\approx$ 10 to account for the higher ionization densities and its effects. That is, one alpha can do as much damage inside tissue as ten betas. For betas, RBE $\approx$ 1 is usually assumed, although some radiologists estimate that RBE $\approx$ 1.5 for betas with energies above 1 MeV is probably justified depending on what is irradiated.

In therapeutic nuclear medicine, advantage is taken of the high-density deposition of ionizing energy by betas and alphas. In this case, beta- or alpha-emitting radioisotopes are synthetically incorporated in certain pharmaceuticals which when taken internally, are adsorbed by tumors. Of course in nuclear medicine one intentionally wants to overdose a selected target (the tumor) while one tries to minimize possible radiation damage to non-malignant organs. Using sufficiently strong doses, betas or alphas can destroy tumor cells. Nuclear treatment is ideal since betas and alphas can travel only a fraction of a millimeter in tissue as they slow down, thus avoiding damage outside the selected tumor. The main problem is to get a therapeutic radioisotope or radiopharmaceutical only in the tumor cells and not elsewhere in the body. For this reason radioactive “seeds” in the form of nano- or micro-spheres are sometimes implanted in the tumor, as in the case of prostate cancer.

While most electron knock-offs from DNA molecules by gammas are assimilated by irradiated tissue as described above, now and then a collision occurs that causes a DNA or other biomolecule to break up or causes the molecule to restructure itself. These events are rare on an individual basis but do happen regularly if billions of gammas, betas, or alphas are continuously traversing biological tissue. Occasionally they can lead to a rearrangement in a biomolecule which might be the beginning of a possible cancer-forming mutation or carcinogen.

Since the radiation interaction process is a random one, the probability of producing a "bad" atomic rearrangement from lesions in a biomolecule is proportional to dose. It therefore has become practice to assume "linear scaling" of lesions or cancer formation rates with radiation dose, although this has not been proven. Biochemistry professor T.D. Lucky at the University of Missouri in Columbia has collected statistical data that indicate low-level radiation is actually beneficial to man (called "hormesis", Ref. II-16). We shall further argue below that cancers due to "bad" lesions might be proportional to the square of radiation dose and not linearly. We also show that it is more likely that mutations in DNA are induced by localized atomic-scale electric fields of non-regular invasive groups of molecules or atoms rather than by radiation. This refutes the assumption by some anti-nuclear activists that each cancer has its origin in a radiation interaction.[1]

Before discussing possible cancer formation pathways initiated by radiation effects, we need to point out that the wound from a knife cut, a bruise, or a burn from a fire or hot stove on a person's body also produces a large number of lesions in quadrillions of molecules. The act of driving the sharpened edge of a sharp metal through flesh causes the electrons on the metal edge to break biomolecular bonds by the trillions. The end effect does not differ from the atomic displacements caused by alphas, betas, or gammas, except that the concentration of actual lesions is higher in the case of a cut, bruise, or burn. The body can not tell the difference whether these lesions were caused by betas or gammas, or by knife-edge electrons. After defining radiation dose in Section 7.3, we shall show in fact how one can relate micro-scratches or knife-cuts to radiation exposures levels.

Probably the most frequent biomolecular mutations and lesions in the body are caused by unnatural impurity atoms or molecules taken in via food or drinks, and/or created by a bacterium or virus. When lodged in some internal organ or other part of the body, the intermolecular force fields of such "foreign agents" can cause bond angle rotations, bond breakages, helicity changes, or a "cross-over" of components during a DNA replication process. Particularly atoms or molecules with strong dipole moments may influence and possibly distort a biomolecule that is contacted. That chemical agents can cause biomolecular rearrangements resulting in cancer forming mutations is well proven. Many chemical "carcinogens" have been identified and are now banned from food or drinking water. To date only leukemia has been proven to be inducible by radiation. In summary, although radiation can be a cause, the majority of cancers appear to be of chemical origin, *not* radiation related.

---

[1] The "First Law" of antinuclear activist Gofman claims that all cancers are caused by radiation (Chapter 2 of "Population Control through Nuclear Pollution", by A.R. Tamplin and J.W. Gofman; Nelson-Hall Co., Chicago). If this "law" (called Gofman's "First Flaw" by some) were correct, one deduces that every person on our planet should have died already ten times over from cancers due to cosmic radiation.

The chain of events that may lead from a single lesion or re-arrangement in a biomolecule to a cancer or genetic defect is believed to be initiated by a faulty replication of a "healthy" biomolecule in an organism. Since biomolecules are repeatedly replicated, it takes but one wrong template to build up a generation of defective or cancerous biomolecules and cells. Fortunately conditions that allow replication are rather restrictive and not every rearranged or broken biomolecule is replicated; most are eliminated. Nevertheless there are some replications that can cause a problem occasionally.

When a biomolecule is broken up in an ionizing radiation event, it is unlikely that the broken-off portion can replicate all by itself. It might re-attach itself to its broken-off partner in which case there is no net change except for possible bond-angle changes. Or it attaches itself to another broken-off biomolecular part to form a modified molecule that may or may not be replicable. Replicable recombinations of two broken-off molecular pieces might lead to multiplication of faulty genetic material and thence to cancer. If cancer-forming mutations are formed in this manner, cancer rates would be proportional to the square of the radiation dose, not linearly. If proportional to the square of radiation dose, the effect of low-level radiations would be vanishingly small.

If instead of a recombinaton requirement, it is sufficient to induce a bond-angle or helix-angle change in a biomolecule to create a mutation, the cancer versus radiation dose would be linear since such changes can be effected by one ionizing interaction. At present there is insufficient information available to determine whether the relation is linear or quadratic, and it is conceivable that both postulated mechanisms are operative. The most important result from our review is however the fact that the majority of cancers are induced by chemical or biochemical (virus or bacterium) agents, not by radiation. As mentioned, recent research has indicated that low levels of radiation (enjoyed by people living at high altitudes) promotes health rather than worsens it. Like heat, a little bit from a heating pad can be healing, but the heat in a blast furnace would incinerate a person.

So far we only considered alphas, betas, and gammas. Neutrons produced in reactors can also induce mutations but in an entirely different way, since they can transmute atoms into other elements upon absorption. However they can not travel far from the reactor and are metastable, decaying in twelve minutes. Neutrons are only plentiful inside a reactor. Unless neutron flux levels are extremely high, the biological effect of neutrons is similar to that of gammas but with RBE = 3 to 10.

In summary, nuclear gammas, betas, and alphas, like ultraviolet radiation from the sun, can cause: (a) ionizations with no final biological effect; (b) ionizations leading to denaturization of biomolecules repairable by the body; (c) unrepairable lesions of biomolecular bonds (less than one out of a million interaction events). In the latter case there is a small chance that a replicable biomolecular mutation is created which can lead to cancer, but most often the odd molecule is rejected and eliminated by the body. Whether the probability of cancer inducement is directly or quadratically proportional (or in-between) to dosage is still uncertain. If quadratic, the effects at lower dose rates should be much less than what is assumed on the basis of a linear extrapolation of high-level dose effects (where they can be measured).

In conclusion, comparing possible cancer inductions by natural or man-made radiation to cancer inductions by chemical agents, the risk of getting cancer from chemicals in foods, drinks, and air, appears many times more likely than that from brief exposures to natural or man-made radiation.

7.3 Radiation Dose Measurements and Tolerable Exposures

To determine what radiation levels are safe, one must first define a unit of radiation dosage. This unit is the “rad” which is defined as 100 erg = 10^{-5} J of ionization energy transferred per gram of effected body tissue by radiation particles. In formula form:

$$\begin{gathered}1 \text{ rad} = 100 \text{ ergs } (= 10^{-5} \text{ J}) \text{ of deposited ionization energy} \\ \text{per gram of effected tissue}\end{gathered} \tag{7.1}$$

This definition still does not mean much without a comparison or reference as to how much or how little damage a rad does to man and how one measures it. This is discussed in what follows.

The amount of radiation energy deposition, the rad, must be multiplied by the relative biological effectiveness factor or RBE, before one can speak of a biologically meaningful dose. Different energetic particles have in general different RBE’s. The RBE for gammas and betas is RBE = 1, for alphas RBE = 10, and for neutrons one assumes RBE = 3 to 10. When the rad is multiplied by the RBE, one obtains dosage in terms of rem (roentgen equivalent man):

$$\text{RBE} \cdot \text{rad} = \text{rem} = 1{,}000 \text{ mr (millirems)} \tag{7.2}$$

Thus if a source of alphas deposits 100 erg/g in tissue, it injects a physical dose of 1 rad and a biological dose of 10 rem, since alphas have an RBE = 10. Since the RBE for betas and gammas is RBE = 1, for all practical purposes the rem and rad are equal for betas and gammas.

To get a better feel for the rad or rem, it is useful to compare rad damage with body damage created by a knife cut. If we define a “micro-cut” as a 1 mm deep by 2 cm long knife cut or scratch on the skin of one’s hand, one can show that the sharp knife edge causes approximately 3×10^{14} severances of biomolecular bonds in the knife wound. If one assumes that on average each bond breakage required 10 eV, the total energy dissipated in the wound would be 3×10^{15} eV = 4,800 erg. If it is further assumed that a hand weighs approximately 480 g, the damage to the hand spread over the whole hand would be 4,800/480 = 10 erg/g or 0.1 rem = 100 mr:

$$1 \text{ micro-cut} = 1 \text{ mm deep by } 2 \text{ cm long knife-cut} \sim 100 \text{ mr (on one hand)} \tag{7.3}$$

It is clear from this analysis that it matters greatly whether tissue damage by radiation or knife-cuts is for the whole body or partial body. If we had allocated the knife-cut damage to one finger with a weight of 48 g, the equivalent rad damage would have been 1,000 mr. Thus if one holds one's hand over a radiation source (e.g. Co-60) but the rest of the body is shielded, one should reduce the locally measured dose on the hand by the factor (mass of hand)/(mass of whole body) to arrive at the whole-body dose. Tissue damage from a directed beam of radiation which illuminates an area less than that of a person's body should also be adjusted accordingly. In measuring and recording radiation exposures, it is usually tacitly assumed that the observed radiation was permeating all of the space around a person. It is important therefore to record if a radiation exposure is "whole-body" or "part-body". If not indicated, it is assumed to be whole-body.

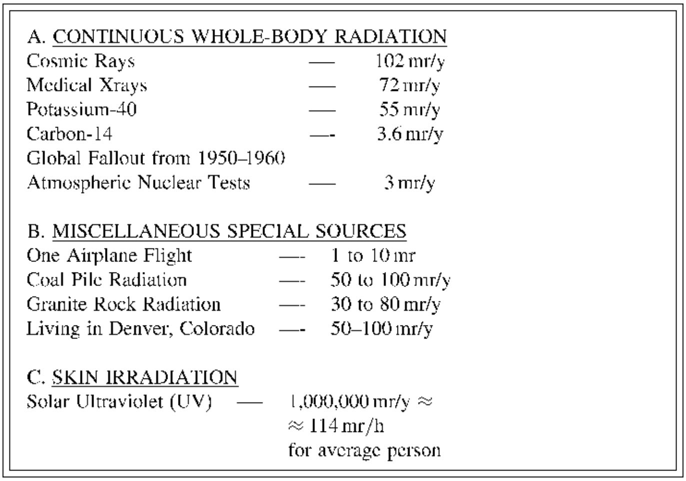
It has been found from experiments with rats and many tests that a man working near a source of radiation can be exposed to about 1 rem = 1,000 mr/week without noticeable effects. Assuming a 40-h work-week this means an exposure rate of 1,000/40 = 25 mr/h. For conservative reasons, the International Commission on Radiological Protection has added another factor of 10 and recommends that the so-called maximum permissible dose (MPD) be set at:

$$\text{MPD} = 2.5\ \text{millirem/hour} = 2.5\ \text{mr/h} = 5\ \text{rem/y}\ (2{,}000\ \text{hr work-year}) \quad (7.4)$$

Nuclear reactors are therefore designed with radiation shields such that the highest radiation level is not more than 2.5 mr/h in areas where men may walk near a reactor. Actually reactor operating personnel rarely stay for extended periods of time at such locations and their usual exposure is much less than this. In handling radioactive materials, they are also encouraged to implement the ALARA (As Little As Reasonably Achievable) principle even though the law requires only that exposure levels do not exceed 2.5 mr/h in areas where personnel may be exposed.

Directly outside a nuclear reactor building, radiation levels are much less than 2.5 mr/h because of the inverse-square-with-distance attenuation. That is if 10 m (30 ft) from the reactor core the level equals say 2 mr/h, one finds that at 100 m (300 ft) the level is $(10/100)^2 = 0.01$ times less or 0.02 mr/h. If one is 1,000 m (3,000 ft) from the reactor core outside the gates of the nuclear reactor plant, the level has dropped to 0.0002 mr/h which compares with 0.01 mr/h of background radiation one receives from cosmic radiation. If there are intervening structures (and there almost always are), the radiation levels outside the plant are even lower and undetectable.

To improve our understanding of what these radiation levels mean, it is instructive to compare them with naturally-occurring forms of radiation. As mentioned, the cosmos bombards us continuously with approximately 102 mr/year, while the average person receives about 72 mr/year from medical x-rays and 59 mr/year from naturally radioactive potassium (^{40}K) and carbon (^{14}C) which are always present in our bodies. That is, everyone is slightly radioactive!. Someone living on granite rock like Manhattan Island, or near a stockpile of coal, receives another 1–10 mr/year of radiation from radon, a radium decay-chain element. People living at high altitudes like Denver, Colorado, receive an additional 50–100 mr/year. Finally the sun can give each person a skin dose of an astounding 1,000,000 mr/year from solar UV photons if he stood in the sun all year long (staying out of the direct sun for long times is highly recommended!). Brief 38 summarizes the radiation exposure each person gets from natural sources.



A. CONTINUOUS WHOLE-BODY RADIATION

Cosmic Rays	—	102 mr/y
Medical Xrays	—	72 mr/y
Potassium-40	—	55 mr/y
Carbon-14	—	3.6 mr/y
Global Fallout from 1950–1960 Atmospheric Nuclear Tests	—	3 mr/y

B. MISCELLANEOUS SPECIAL SOURCES

One Airplane Flight	—	1 to 10 mr
Coal Pile Radiation	—	50 to 100 mr/y
Granite Rock Radiation	—	30 to 80 mr/y
Living in Denver, Colorado	—	50–100 mr/y

C. SKIN IRRADIATION

Solar Ultraviolet (UV)	—	1,000,000 mr/y $\approx$ $\approx$ 114 mr/h for average person

Brief 38. Natural radiation exposures

Clearly man has been continuously exposed to different natural radiation sources for millions of years, and successfully evolved in this environment. Recent studies show that small amounts of radiation are actually beneficial. This phenomenon is called “hormesis”. Although other factors may be involved, people living at high altitudes like in Colorado or the Andes, are on average healthier than plain dwellers.

Aside from the safe maximum permissible exposure of 2.5 mr/h, on the other extreme one has found that a dose of 500,000 mr = 500 rem is generally lethal to a man if received all at once:

$$\text{Accute Lethal Dose} = 500{,}000\ \text{mr} = 500\ \text{rem (instant whole-body)} \qquad (7.5)$$

If one receives this total-body dose of 500,000 mr in a few seconds, there is a 50–50 chance that death will follow. This high level corresponds to throwing a lobster in boiling water or a person into a furnace. The heat generated by this heavy dose kills a super-critical fraction of living cells in the body which the body is unable to replace fast enough.

Unless death is instant, victims who receive a dose of 500 rem can sometimes still be saved by administering injections of transplant bone marrow. An excessive dose of radiation destroys most of a person’s bone marrow which is needed to manufacture new blood-cells. Normally the body would try to repair itself after a trauma, but if the bone marrow “factory” itself is put out of commission, new blood cells can not be made any more at a sufficient rate to keep up with the demand. By providing bone marrow artificially to a victim from a bone-marrow bank (like a blood bank), his body can build up a new blood-cell supply until the bone-marrow factory can rebuild itself. Two men from the 1958 Yugoslavia reactor accident, were saved in this manner after they were flown to Paris and given bone-marrow injections for a few months till their bodies resumed blood-cell manufacture again. However application of bone marrow transplants to Chernobyl victims in 1986 show that this treatment is only effective for a narrow range of exposures between 100 and 400 rem (Section 7.6).

Some remedies against inadvertent internal radiation exposure have been developed in the form of radioactivity elimination tablets. In cases where a victim accidentally inhales or swallows fission-generated radioactive iodine-131 which tends to lodge in the thyroid, one has found that taking pills containing potassium iodide (KI) are a preventive. If taken quickly after the accident, KI will saturate the thyroid with its non-radioactive iodine and block additional radioactive iodine-131 (half-life = 8 days) from entering. The radioactive iodine-131 is thus prevented from accumulating in the thyroid and is eliminated by the body. Iodine-131 is the longest-lived of several radioactive bio-sensitive iodine isotopes produced in nuclear fission. Accidental inhalation of iodine-131 could happen for example in handling a gas-leaking cracked fuel rod, or if one drank contaminated milk from cows that grazed on grass covered with radioactive fall-out. After 2 months (8 half-lives), I-131 is essentially decayed away. Administration of potassium iodide pills to 130,000 residents within a radius of 30 km exposed to Chernobyl radio-iodine fall-out (Section 7.6), proved quite successful with no side effects. Pills that scavenge radioactive Sr-90 and Cs-137 in the body to help eliminate them are reported to be under investigation and evaluation.

Gamma and beta radiation doses can be measured by a number of instruments, the oldest one being the radiation survey meter which uses a gas-filled Geiger-Müller (GM) tube (Ref. II-2). Any ionizing particle passing through the thin metal window of the tube into the gas generates free electrons whose current is measured. The survey meter is calibrated against a source of known strength and indicates the radiation level on a dial in proportion to the electron current. Semi-conductor radiation detectors like zinc-doped cadmium telluride have also been developed for gamma detection. Some sensors convert current signals into sound, making a crackling noise proportional to radiation intensity.

Workers in nuclear facilities carry "dosimeters" or "film badges" clipped to their clothing. The dosimeter or "radiation pencil" comprises an electroscope device that measures integrated radiation exposure and is checked daily, while the film badge exposes a special nuclear-radiation-sensitive film which is checked for exposure effects at least once a week or sooner if there is cause for a possible radiation overexposure. The resident health physicist is usually responsible for regular monitoring, log-keeping, and maintenance of personnel dosimeters and film badges.

Instead of the historical rad and rem, one has now also defined the "Gray" and "Sievert" as:

$$\begin{gathered}1\ \text{Gy (Gray)} = 100\ \text{rads} = 1\ \text{Joule energy deposited}\\ \text{per kilogram irradiated tissue}\end{gathered} \tag{7.6}$$

$$1\ \text{Sv (Sievert)} = \text{RBE} \cdot \text{Gy (Gray)} = 100\ \text{rem} \tag{7.7}$$

These units follow the international mks system (mks = meter-kilogram-second). In therapeutic nuclear medicine where tumors are irradiated, quoted doses are *not* whole-body as is customary in reactor operations, but instead apply only to the kilograms of tissue in the tumor. Thus doses of 5 Gy (500 rad) which would be lethal if it was a whole-body exposure, are not uncommon for killing a cancerous tumor. However the radiation energy is focused on and/or restricted to the tumor only. The milli-Gray (mGy) = 0.1 rad or the milli-Sievert (mSv) are often used as basic units in diagnostic applications where low doses of a nuclear tracer are injected to follow a biological process.

7.4 Radiation Protection in Reactor Operations

Neutron reflectors and gamma shielding in reactors are designed to ensure minimum radiation exposures to reactor operating personnel. Compliance with safe reactor design rules and regulations are checked by the NRC (Nuclear Regulatory Commission) when an application is filed for reactor construction, which is repeated after a license is issued and the reactor is built. After reactor start-up, there is still another checkout. Upon commencement of routine nuclear power generation, the NRC appoints a health physicist (HP) to be in residence at the reactor, who monitors and records radiation levels around the reactor and who verifies there is continued compliance with all safety features specified in the NRC-issued reactor operating license. The HP makes sure that personnel radiation levels in the reactor building as well as throughout the reactor site are always below maximum allowed levels (Section 7.3), and that all radiation monitors and alarms are in working condition.

The resident HP usually reports directly to the NRC and can bypass the reactor plant operations manager if he chooses. This ensures that reactor safety is never compromised in favor of economic or other considerations. The job of a reactor health physicist is comparable to that of an air traffic controller at an airport. Careful selection of a mature responsible health physicist is an important task of the NRC. Although independent, an HP must not misuse his powers and must promote safe operations through teamwork and good relations with reactor management.

The most often used reactor shielding materials are lead, concrete, and water. Besides a neutron reflector of water, most reactors have a shield of concrete and/or lead around it to stop gammas (Brief 26). Betas, alphas, and fission fragments are completely stopped in the solid reactor core, and only neutrons and gammas can escape from it. Most neutrons in a power reactor are reflected back into the core by 30–100 cm (1–3 ft) of water since they are valuable in maintaining the fission chain reaction and as few as possible are allowed to escape. The thickness of the gamma shield is usually about 30 cm or more of lead, and/or 1 m or more of concrete.

Around the basic reactor is the “containment vessel”, which surrounds the “reactor pressure vessel”, the reflector, and shielding. The containment vessel is usually a enormous sphere or cylinder of 5 cm thick steel whose sole purpose is to keep all radioactive vapors and debris inside it in case of an accidental reactor meltdown. There is also an emergency core cooling system (ECCS) which provides backup coolant for the core, should the regular cooling system fail. Because of “after-heat” from radioactive decay products, core cooling needs to be continued even after a reactor scram, and this is done by the ECCS if the normal system fails. In case of a reactor scram, spring-driven control rods which are designed to be fail-safe (Section 6.2.1), drop immediately back into the core causing cessation of any further uranium fissioning.

In the reactor building, a number of radiation monitors are mounted on walls or on the ceiling which will sound an alarm if they detect radiation above a certain threshold value. In ventilation ducts and air circulation passages, additional radiation monitors are usually situated at strategic locations. For the sake of safety, several redundant monitors are present which are checked weekly to insure their operability. The power supply for each monitor is automatically switched to a standby battery in case of an electric power grid failure. These batteries are kept charged and checked continuously. Besides gas-filled ionization chambers, solid-state semiconductor detectors have been developed and are used today to perform the basic sensing function in radiation monitors.

7.5 Mishaps and Malfunctions in Reactor Operations

Nuclear reactor power plant operations, like all other human undertakings, occasionally experience a malfunction or other disturbance that leads to an accident. Many people ask if reactor accidents are tolerable and reasonable when compared to other human endeavors. We shall show that the risk of running a nuclear plant is no different and probably less than that of an oil-, natgas-, or coal-fired power plant or chemical industry. Can reactors be operated safely? The answer is a definite yes.

In the 50-year history of nuclear reactor operations, one finds that most accidents in nuclear power plants or nuclear-powered submarines are of a non-nuclear nature and do not breach nuclear radiation safety features. The most common accidents which cause a reactor to be shut down are malfunctions in coolant flow valves, electronic circuitry, electrical systems, and human error. Because reactor operating procedures require that all reactor electronics be fully functional all the time, a temporary reactor shutdown is sometimes necessary for electronics repair. Such shutdowns cause a costly temporary loss of electric power generation, so in modern reactors, two or more parallel or redundant electronic systems are provided which can take over from each other should one system fall out. This allows quick modular repair of a failing component without disruption of power plant operations.

In addition to simple electronic component failures, other typical non-nuclear accidents have been electrical fires, the failure of a valve in a coolant system, or the cracking of a pipe. Typical nuclear accidents that occurred in earlier phases of the nuclear power program were the swelling and cracking of cladding or encapsulation materials in fuel elements which resulted in the release of some radioactive fission products into the coolant. None of these accidents were catastrophic or caused major radiation overexposure to personnel and most were satisfactorily repaired. Many early mishaps led to significant improvements of component design to avoid similar occurrences in the future.

Radioactivity build-up in reactor coolants is quickly detected by monitors that sound an alarm and, if severe enough, initiate a reactor scram. The contaminated coolant is usually filtered so radioactive products can be removed. Still in a 1957 reactor accident in England, some semi-volatile iodine-131 fission product escaped into the atmosphere due to a sudden crack in a gas-cooled fuel element. It temporarily contaminated a cow pasture adjacent to the Windscale reactor site. The leak was detected by a radiation monitor in the ventilation stack of the reactor and the latter was scrammed. Radiation levels in the pasture and in cow milk subsided below natural background levels in a few months.

Besides in-core fuel element cracking, other typical accidents of a nuclear nature have been the accidental dropping of a spent fuel element which was pulled out of the reactor core for transient storage in a swimming-pool before shipment to a reprocessing plant (Section 6.2). Dropping a fuel element can sometimes crack the cladding or fuel rod, resulting in release of fission product gases such as xenon-133 and krypton-85. Other nuclear accidents which are not strictly reactor related but which happened in fuel processing plants (Section 6.3.2) are the accidental spilling or leakage of radioactive fission product waste from temporary or permanent storage tanks. So far, no radioactive leaks or spills have ever caused a fatality due to radiation, and all have been remedied.

Both the US and Russia have had accidents with nuclear-powered submarines. The US lost the “Thresher” on April 10, 1963 in the North Atlantic ocean, and the “Scorpion” in May, 1968 near the Azores. Russia lost the “Kursk” on August 12, 2000 in the Barents Sea. These accidents did not involve nuclear super-criticality malfunctions, but were due to non-nuclear operational mishaps. The US Thresher and Scorpion are believed to have sunk because of excessive overpressure or collision at great depth in experimental test dives, while Russia’s Kursk sank when an undersea launch of one of its torpedoes misfired and exploded. In all cases the entire crew of 129, 99, and 118 men lost their lives. Reactors on the sunken subs shut themselves down automatically as designed. If not salvaged, the reactors will stay sub-critical for ever and pose no danger, contrary to alarmist’s claims.

7.6 Nuclear Criticality Accidents

Nuclear accidents are most serious if they involve uncontrolled supercritical masses of fissile material (see Section 6.1). Since the beginning (1945) of the age of nuclear power, several purely nuclear “criticality accidents” have taken place. It is important we diagnose how they happened, so repetitions can be avoided. We first briefly describe each accident and then comment on them.

During the ultra-secret Manhattan project, two criticality incidents occurred at Los Alamos, New Mexico. One was in August 1945 and the other in May 1946, each causing one death. In both cases, too much dissolved U-235 or Pu-239 were poured in a container, causing fission and a supercritical "flash" with release of lethal amounts of non-shielded radiation (more than 500 rad). In June 1952, an experimental Chicago reactor overexposed four workers (maximum dose was 176 rad) before it was shut down; all workers fully recovered. On June 16, 1958, a supercritical mass of U-235 was accidentally formed in a drum at the Y-12 fuel processing plant in Oak Ridge, Tennessee. The super-critical U-235-bearing solution "flashed", overexposing eight employees to radiation between 20 and 230 rad. All men were hospitalized but survived. Three were released in 10 days, and the other 5 on July 20, 1958. Still another criticality accident occurred at a Los Alamos plutonium processing plant on December 30, 1958. A supercritical mass of plutonium was created in a receptacle due to a piping connection error, and flashed. One man died in this accident one and a half days after the accident.

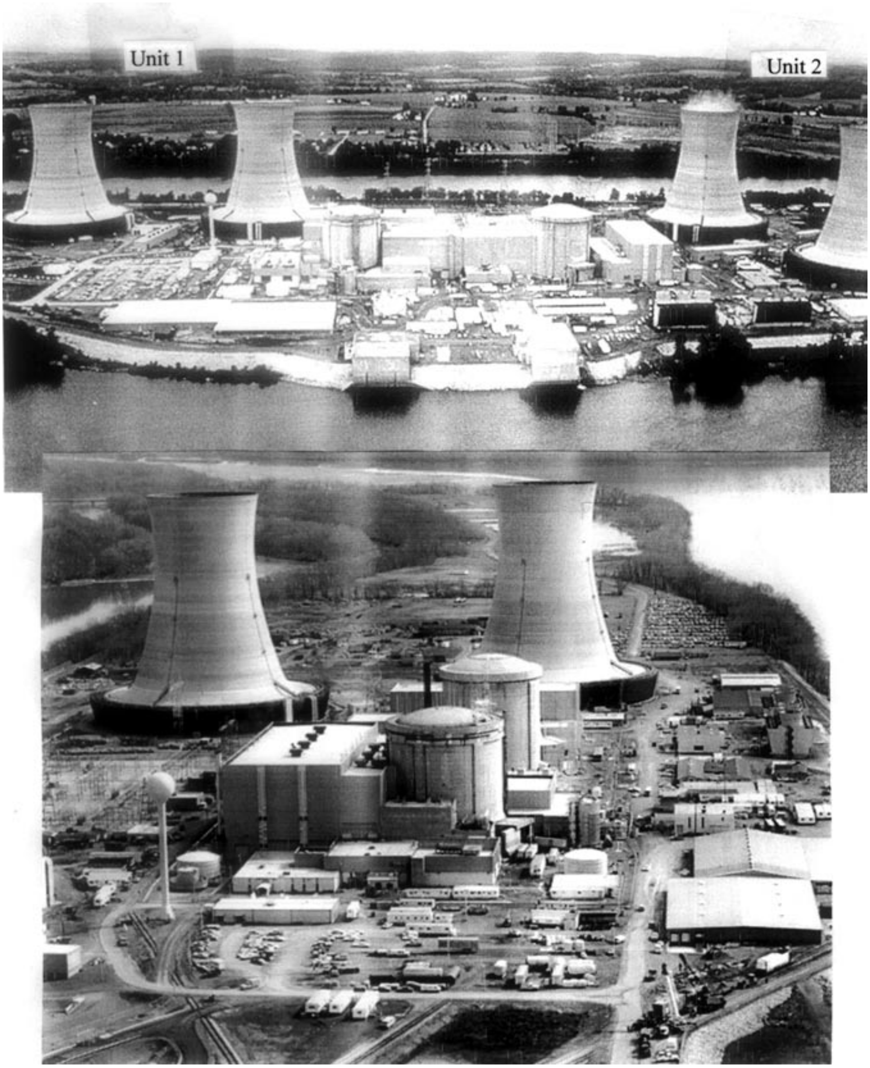
An experimental US Army reactor called the SL-1 went accidentally supercritical on January 3, 1961 at the US Reactor Testing Station in Idaho, when careless experimenters pulled out all control rods. It caused a core meltdown and explosion that killed the three experimenters standing on the bridge above the core. Two died instantly due to flying debris from steam-generated overpressures while the third man died hours later from combined concussions and radiation. Violation of safety rules and unfamiliarity with reactor physics were blamed for the accident. In summary, criticality accidents killed six workers in the US in 1945–1961: three in fuel-handling and three in reactor operations.

In Vinca, Yugoslavia on October 15, 1958, researchers were experimenting with a nuclear reactor when the core went supercritical, causing six people to receive serious overdoses of radiation. One died shortly after the accident, but the other five recovered after receiving bone marrow transplant injections at the Curie Foundation's Institute of Atomic Hygiene and Radiopathology in Paris.

On September 30, 1999, three workers at a nuclear fuel reprocessing plant operated by JCO Company, Ltd at Tokaimura, Japan, mixed batches of uranyl nitrate solutions in stainless steel buckets with 18.8% U-235 enrichment. The total amount of uranium was not to exceed 2.4 kg to prevent criticality, but being in a rush, they added a total of about 16 kg into a precipitation vessel. This amount went critical and started to boil, setting off radiation monitoring alarms on the site some distance away; there were none in the workshed with the precipitation vessel. Upon hearing the alarms and seeing a blue glow in the vessel, the workers ran off. Two were found to have received an estimated 1,700 and 1,000 rem, and a third one 300 rem of radiation. The first two men, whose white-blood-cell counts dropped to zero, died a few weeks later. Bone-marrow transplants were to no avail. The apparently self-controlling critical solution in the precipitation vessel continued fissioning and boiling for 18 h before it was terminated by draining water from a cooling jacket around the bottom half of the vessel which had acted as a neutron moderating reflector. The JCO workers had not had any nuclear training and were unfamiliar with the concept of nuclear criticality. They had previously worked with uranyl nitrate batches that were only 3% U-235-enriched for use in power reactors, and the 18.8% enriched material was a special job for a rush research-reactor order. They were unaware that a higher enrichment was much more serious than simply staying within prescribed quantity limits. After this accident, many new government rules and regulations have been introduced at all of Japan's nuclear reprocessing facilities, including mandatory nuclear criticality physics instructions for all workers handling uranium.

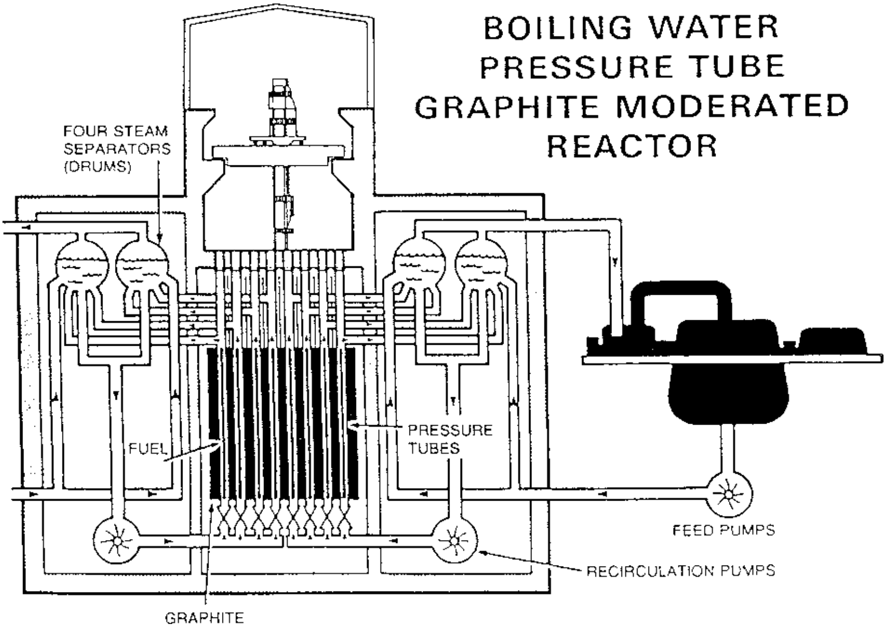
Before describing the Three-Mile-Island (TMI) and Chernobyl reactor meltdowns, we mention that some nuclear accidents took place in Russia during the 1950s and 1960s, which were kept secret by the Soviet government at the time. After the cold war ended, Russian scientists reported that one nuclear accident occurred at Russia's Mayak Plutonium Production facility in the Urals. In 1957 too much fissionable material, more than a supercritical mass, was pumped into a storage tank for liquid "waste" uranium solutions. This supercritical liquid mixture started to boil violently and blew radioactive material over 23,000 km^2 of Western Siberia. After dilution of what was left and temporary transfer to other tanks, the radioactive liquid solutions were later dumped in an artificial lake which still emits low levels of radiation today. In 1968, a windstorm swept radioactive waste from a dried-up lake-bed that had been used as a dump, spreading it over 2,700 km^2. These and the 1986 Chernobyl accident were mostly due to cavalier attitudes in some of the nuclear programs operated by semi-military government agencies. Russia has now instituted much more rigorous safety measures and supervisions similar to those in the USA and Europe to avoid recurrences.

The Three-Mile-Island (TMI) accident in Pennsylvania took place on March 28, 1979. Unit 2 of the two operating PWRs (Pressurized Water Reactors) at TMI developed a failure of a water pump in the secondary coolant loop that takes heat from the primary coolant to the steam turbines (see Briefs 24 and 26). This pump failure initiated a reactor scram that halted the fission chain reaction, but decay heat kept heating the water in the primary pressurized water loop. Pressure build-up in this loop then caused a relief valve to open which allowed some primary coolant water to convert to steam and exit. Unbeknownst to the reactor operators the relief valve was stuck and stayed open, allowing more and more water/steam to escape from the reactor core and causing the latter to overheat. All the while the reactor instruments did not detect that the relief valve was stuck, and falsely indicated that the core was covered with high-pressure cooling water, while in fact the core was partially bare and the high pressure was due to an increasing buildup of steam. The operators mistakenly believed that the core was getting too much pressurized water and shut off the emergency core cooling system (ECCS). This action exacerbated the situation and the overheated core started to melt. Radiation monitors sounded alarms indicating that the core had released vaporized fission products. It finally became clear that the worst had happened: the core had disintegrated and suffered a (partial) meltdown. The containment vessel did perform its function however and kept all nuclear debris contained, as the core slowly cooled down. Two days later, a concern arose that hydrogen gas (H_2) might be building up inside the containment vessel due to radiolysis of water (H_2O) by slowly decaying radioactive products. This turned out to be a false alarm based on erroneous interpretation of instrument data. Release of some steam into the atmosphere which carried minute amounts of radioactivity, exposed those living near the reactor to a dose of at most 1 mr, less than one hundredth from natural sources (see Brief 36). While very costly to the utility, the TMI reactor meltdown did demonstrate the basic soundness of TMI's reactor design and safety features, particularly its containment vessel. Not one person received a radiation overdose in this "maximum credible accident" (= reactor meltdown). Except for destruction of the core vessel inside the Unit 2 reactor building, no buildings were damaged. Brief 39 shows a photograph of the TMI Nuclear Power Plant after the accident.



Brief 39 Photographs of the three-mile-island nuclear power plant after the accident

The most disastrous nuclear reactor accident in the history of nuclear power took place on April 26, 1986 at Chernobyl in the Ukraine. The following is from a report of a special meeting held by the International Atomic Energy Agency on August 25–29, 1986 in Vienna, Austria (Ref. II-20). The Chernobyl-4 reactor was a graphite-moderated boiling water model of Russian design labeled RBMK-1000 (see Brief 40). Tests were being conducted at Chernobyl-4 to check out a new voltage regulation system that allows the inertia of the steam turbines during reactor shut-down to continue delivering enough power during the run-down to pump primary water coolant for a while, before the emergency core cooling system (ECCS) would kick in and take over. The tests involved the powering down of the reactor and the temporary shut-off of some of the core cooling pumps. After several interruptions of the testing program because of electric power grid demands from other units, the power-down was finally carried out. But it went far below the normal 1,000 MWe operating level to 10 MWe instead of the intended 300 MWe level. The operators belatedly corrected for this overshoot by pulling the control rods out again. But because of the usual xenon-poison build-up common to all reactors after a partial shut-down, the reactor behaved sluggishly. To speed up a return to the desired 300 MWe level, they moved the control rods back out excessively and in addition pulled out some manually operated emergency standby control rods. This caused the reactor's reactivity margin to drop below safe limits in violation of operating procedures. Normally this would have initiated an automatic reactor scram, but the operators had turned off this electronic safety feature to speed up their tests. The reactor slowly regained power at first, but cooling water was colder and flowing at higher rates than usual. This caused a decrease in the formation of steam that ran the turbine which was being tested. The other one had been shut down. To counter the excessive water coolant flow, the operators turned off the emergency core cooling system (ECCS) which they were afraid might automatically kick in and exacerbate the steam deficiency that their instruments indicated. When more steam was finally produced, the reactor power suddenly started running up exponentially (a "prompt critical") which the control rods were unable to compensate for fast enough because they were overly withdrawn beyond the margin of safety, and the automatic scram control circuit had been turned off. In a graphite-moderated water-cooled reactor the coefficient of reactivity becomes *positive* when too much water turns into steam inside the core. This means the neutron multiplication chain reaction is enhanced when the temperature increases due to increased replacement of liquid water with steam. Had the reactor been a water-moderated and -cooled PWR or BWR (see Section 6.2.1) both of which have *negative* reactivity coefficients, the reactor would have shut itself down in this situation, even with all control rods out and no water flow.



Brief 40 Diagram of the Chernobyl RBMK-1000 reactor

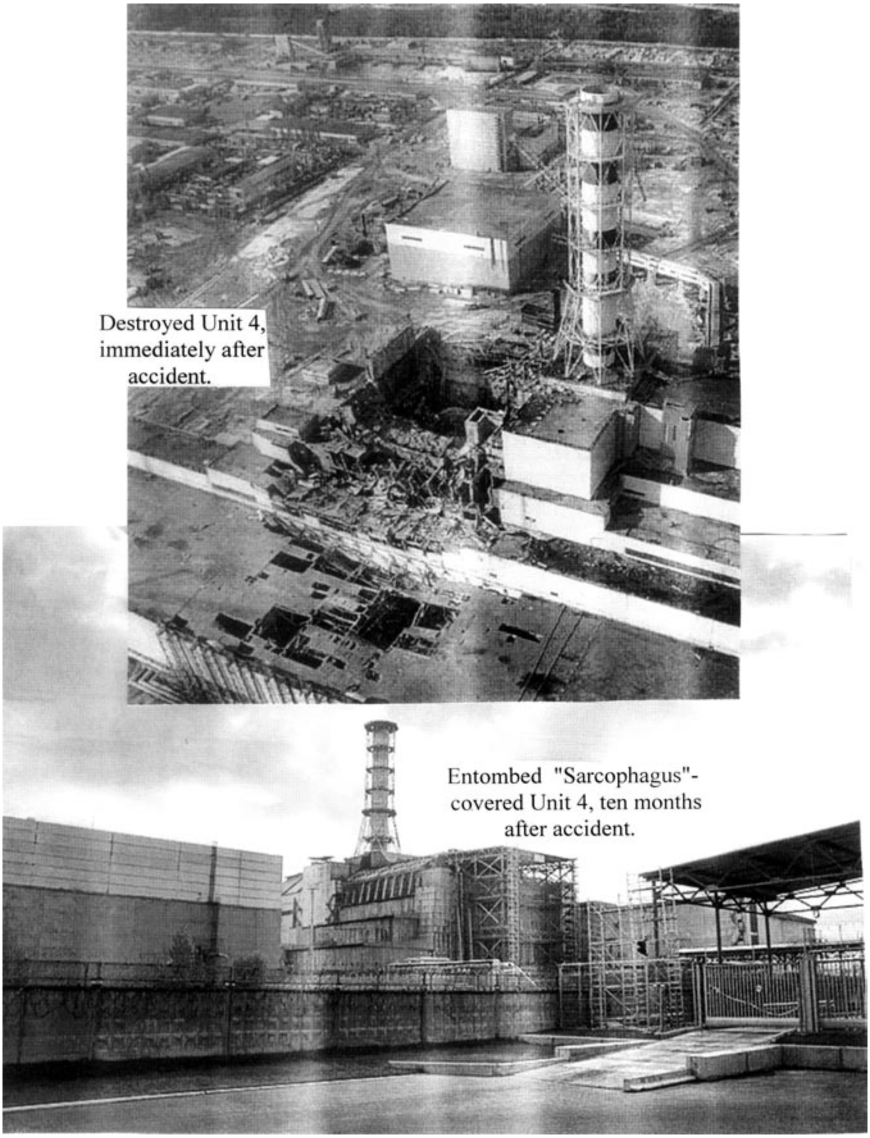
Chart records retrieved from the reactor operating room showed that the following chain of events took place just before the Chernobyl-4 reactor disintegrated. When the reactor operator saw the exponential rise of power, he pushed the emergency manual scram button that activates the dropping of all control rods back into the reactor core. A few ominous shocks were heard next and when the rods appeared not to reach their lower stops, the operator deactivated the electromagnets of the rods to allow them to fall by gravity. A few seconds later two explosions were heard, one shortly after the other, and burning lumps of material shot into the air from the reactor building, some falling on the turbine hall and setting it on fire. Two of the three reactor operating technicians were killed instantly by flying debris, while the third one died an hour later.

Since the Chernobyl reactor had no overall containment vessel and was housed in a hangar-like enclosure, air immediately penetrated the cracked reactor vessel and started to burn the overheated graphite moderator in the reactor core. This fire evaporated large quantities of radioactive fission products in the core and carried them into the air. The resulting plume of contaminated reactor debris deposited radioactive fall-out on the bedroom community of Pripyat, 10 km away. Firemen from nearby Chernobyl and Pripyat were called and rushed over to extinguish the reactor fire, but few if any had ever been briefed or were aware of the effects of nuclear radiation overexposures. A total of 28 of these firemen and other rescue workers died later over a period of 3 months due to heavy overdoses of radiation. Three more died from heart attacks and 11 succumbed from medical complications one to 2 years after the accident. Another 30 rescue workers suffered permanent disabilities. Total human casualties from Chernobyl 2 years after the accident were 45 dead and 30 permanently disabled.

The local administrative bureaucracy reacted slowly and did not immediately grasp the significance of nuclear fall-out radiation. Only after radiation monitoring service personnel from the Chernobyl plant detected serious levels of radioactive fall-out radiation at Pripyat, was the entire population of the town evacuated. The 45,000 residents were also given potassium iodide (KI) pills to prevent possible thyroid take-up of radio-iodine from the fall-out. This proved effective and caused no side-effects. Pripyat is still a ghost-town, but none of its former inhabitants suffered permanent health problems attributable to the Chernobyl-4 fall-out. Alarmists claim that thousands may still die in the future from fall-out consequences, but there is no scientific basis for this.

Besides Pripyat, fall-out from the Chernobyl disaster also fell on more distant meadows where cows were grazing. Milk from these cows was later found to be contaminated with radioactive iodine from the fall-out. A dozen or so children who had consumed this milk were subsequently found by doctors to have some radioactive iodine in their thyroids and were hospitalized for a while. None died from the exposure and all were dismissed after most of the radio-iodine had decayed away. The whole affair could have been prevented if more immediate action had been taken to quarantine all livestock grazing or feeding on land under the path of the fall-out cloud, and if milk and other agricultural products from the effected area had been monitored for possible radioactive contamination. Also more potassium iodide (KI) pills should have been given immediately to all people living under/along the path of the atmospheric fall-out cloud over at least a distance of 60 km.

The Chernobyl disaster has caused Russian reactor designers to completely overhaul and substantially improve reactor safety features. Prior to Chernobyl these had been deemed inadequate and insufficient by US and West-European standards. A Chernobyl-like reactor accident with atmospheric release of fission products could never happen with US or West-European reactors, because of the insistence that an overall containment vessel surround all reactor activities so it can keep all nuclear debris contained in the event of a "maximum credible accident" (MCA). An MCA includes unexpected earthquakes of magnitude 8, the crash of an airplane on the reactor, etc. Although a reactor core and moderator is itself confined by a reactor pressure vessel that can withstand limited overloads of heat and pressure, the containment vessel surrounding the reactor vessel and gamma shield is the final barrier between nuclear reaction products and the atmosphere in case the reactor vessel disintegrates. The TMI accident was of course unintentional but demonstrated the basic soundness of the original 1970s reactor safety design features. Not one person was hurt. Since the TMI accident, a large number of improvements in reactor operational safety and reactor design have been made, making it virtually fool-proof against human error. Unpredictable earthquakes and airplane crashes will cause automatic shut-down scrams, and as mentioned, even if all control rods froze instantly, reactors with negative reactivity coefficients shut themselves down. Sabotage or suicide missions by terrorists could damage a reactor, but they would be unable to initiate a Chernobyl-like explosion in a modern reactor. A negative reactivity coefficient makes it physically impossible for reactors to go much beyond the onset of “a prompt critical” which shuts them down automatically when too much fission heat is generated. Brief 41 shows photographs of the Chernobyl reactor after the accident.



Brief 41 Photographs of the Chernobyl reactor after the accident

The International Nuclear Event Scale (INES) ascribes a value of 4 for the Tokaimura incident, a 5 for the Three-Mile-Island accident, and a 7 for the Chernobyl disaster. This scale is exponential like the Richter scale for earthquakes, so that a 5 is 10 times more serious than a 4, and a 7 is a 1,000 times worse than a 4. Even though 45 fatalities at the worst nuclear accident in Chernobyl are deplorable, 60 years of worldwide nuclear electric power operations with less than a 100 human casualties is remarkable when compared with the thousands of people that have perished in airplane crashes and refinery or chemical industry fires. It should give one great confidence that the nuclear power industry can be and is a safe human enterprise, and a whole lot safer than warfare!

Chapter 8
Nuclear Weapon Controls and Non-proliferation

8.1 The Nuclear Age and World Realities

Because uranium and plutonium are also sources for nuclear weapons, a lot of public concern has been expressed about the danger these materials might pose if they were clandestinely diverted from use in civilian nuclear power plants to more sinister applications. These concerns are the true motives behind many who want to abolish nuclear power. They fear that proliferation of nuclear weapons is promoted by the existence of nuclear power reactors. Thus some keep fabricating unsubstantiated charges that there are "problems" with nuclear waste disposal e.g. at Yucca Mountain, while their real intention is to disrupt nuclear power development. To be believable, they should isolate and separate their valid concern for nuclear weapons proliferation from the issue of whether the operation of nuclear power plants and disposal of radio-waste can be done safely. The two issues are totally distinct and different. In this book I hope I have clearly shown that the second issue is a non-issue and that we have no choice but to expand nuclear electricity production if we want to avoid a no-oil calamity after 2030. Regarding the first issue, some thoughts on promoting non-proliferation are presented below. They require a review of non-scientific unpredictable human mass behavior.

The question is how one can prevent construction and use of new nuclear weapons in addition to those already possessed by the USA, Russia, Great Britain, France, China, India, Pakistan, Israel, South-Africa, North-Korea, and perhaps others. Coarse estimates of present (2009) nuclear weapons arsenals are: USA – 7,900; Russia –14,000; France – 300; Great Britain – 200; China – 400; India – 60; Pakistan – 50; Israel – 150; North Korea – 10. South-Africa destroyed its small nuclear weapon stockpile around 1993. These quantities, particularly of the USA and Russia, are outrageous (Ref. I-33). Would a world-wide ban or moratorium on new construction of nuclear *power plants* as some have suggested, promote the goal of halting further weapons manufacture? In anticipation of arguments given below, the short answer to this question is an emphatic NO! Just the opposite effect will be promoted: increased nuclear weapons acquisitions and proliferation. I base this belief on history and world realities.

J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_8,

Uranium does exist on planet Earth just as surely as the raw materials for nitroglycerine and dynamite. Nobody can change this unalterable fact. Knowledge of how to extract explosive energy from uranium or nitroglycerine for destructive uses is also universal. No amount of book-burning or suppression of dissemination of scientific information is going to change that. Even if one was able to eradicate knowledge of uranium fission in this generation, the next generation will rediscover it for sure. If the present generation shirks its responsibility and fails to organize a world where peaceful use of nuclear energy can thrive as in Eisenhower's vision, it will only pass the job on to the next generation who will try to resurrect it amidst enhanced energy shortages, economic upheavals, and probably widespread warfare for control of the last remaining fossil fuel and coal reserves.

Some anti-nuclear activists who never built an electrical, optical, or mechanical device in their life, often brandish the terms "nuclear technology" and "nuclear materials" without knowing precisely what they mean. They seem to think that the adjective "nuclear" somehow permits separation of techniques and materials used in making nuclear weapons from other technologies and materials, so they conveniently advocate banning all "nuclear technology and materials" with the stroke of a pen. The making of a nuclear weapon entails using nuts, bolts, special metals, electronics, chemicals, etc., which are the same as used in hundreds of modern equipments in laboratories, aviation, the space program, mining, chemical industries, and many other endeavors. The hardware technologies such as calutrons, centrifuges, e-beams, lasers, etc., used in separating medical isotopes for nuclear medicine are the same as in isotope enrichment of uranium. For diagnostics, every analytic laboratory in the world utilizes the same "technologies" as in uranium enrichment. One can not simply issue an edict prohibiting the use of "nuclear technology" without incapacitating nuclear medicine, biotechnology research and development, and many other high-tech operations. The only difference between isotope separation of uranium and other isotopes is the scale, i.e. the quantity that is processed. For nuclear power plants (and weapons), one needs kilograms to tons of material, whereas in most other isotope separation applications only milligrams to grams are needed.

Placing export restrictions on technical equipment to countries that might want to develop nuclear power or possibly weapons only causes such countries to develop their own infrastructure for building "nuclear" components like Pakistan did. The manufacture of high-tech hardware is a matter of investment capital and collecting capable engineers and scientists; many are unemployed and available during recessions. It does not require any "secret" knowledge. The USA once held nuclear fission "secrets" exclusively for a few years during and after WW-II, and some people seem to be under the illusion that only the USA possesses "the nuclear secrets". Secrecy surrounding the US nuclear labs at Los Alamos and Livermore only involves engineering design details, test results, locations, and hard-won quantitative data about nuclear weapons, which of course can not and should not be disclosed to the public. But it should not give one the false impression that no one else can make nuclear weapons.

It is more productive to persuade nations to sign the Non-Proliferation Treaty (NPT) monitored by the International Atomic Energy Agency (IAEA) than to boycott them (Section 7.3). Rather than encumbering international trade and promoting enormous bureaucracies and paperwork that invites corruption, the IAEA should place resident monitors/inspectors (rotated yearly) in signed-up NPT countries which have declared possession or planned possession of complete uranium fuel-cycle facilities. Only countries that refuse to sign the NPT should perhaps be ostracized and kept under continuous pressure to join the world federation of NPT-signed nations.

The problem of a regime change from peaceful to hostile, which might alter or rescind an earlier NPT agreement like North Korea did, is always present and must be dealt with through the United Nations. An unlikely but possible ultimate solution is that all nuclear fuel-cycle operations in the world be placed under management of the IAEA. That is, all fuel-cycle operators in the USA and Europe like USEC, URENCO, AREVA, and all such operations in Russia, China, Japan, India, Pakistan, etc. could be controlled and operated by one global organization. However without competition, innovations and productivity may become stifled and cost-fixing may become a problem. Also, it is improbable that the military would allow their direct access to be severed. A more realistic ultimate solution might be co-management, in which employees of the IAEA NPT-monitoring staff are interspersed among the top administrators of uranium fuel handling organizations.

Some realities in today's world with relevance to nuclear weapons and warfare between nations (terrorists will be considered later) are the following:

1. Many nations and ethnic groups fear domination by neighbors which they resent (e.g. Israel vs Palestine; Iran vs Iraq; India vs Pakistan; North-Korea vs South-Korea; Catholic Irish vs Protestant Irish; North-African Arabs vs African Blacks; Christian Serbs vs Moslem Bosnians and Albanians; Greek Cypriots vs Turkish Cypriots).
2. Many poorer countries have the perception, right or wrong, that citizens of the prosperous USA, EU, and other big powers flaunt superior attitudes of knowing what is best for them. They also feel they are being exploited and deprived of their natural resources to enrich others.
3. No country, least of all the USA, wants to have to rely on another country for support in a conflict that threatens its existence.
4. No country wants to accept the idea that the USA will be the super boss of the world and dictates world policy for everyone.
5. No country believes that the United Nations can settle all wars and disputes fairly.
6. Any nation that presently has abundant energy resources whether oil, coal, natgas, or uranium can wield power (e.g. the OPEC countries).
7. Any country that produces large amounts of electric power efficiently and runs modern industries economically, can produce competitive products that allow it to be in a powerful position opposite other nations (e.g. Japan, Europe, USA, China).

8. Presently, fossil fuels energize all transportation fleets in the world. Their supply is controlled by a small group of giant oil companies and OPEC nations. After oil is gone, a shift to uranium as prime energy source for producing synfuels will assuredly take place. Expansion of nuclear power can not be stopped by opponents simply because they fear it would lead to nuclear weapons proliferation. Countries that possess fuel-cycle capabilities (Section 6.3) and have access to uranium ore will become the future suppliers of portable synfuels, like the big oil companies of today. It should be no surprise that countries like Iran also want to develop such a capability before their oil reserves are depleted. Calls for international sanctions by present uranium-cycle countries to keep others from joining their club, will be perceived as attempts to protect present monopolies.
9. Any sovereign nation of moderate size and means can design and build nuclear power reactors and enrich and reprocess uranium if it decides to do so. The USA, Russia, Europe, China, Japan, India, Pakistan, South-Africa, or Israel have no special privileged information except that they are ahead with research, development, and improvements of the fuel cycle, and have spent at least 5 years and billions of dollars on it.
10. Any sovereign nation of moderate size, if it so desires, can build a nuclear bomb by producing plutonium in a breeder reactor, or by high-level enrichment of uranium. It takes only 3–4 years from the moment such a decision is made, to possess a weapon. A country might decide to do so if it feels threatened. It will intensify its efforts to develop the technology even more, if the superpowers prohibit equipment exports to it (e.g. Pakistan, North-Korea, Libya).
11. A nation in the nuclear weapons club can threaten nuclear retaliation if another nation threatens to overrun it. The best protection against nuclear blackmail is to possess nuclear weapons (e.g. USA and former USSR; India and Pakistan).
12. Detonation of one or even ten nuclear weapons, although abhorrent, is not the end of the world.

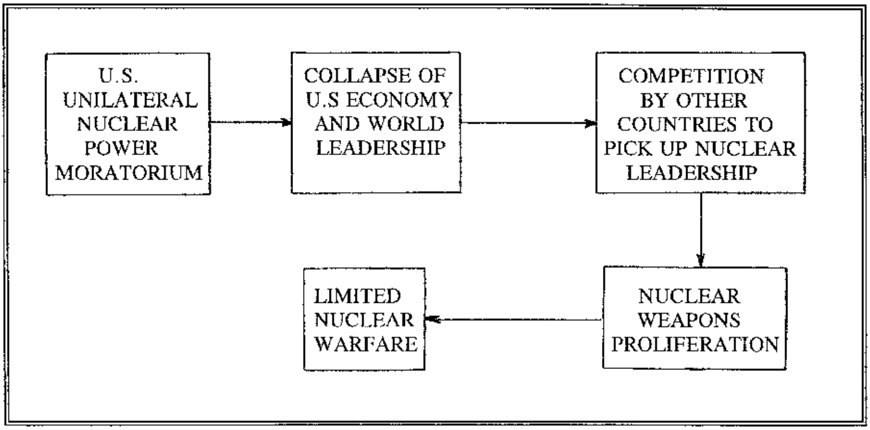
I listed these causes of discontent and insecurity in the world as a reminder that humanity is not at peace, and at any time can generate conflict and warfare. In the twenty-first century, such hostilities may involve the use, or threatened use, of nuclear weapons. This in turn has lead many pacifists to oppose development of nuclear power even for the peaceful generation of electricity. But to curtail nuclear power programs, hoping to prevent nuclear weapons proliferation will not change realities (1) through (12). Halting nuclear electricity generation would be tantamount to committing national suicide. Thanks to earlier forward-thinking governments and industries worldwide, nuclear electric power generation was solidly developed during the 1950–1990 period. Should governments now accede to the whims of special interest groups who clamor for the abandonment of nuclear power, all earlier achievements by diligent energy planners and engineers would be lost for no good reason. If the US abolished nuclear electricity, the escalating costs of imported oil, synthetic fuels, and purified coal would assuredly lower the standard of living and impoverish it as the year 2030 approaches (before total oil depletion arrives). It would be unable to compete in international markets, while more forward-thinking disciplined countries like China take over leadership positions in nuclear power expansion. The proverbial “terror of democracy”, in which a majority of misinformed non-professionals rules and ignores the advice of seasoned professionals, may come to haunt us.

The notion that solar- and wind-power could replace nuclear fission power as a substitute for oil, is incompatible with reality as shown in Chapters 2–4. At best it might provide up to 10% of man’s energy needs after the year 2030, when oil shortages will become severe.[1] That one could learn to do without another 90% through energy saving techniques such as improved insulations, is also a pipe-dream. The other 90% are needed to make synfuels and run the heavy industries that make our cars, trucks, airplanes, ships, bridges, etc. One can not melt and forge steel or aluminum without enormous amounts of electricity and heat energy, which windmills and solar cells alone just cannot provide. No amount of wishful thinking can change the basic laws of physics and economics. I also don’t believe that back-to-nature protagonists will be able to convince third-world citizens they should stick to tending camels and llamas, and burn animal dung for cooking food and heating their huts. Most young people in the third world want energy-consuming cars, stereos, televisions, computers, refrigerators, etc.

Though I digressed from the subject of nuclear weapons proliferation, the main point here is that the privileged in the world can not force others on the planet to accept their philosophies and viewpoints. One can influence, frustrate, and delay the realization of other people’s aspirations but one can never control them forever, as shown by the collapse of totalitarian communism. Should the USA impose a nuclear power moratorium like Germany did, other nations who comprehend the gravity of the upcoming oil-depletion crisis more clearly, will take over nuclear power development. This includes the capability of building nuclear weapons. Acquiring or stockpiling nuclear weapons will be encouraged particularly if it appears that the balance of power is shifting in the world. If a country is no longer sure of its own security, it is going to take countermeasures. No amount of pleas by pacifists and others with noble intentions are going to change such a trend, as history has shown over and over again. In conclusion, it is my belief that the result of any moratorium on further development of nuclear power will enhance worldwide nuclear weapons proliferation instead of abating it, as illustrated in Brief 42. How we might minimize and best cope with nuclear weapons proliferation is the subject of Section 8.3, after we first consider the problem of terrorists who wish to blackmail the world with nuclear weapons.

---

[1] Recent announcements that Denmark obtains 20% of its electricity from wind-mills, only applies to that country’s electric grid. If energy from natural gas and petrol used by its transportation fleets are added, the wind-energy percentage of *total* energy usage is less than 10%.



Brief 42 Likely chain of events after a unilateral moratorium on nuclear plant construction

8.2 Safeguards Against Terrorists

It has been suggested that a terrorist gang could steal nuclear fuel elements from a reactor and make a bomb out of it. As already mentioned in Section 6.2.3, the fuel elements of a nuclear reactor are totally unsuitable for a bomb. If terrorists wish to build a nuclear weapon from reactor fuel elements by stealing them from a nuclear plant, they must steal several hundred highly radioactive fuel elements from two or more nuclear reactors. They must first construct a hundred-million-dollar special fuel reprocessing plant whereto they can take the stolen reactor fuel. Next they would have to spend 6 months or so to carefully extract fissionable uranium and plutonium in such a plant and figure out how to construct a nuclear bomb, which requires a technically very advanced group of engineers. Clearly from the review of criticality accidents in Section 7.6, ignition of a nuclear critical mass like happened at Tokaimura, does not produce a Hiroshima-like explosion. To make an effective nuclear bomb requires extensive research and backing by a sovereign government. For an illegitimate gang trying to pull off such a project clandestinely after armed robbery of two or more reactors is certain to catch the attention of the world's intelligence agencies and international police (Interpol).

Another possible target for terrorists might be "hot spots" in the nuclear fuel cycle (Section 6.3), where large amounts of enriched uranium and plutonium occur in concentrated form, namely enrichment plants, reprocessing plants, and nuclear fuel element fabrication plants. Even after overpowering all the guards of such heavily guarded installations, and carrying off all the raw plutonium or highly enriched uranium, the job of making a workable nuclear bomb from these materials is still a very complicated task. Actually many precautions are taken at enrichment, reprocessing, and fuel fabrication plants, that make it very difficult to obtain enough material for a bomb in one raid. To avoid any accumulation of a critical mass, many of the operations in these plants are compartmentalized so that there is never more than half a critical mass in any one section. To obtain enough for a nuclear weapon, one would have to raid many compartments, each one of which can be hermetically sealed remotely by guards in case of an emergency or alarm. If nevertheless successful, terrorists would have to take precautions to keep sub-critical quantities of nuclear fuel taken from different cells separated, lest they don't incapacitate themselves with a supercritical flash (Section 7.6). If on a suicide mission they might do this intentionally, but the resulting nuclear flash and resulting damage would remain localized, similar to the Tokaimura criticality accident in Japan. There would be a minimal effect to the general public.

Stealing small amounts of U-235 or Pu-239 by a corrupted insider in any one of the three fuel handling plants of the fuel cycle is easier done but still difficult. Small processing losses of fuel always occur and it is possible that if such stolen losses are small enough, they would go undetected. Modern accurate accountability controls and certifications, thorough personnel screening for security clearances, and monitoring of workers entering and leaving the plant at all times, should minimize the chance of small-quantity thefts of fissionable materials. From many years of operation, the statistics and amounts of processing losses in these plants are well established now and discrepancies can be quickly detected. If someone stole such small amounts that losses would be undetected, he would have to spend many years collecting before he had enough for a critical mass. Quite possibly he would have changed his mind by then to make a nuclear bomb.

Still another operation that might be vulnerable to terrorist attacks is the shipment of unirradiated (fresh) U-235 or plutonium fuel elements when they are transported from the fuel fabricator to a reactor plant. To minimize the consequences of armed attacks and thefts, precautions are usually taken which include insuring that the amount of fuel in one transport is less than required for a critical assembly. Thus the theft of fuel from two or three transports would have to be carried out if the objective of the terrorists is to obtain enough for a nuclear weapon. Should a shipment of irradiated fuel elements with freshly bred plutonium be attacked and robbed on its way to a reprocessing facility, not much could be done with the stolen fuel since it is intermixed with Pu-240 and other neutron "poisons" that prevent nuclear chain reactions. It is the reason why the shipment was on its way to be "reprocessed" to take out undesirable elements that inhibit nuclear fission. Thus unless the terrorists possessed a reprocessing facility or just wanted to produce a scare, such a heist would be useless to them.

Recently the news-media have disseminated a lot of "chatter" about "dirty bombs". Such bombs would be made of ordinary explosives except that they would be seeded with radioactive materials, most likely fission products. They rely mostly for their effectiveness on the fear-factor of many citizens for things "nuclear". While a bomb is still a (lethal) bomb, the fact is that little extra is accomplished in terms of casualties by putting radioactive elements in a bomb charge. Except for casualties killed by the non-nuclear shockwave of the explosion, bystanders covered with radioactive dust will survive and can be de-contaminated by washing off the dust and/or taking a shower. Should radioactive elements from the bomb blast include iodine, strontium, and cesium, and should some dust have been inhaled or ingested, pills can be taken by victims to help eliminate these biologically unfriendly species (see Sections 6.4.2 and 7.6). Radioactive dust is easily traced with radiation monitors. Objects covered by it can be decontaminated with "radwaste", a soapy solution that soaks up most radioisotopes. In conclusion, "dirty bombs" can never have the same effect as a real nuclear bomb explosion with kilometers of massive destruction; damage would be the same as from a non-nuclear device except it generates fear and requires a radioactivity decontamination crew to clean up.

Instead of stealing fuel elements out of nuclear reactors, or obtaining nuclear fuel from enrichment and reprocessing/fabrication plants, or from transports between them, a more likely possibility is that a terrorist gang might attempt to steal a complete nuclear weapon from any one of the nuclear arsenals around the world. Though contents and locations of such arsenals are kept secret, a well-organized terrorist gang might infiltrate the military and discover how to break into one. The military have of course considered this and have taken appropriate countermeasures. The theft of a complete anti-aircraft missile some years ago in Germany shows that stealing a military weapon is not entirely impossible. One special measure for nuclear weapons that prevents or frustrates such a possibility is that nuclear warheads usually require final assembly of one or more separated special parts that can be inserted only by one or two officers to produce a trigger-ready critical mass. These officers must have special tools to "arm" the weapon but can only do so if given coded instructions. While details must remain secret, it is believed that last-step critical weapon components to be mated are stored at different locations only known to and accessible by the special-duty officers, whose identities are kept confidential and who are frequently rotated. Thus should a terrorist succeed in breaking into a weapons storage bunker, he would still only be able to get an incomplete un-usable nuclear weapon. If tampered with by non-coded tools, alarms may go off and neutron poisons released internally that make the partial bomb totally un-fissionable, even if another stolen bomb half (or part) were to be brought in contact with it to increase critical mass.

Military and professional nuclear engineers around the world have worked with nuclear materials for over 60 years and have long learned how best to safeguard these materials against unfriendly interveners, including terrorists. Besides the precautions already discussed, additional secret safeguards exist which so far have successfully prevented any terrorist from capturing a nuclear device. Unless a rogue sovereign nation cooperates, clandestine capture of a functional nuclear weapon by terrorists is about as impossible as breaking into Fort Knox to steal gold. A much simpler and more frightening way for extremists to terrorize a civilian population is their use of chemical or biochemical agents.

After the September 11, 2001 attacks on the New York World Trade Center, security has been considerably increased at power plants, water treatment facilities, chemical plants, oil refineries, and other vulnerable factories. Armed guards, monitors, and concrete barriers have been placed around most of them to protect against terrorist attacks. The question often asked is what havoc can result if in spite of all these measures, a terrorist suicide team would succeed in entering a nuclear power plant after killing the guards and capturing the reactor operator(s). Most likely, the reactor operator would have scrammed (shut down) the reactor before they could get to him. This makes it physically impossible for the reactor to restart immediately due to so-called “xenon poisoning” (built-up of neutron absorbing xenon from post-operation nuclear decay). Should terrorists capture the operator somehow before a scram, and force him at gunpoint to pull out all control rods, the reactor would still shut itself down because of the negative reactivity produced by overheating. It also automatically activates the emergency core cooling system (ECCS). If the terrorists disabled the ECCS, the core would partially melt. However except for some gaseous xenon and krypton, core contents would stay in the core vessel (Section 6.2), because core materials are solid or now a liquid melt. The result would be the same as what actually happened in the TMI accident (Section 7.6). The large outer containment vessel (Brief 23), would still keep core-vessel-escaped gases contained should the core vessel crack.

In a suicide mission, terrorists would probably detonate a bomb in the reactor control room, once inside. This would destroy all reactor controls, but as stated, the reactor shuts down automatically. It is almost impossible for bomb fragments to penetrate the 1-ft (30 cm) thick steel and concrete shell of a containment vessel. Even armor-piercing mortar shells would have difficulty puncturing it. Should it be breached, the negative pressure maintained in most containment vessels would inhibit outflow of radioactive core gases, and only permit inflow of air or pure nitrogen if so designed. Unlike the Chernobyl reactor whose core was made of ignitable graphite and which had no containment vessel, core-burning fires can not break out in a water-moderated reactor. The radioactive cloud produced at Chernobyl could never occur. In conclusion, a successful terrorist infiltration of a civilian nuclear power plant would at worst result in a TMI-like core melt-down, with reactor operations personnel most likely killed.

8.3 The Non-Proliferation Treaty (NPT) and International Atomic Energy Agency (IAEA)

With the unpleasant picture painted in Section 8.1, one asks how one can best prevent or minimize the proliferation and use of nuclear weapons by unfriendly sovereign nations. We have already argued that inhibiting the expansion of nuclear electric power will set the stage for an enormous world energy crisis when oil runs out. Only with nuclear electricity is it feasible to empower the large fleets of electric plug-in vehicles for short-haul transport and power for heavy industries, as well as large-scale manufacture of synfuels to replace petrol for our long-haul transportation systems. And this can be done without biosphere pollution. By sharing man’s accumulated knowledge and the planet’s resources with everyone, more people in the third world will have hope for a tolerable existence, and chances are less that warfare will break out for control of the last remaining fossil fuels on earth.

A free exchange of nuclear reactor information world-wide, started under President Eisenhower's "Atoms for Peace" program, would unite nuclear engineers and scientists from different nations and insures regular contacts. If somewhere in the world a country would suddenly place a nuclear project "off limits", the world would be forewarned that someone may be "diverting" for nuclear weapons. Pressure could then be brought upon that country to disclose its intentions and to cease further "diversions". If on the other hand information exchange about nuclear power technology were restricted between nations, a country could much easier conceal any work on nuclear weapons.

What still appears to be the best international solution to the nuclear weapons proliferation dilemma is the so-called Non-Proliferation-Treaty (NPT), and the NPT monitoring and enforcement program of the International Atomic Energy Agency (IAEA) headquartered in Vienna under the auspices of the United Nations. The 1970 NPT is an international agreement signed by many (but unfortunately not yet all) countries in the world who pledge not to "divert" uranium or plutonium fuel from use in nuclear reactors to use and development of nuclear weapons. By signing the NPT, countries also allow periodic inspections of their nuclear facilities by officers of the NPT enforcement arm of the IAEA. Any plant or facility in the nuclear fuel cycle that handles uranium or plutonium is defined to be a nuclear facility. Thus nuclear reactors, fuel element fabrication plants, reprocessing plants, enrichment plants, uranium mines, and radiowaste disposal facilities all qualify as nuclear facilities. Of these, the main "hot spots" where diversion is most easily carried out are: (a) reprocessing plants; (b) enrichment plants; and (c) fuel element fabrication plants. The fuel placed in nuclear reactors is itself only "reactor-grade" and unsuitable for weapons unless it is purified to "weapons-grade". Even reactor fuel elements that use plutonium could not be changed into a bomb device without considerable reprocessing, enrichment and reconstitution, requiring high-vacuum furnaces and other expensive chemical processing equipment.

While the 1970 NPT was a good start towards the curtailment of nuclear weapons worldwide, a second follow-on international agreement, called the "Comprehensive (Nuclear) Test Ban Treaty" (CTBT) provides additional assurances that the further spread of nuclear weapons is controlled. It was first formulated in 1996 and finally ratified in 2005 by the minimum of 44 countries of the United Nations (UN). Nearly all countries that signed the NPT have now (2009) also signed the CTBT, except for a few hold-outs. The CTBT strengthens the NPT in that it allows the CTBT enforcement body to conduct unannounced inspections of nuclear facilities in CTBT countries and obligates the signatories not to allow any independent group to develop nuclear weapons on its territory (Ref. I-34). It also tightens and clarifies some language in the NPT that has led to misinterpretations and circumventions. The CTBT and NPT enforcement staffs are both headquartered in Vienna, Austria and work together under the IAEA of the UN.

At the heart of a successful nuclear safeguards program is a strict accountability program for uranium, thorium, and plutonium. Theoretically if one could track every gram of these three elements around the globe, one would have a perfect NPT/CTBT monitoring system. In the USA and other countries that signed the NPT/CTBT, anyone possessing or overseeing work with enriched uranium or plutonium for whatever reason, must be licensed and by law must maintain an accounting of every gram of these materials. The accountability records must be open to inspection by IAEA agents at all times. While such accountability measures are enforceable in the USA and most other NPT/CTBT countries, there are large gaps at present which makes a worldwide system fallible. Natural uranium can be bought freely from a number of sources in the world and could be (has been) secretly enriched in a non-NPT country. Even if present major uranium and thorium mines and suppliers would register and account for all their transactions, new ore deposits are discovered all the time and could be kept hidden. However to enrich natural uranium requires conversion to gaseous uranium hexafluoride which is much easier to track.[2] Thus keeping an account of the manufacture and subsequent routing of uranium hexafluoride should enable NPT/CTBT monitors to determine its downstream use. Two tons of hexafluoride are needed to enrich natural uranium (0.7% U-235) for production of either 10 kg of weapons-grade (99% U-235) uranium, or 210 kg of reactor-grade (5% U-235) material. In the first case there would be a tails stream of 1.97 t of depleted (0.2% U-235) uranium hexafluoride, while for reactor-grade enrichment 1.79 t of 0.2% depleted uranium hexafluoride tails would exit the enrichment plant. Thus even if direct measurement of U-235 enriched samples is denied or difficult, monitoring the large quantities of uranium hexafluoride feed and tails entering and leaving an enrichment facility, discloses how much material was enriched and to what level.

Although the NPT/CTBT program has not been signed by all countries in the world and there are still imperfections, it is a positive step in the right direction. Notably weapons-possessing India, Pakistan, and Israel have refused to sign because the original five weapons countries USA, Russia, France Britain, and China who formulated the 1970 NPT agreements, have not carried out their promise to greatly reduce and ultimately eliminate their stockpiles. No fixed timetable was set in 1970 for the dismantling of nuclear arsenals held by the weapons-possessing countries. Only very recently did the USA and Russia meet to discuss gradual arsenal reductions to around 1,600 weapons each within 7 years. Presently Russia possesses approximately 14,000 and the USA about 8,000 nuclear weapons!

Instead of searching for alternatives to the NPT such as moratoria on enrichment and further expansion of nuclear power, it is the author's opinion that the only realistic approach to avoid nuclear proliferation is to continually improve, strengthen, and upgrade the existing international nuclear safeguards program. One of the first objectives should be to persuade all nations that have not done so, to sign the international NPT/CTBT agreements. Some countries who refuse to sign the NPT/CTBT on grounds that it gives the weapons-possessing superpowers and other non-signatories a big advantage in a future conflict (which is a reasonable position)

---

[2] In spite of more than 60 years of uranium enrichment research, the most suitable form for uranium isotope separation remains gaseous uranium hexafluoride (UF_6). Enrichment of uranium metal vapor by the calutron and AVLIS processes are the only non-hexafluoride methods that produced experimental batches of enriched U-235. While technically feasible, both have been abandoned for being too costly for large-scale industrial uranium enrichment.

might be offered a provisional or modified NPT/CTBT agreement similar to the one recently hammered out between India and the USA. This agreement would allow possession or the making of a limited number of nuclear weapons, provided they are registered by the IAEA, and with the promise they will never be used except in defense of the country's existence or other restricted set of circumstances. It is better to know than not to know who has nuclear weapons. With such an agreement, late-joining countries should also pledge to support the ultimate goal of a total worldwide nuclear disarmament by all nations. To further persuade a nation which presently refuses to sign the NPT/CTBT to join, a guarantee might be offered that the country's sovereignty and boundaries will be respected by all other nations of the UN. This idea is admittedly simplistic and difficult to implement for example in the Middle East or the Koreas. However negotiations might at least be initiated and an attempt made to find possible solutions that avoid future nuclear armed conflicts.

Returning to the technical aspects of a NPT/CTBT-governed future world, it is in principle possible today for a global satellite system to monitor all major constructions, excavations, and earth-moving operations on our planet and to keep tabs on for example uranium and thorium mining. In fact the characteristic emissions from radon gas which is almost always present near piles or tailings of uranium ore may be used to detect such activities. Once uranium is concentrated and refined, detection and tracing of its whereabouts becomes more difficult until it is converted into uranium hexafluoride, where a lot of detectable fluorine is used. A two-part global nuclear fuel tracing and monitoring system might be effective: Satellites would keep a continuous global watch over new uranium/thorium mining operations and movements from the mines to uranium hexafluoride manufacturing plants or other sites, while remotely monitored tamper-proof tagging systems would separately track, verify, and double-check such movements. The concept of monitoring uranium mines was already proposed as early as 1946 by Robert Oppenheimer, chief scientist of the WW-II Manhattan Project.

Assuming all nations have signed the NPT/CTBT or a modified treaty so that IAEA inspectors can monitor fissionable fuel movements in every country, an IAEA team can be dispatched to any spot on earth where a new unannounced uranium/thorium mining operation is discovered by the global space-watch satellite system. All productions of uranium and thorium at mines in any part of the world are thus logged and entered into the global accountability system of the IAEA. Shipments of ore from mines to fluoridation plants or other uranium pre-processing plants are also monitored and accounted for at all entry and exit points much like money-balancing operations employed in world-wide banking.

Since uranium is radioactive and emits characteristic gammas and neutrons that can be sensed by detectors, engineers can think up many schemes that could make the nuclear accounting system semi-automatic. Of course random inspections must still be made by IAEA officials to ensure that installed uranium monitors are operating properly and not compromised. False and secretly hidden monitors whose locations are randomly switched now and then may be deployed to protect against possible fraud. To design, develop, and install a reasonably tamper-proof monitoring system for nuclear accountability requires more in-depth studies but is feasible. Special protection and measures against terror gangs bent on making a nuclear weapon as considered in Section 8.2, would of course be an integral part of the overall worldwide nuclear safeguard program. The IAEA's future NPT/CTBT enforcement organization may thus consist of one or more central terminals located at strategic locations in the world which collect space satellite data and ground-based readings from monitors around the globe. A daily balancing of the books would be carried out by computer and if irregularities appear anywhere, a special team of NPT/CTBT officers is dispatched to the location for a check-out.

Anonymous rewards should be given to anyone who reports a cheating event or a conspiracy to steal nuclear fuel if proven correct. That such awards are given should be widely publicized. Jail sentences for guilty parties should be stiff and internationally agreed upon to deter anyone from trying to cheat the system. The NPT/CTBT police force should have direct liaisons with Interpol and national police forces in the world as well as with international intelligence agencies. A concerted international cooperative manhunt could be started if and when it is found that nuclear material had been stolen by criminals.

Countries that join the provisional NPT/CTBT program with a small stockpile of nuclear weapons, can register these with the IAEA, but the whereabouts could remain a military secret of the country. Pledges are obtained from such countries that adequate safeguards are maintained to prevent some madman in the military establishment of the country from starting a nuclear war. Information on safeguard techniques to prevent such a possibility, as practiced by the USA and Russia, should be made available to all nuclear club members. It is hoped that ultimately a world order can be achieved where all nuclear weapons are turned over to the IAEA and reprocessed for fuel in nuclear reactors.

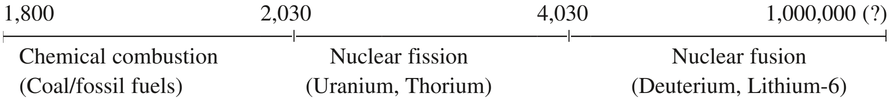
In organizing the IAEA's NPT/CTBT enforcement organization, great care must be taken that it can function semi-autonomously and not be subjected to partisan political pressures from powerful members of the United Nations. People in key positions of this organization should be chosen from scientific institutions all over the world. They should have impeccable reputations for honesty, have reached a certain level of maturity, and be moderate in their personal political convictions. Their appointment to office must be approved multi-nationally perhaps by a 60% majority vote in the UN. It is very important that IAEA overseers of the NPT/CTBT agreements be impartial yet undeceivable. Accusations that a country is "diverting" made by another nation for political reasons, should be evaluated with impartiality. No judgments can and must be made by the IAEA without hard technical evidence that the accusations are correct. It is important to keep in mind that any sovereign country has the right to possess, operate, and acquire nuclear reactors for electric power generation or radioisotope production. It is also entitled to carry out all the necessary fuel-cycle processes of mining, isotope enrichment, fuel fabrication, reprocessing, and waste disposal for its nuclear power program. As long as a NPT/CTBT-signatory country allows entry by IAEA inspectors to verify compliance at any time and unannounced, it can not be demanded that it forego development of a fuel-cycle process only because it *might* lead to development of a nuclear weapon.

Some may still feel that the cost and labor involved in running and maintaining the IAEA's NPT/CTBT program are excessive and that it will be ineffective. They still would like to simply ban all nuclear activities including nuclear power plant development. Such people should be reminded once more of the fact that the reason the NPT/CTBT program is needed is because of the weapons aspects of nuclear materials, *not* nuclear electric power. We don't abandon flying airplanes because they can be used alternatively in warfare to bomb cities. Even if it was impossible to build nuclear power reactors from the same materials, the world needs a NPT/CTBT program to curb or minimize chances of nuclear warfare. Knowledge that nuclear weapons exist and can be built is an irreversible fact today which we must learn to live with. When compared with the cost of military establishments of different countries, the international NPT/CTBT police force is rather inexpensive, considering that such an organization can impede, moderate, and ultimately cause a ban on the use of nuclear weapons on our planet. It is worth every financial investment that is needed!

Those campaigning against nuclear electric power plants because of their fear of other Hiroshimas, are urged to study this book for the complete story ("the rest of the story" as US radio commentator Paul Harvey was fond to say). If convinced of the safety and pollution-free features of nuclear power plants and the benefits they bring to man, they ought to re-evaluate their thinking and campaign for a stronger and better IAEA-NPT/CTBT police force. Foreign governments that are still uncommitted should be persuaded to join the NPT/CTBT club. That nuclear energy will be interwoven with our future is a certainty whether wanted or not. Rather than fighting change as is the natural tendency of many, being open-minded and understanding of our changing world is more productive. These changes are less frightening when one comprehends the true issues and knows what needs to be done. If proper safeguards are developed, nuclear energy can become a blessing for all future generations instead of a perceived curse. The dire predictions made by some doomsday prophets of pending calamities due to energy and material shortages will only come true if the benefits from nuclear technology are withheld from our children.

Chapter 9
Conclusions, Action Items, and Predictions

Past and future exploitations of prime energy sources by man might be charted as follows:



This time-line is based on the calculated resource depletion periods discussed in Chapter 3 and today's knowledge of atomic and nuclear physics. Most scientists are quite certain that present knowledge is sufficient to assess the order of magnitude of dormant energies in molecules, atoms, and nuclei. However how to best harvest that energy can change. Cold fusion (Section 6.4) for example, if proven feasible, could alter the above timetable and bring fusion extraction schemes into the picture earlier. "Dark energy" is another mysterious force of nature discovered by astrophysicists and cosmologists, which some day may be understood and perhaps utilized by man. However waiting for a miracle should not delay preparations for the nuclear fixes needed by 2030; we are running out of time.

9.1 Synopsis

Green nuclear power is the only practical solution to simultaneously (1) avoid dependence on foreign oil and gas, (2) overcome future oil and gas depletion, and (3) ameliorate global warming. Only two prime energy sources, coal and uranium, can affordably deliver terawatts of "mother" electricity to: (a) feed heavy industry, i.e. manufacture of automobiles, ships, airplanes, bridges, etc.; (b) power vast fleets of future electric plug-in autos; and (c) produce enormous quantities of portable synfuels (hydrogen and ammonia) and biofuels to replace oil. However coal worsens global warming and should be preserved as raw material to make plastics and other organics when oil and gas are gone. This leaves uranium and thorium as the only "big-mama" green energy source, an "inconvenient truth". There is only one economic engineers-certified solution to overcome impending worldwide energy shortages. This is the

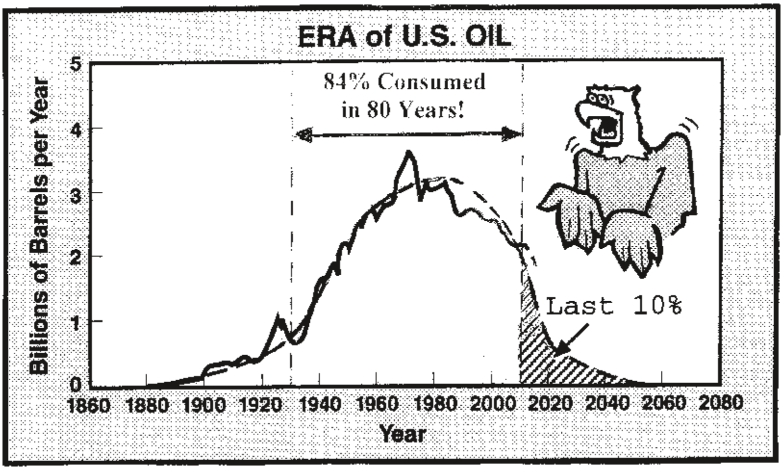
J.W. Eerkens, *The Nuclear Imperative: A Critical Look at the Approaching Energy Crisis (More Physics for Presidents)*, Topics in Safety, Risk, Reliability and Quality 16,
DOI 10.1007/978-90-481-8667-9_9, © Springer Science+Business Media B.V. 2010

introduction of GEN-IV power reactors that burn up all available uranium and thorium to give the whole world at least 3,000 years of all the electricity and heat it needs. It can be done most prudently by developing multinational nuclear fuel (re-) processing operations like the proposed Global Nuclear Energy Partnership (GNEP) program to be monitored by the International Atomic Energy Agency (IAEA). Integrated GNEP facilities can provide GEN-IV fuels optimized for fast breeder reactors that are essentially useless for weaponry (Section 6.3.2).

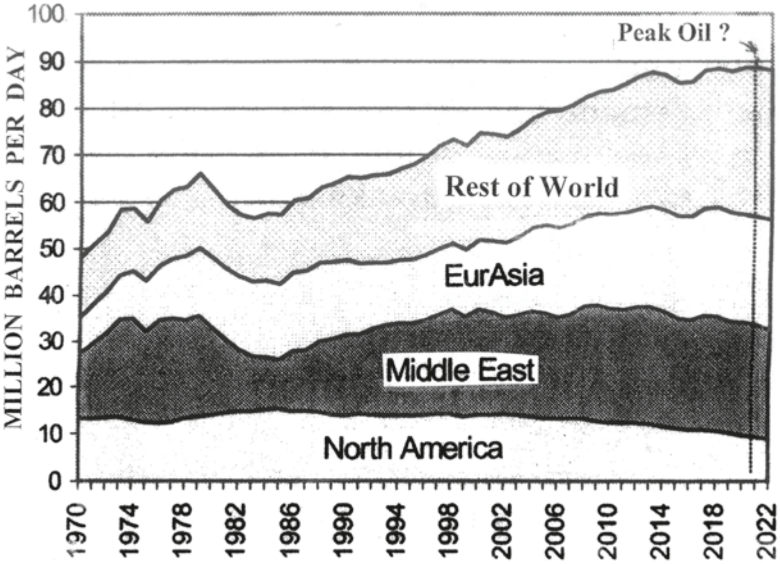
Popular solar and wind energy are useful for small-quantity power generation in select locations and in future energy mixes may contribute as much as 10% of all electricity generation. But at terawatt levels, they can not compete with nuclear power generation. Immense areas of land or sea would be needed, requiring enormous maintenance operations, spoiling scenic land- or sea-scapes, and destroying local ecosystems – an absolute nightmare for naturalists (Chapter 4). A serious in-depth analysis of future energy shortages by professional engineers (*not* by anti-nuclear armchair philosophers) reveals that nuclear power will be absolutely essential to rescue our children from a future economic catastrophe. By the year 2050, at least 500 (preferably 700) additional nuclear reactors should be running in the USA, built on 9,000 acres at a cost of $1.5 trillion. The same amount of energy could theoretically be provided by 1,500,000 windmills with storage batteries on 6,000,000 windy acres costing more than $4.5 trillion. Ten times these numbers, that is 5,000 reactors or 15,000,000 windmills are needed for the entire world. These costs are in 2005 US dollars. For later years they must be multiplied by the dollar inflation factor of course. While it is theoretically possible to run exclusively on windmills, one does not have to be an economics wizard to see that a country doing so will become impoverished and dependent on imported synfuels produced in countries that decided to rely on nuclear fission power instead.

Because it takes 8 years to design, license, and build a reactor, action must be taken immediately to prevent a worldwide depression after 2030 when oil begins to run out. Delusional anti-nuclear groups claim that the cost of electricity from wind or solar is less expensive than nuclear while the facts are just the opposite. Solar and wind power generation requires expensive energy storage systems (batteries, etc.) when there is no sunshine or wind. Also many miles of access roads for maintenance and repair are needed to keep blades or solar panels clean from bird droppings, dead birds, sand erosion, and storm damage, and to periodically replace electrodes on storage batteries. Aficionados of renewables usually quote peak windmill or solar station capacities, neglecting to multiply their numbers by a factor of 4 to account for a year-averaged availability of only 25% of peak wind or sunshine. Reactors run continuously all year at 90% capacity. As mentioned, should a country limit itself to solar and wind energy, it is guaranteed to become impoverished and dependent on portable synfuels imported from other countries (future OPECs → OSECs), who expanded their nuclear power generation before oil fields were depleted.

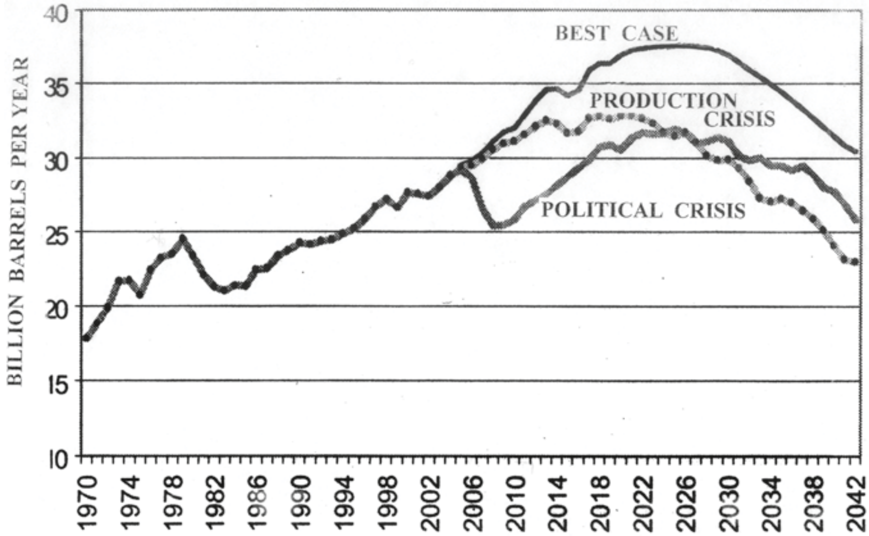
Energy for transportation consumes between 35% and 40% of all energy usage in the world. On the assumption we stop drilling when it costs a gallon of oil to retrieve a gallon, one finds we will run out by 2040/2050, even with exploitation of all the tar-sand fields in the world and horizontal drilling. There is only so much volume in a 1 km thick layer that circumscribes our earth where decayed plants and animals, mixed with lots of sand and river run-off mud, were compressed into oil over a period of 300 million years after being pushed down to deeper levels (≤10 km) by continental drifts and subductions (Brief 1). We are burning all that up in two centuries. With an increasing world population and with Asia and Africa wanting more of the oil, optimistic estimates show it will all be gone by 2050. While in the next 15 years, oil and gas may remain major sources of portable chemical energy for aircraft and transport vehicles, beyond 2030 the world can only survive if synthetic fuels are produced on an enormous scale. Briefs 43–45 show past and estimated future oil production rates and forecasted peak-oil points for the USA and the world (Refs. I-11, I-13, I-17, I-18). They clearly show that the end of inexpensive oil is only one generation away.



Brief 43 USA oil production rates



Brief 44 World oil production rates by geographic region – peak oil



Brief 45 Esitmated world oil production under three different scenarios

Nuclear energy extracted from uranium or thorium can of course not be used directly as a portable fuel to move long-haul transport vehicles (airplanes, trucks, etc.). But its heat or turbine-generated electricity can be converted into portable bio-fuels and other hydrogen-carrying synfuels with reasonable efficiency. In bio-fuel production, nuclear electricity can empower farms and extraction/distillation operations to obtain alcohols or bio-diesel fuels from vegetation. Without input of (nuclear) electricity, bio-fuel farming would be unsustainable since energy needed for cultivation, harvesting, and extraction exceeds the chemical hydrocarbon energy stored in combustible plant or algae. Nuclear-assisted farmed bio-fuels have other limitations however. They can at most replace about 20% of today's petroleum fuels because biofuel farming is limited by available arable land; man also needs to grow food to survive. The other 80% of oil-replacement must come from hydrogen and ammonia synfuels which can empower combustion engines as well as possible future fuel-cells. Hydrogen can be affordably produced by electrolysis or chemical dissociation of water into hydrogen and oxygen. But hydrogen has the fundamental problem of being very difficult to compact into a reasonably-sized fuel tank. So ammonia (called "second" hydrogen by some) is now favored, because it can be stored at very moderate pressure in normal-size fuel tanks for a driving range comparable to that of today's cars. Ammonia is produced by compression of hydrogen with nitrogen obtained from air (80% nitrogen) via the well-developed Haber-Bosch process. This is a less expensive way of storing hydrogen than liquefying it. Ammonia can fuel combustion engines which are already commercially available as well as future solid-oxide fuel-cells, and is less dangerous than gasoline in vehicle collisions. Exhausts of ammonia combustion are again water vapor and nitrogen (air) from which it was synthesized with nuclear "mother" energy – an ideal recycle scheme.

Modern nuclear power plants are absolutely safe. Because of the negative "coefficient of reactivity", reactor fuel elements can only melt during a maximum credible accident in which the emergency core cooling system totally fails. An explosion is not possible. This was "experimentally" proven in the Three-Mile-Island (TMI) accident. A negative coefficient of reactivity means that neutron multiplication is automatically stopped when the temperature in the reactor gets too high. The Russian Chernobyl reactor, which took the lives of 45 people, had a positive coefficient of reactivity because it used graphite as moderator. Such a design for nuclear power plants is now prohibited in all countries. Furthermore the Chernobyl reactor had no containment vessel, as is the law in all Western countries and now worldwide. The assertion that perhaps thousands of people could still die from radioactive fallout around Chernobyl is nonsense. Of the 60,000 inhabitants of Pripyat who were exposed to some fallout, about 9,000 will die at an advanced age of cancer because worldwide 15% of all people ultimately die from cancer. To ascribe those 9,000 deaths to Chernobyl's fallout is equally ridiculous as claiming that such a death toll is due to drinking coffee because 15% of all people drink coffee. Security precautions and containment measures for today's nuclear power plants do reckon with the possibility that terrorists might crash a large airplane or bomb on a reactor. Even if aerial obstructions or underground construction can not prevent penetration of the large dome-shaped containment vessel, the reactor core vessel is designed to remain mostly intact. It can further be inundated with neutron-poisoning borated water which suppresses all further uranium fission in case of an accident.

A stale anti-nuclear cry is "what do we do with all the long-lived radioactive nuclear waste". The volume of waste amounts to one aspirin tablet per year per person using nuclear electricity, compared to tons of air pollutants and globe-warming gaseous CO_2 emitted by coal or fossil-fuel combustion. Nuclear waste can be easily stored and safely transported, as the US nuclear navy has done for half a century. Contrary to allegations that uranium and plutonium in spent fuel elements pose a problem because of million-year half-lives, they are separated from fission products by reprocessing and burnt as fuel in future fast-breeder reactors. They will not be dumped. This reduces 60 t of spent fuel per reactor per year to 2 t of fission products (with shorter decay lives), taking centuries instead of decades to fill the Yucca Mountain repository in Nevada. The notion that long radioactive lifetimes are undesirable is also erroneous. The longer the decay lifetime, the less the radiation emitted per gram of radio-isotope. Most elements that make up our bodies like hydrogen, oxygen, nitrogen, etc., have infinitely long decay lifetimes. All humans are "hot" because everyone has radioactive potassium-40 (K-40; 0.012% abundance) and carbon-14 (C-14 at ~1 ppb) in his body which continuously emit beta particles with half-lives of one billion years for K-40 and 5,700 years for C-14! Man successfully evolved in this environment, and there are even indications that low levels of radiation benefit health, called hormesis. The hue and cry about the possible use of "dirty bombs" by terrorists is also highly exaggerated. The mechanical destruction caused by such bombs is the same as by any other chemical explosive; it is not at all like a nuclear weapon. Radioactive particle dispersions from dirty bombs can be readily decontaminated with liquid radiac solutions since radioactivity is easily detected. By the reasoning of anti-nuclear activists, we should stop flying 707 jets or stop taking ocean cruises because jets can be used as weapons to hit skyscrapers and ocean cruisers can run into icebergs, killing thousands of people.

Energy is man's third most important need after water and food. Those who hinder expansion of nuclear power will be viewed as irresponsible neo-luddites by future generations and must be held accountable. Any further delay of a committed worldwide nuclear energy program will cause certain impoverishment and deaths of many people by 2050. Without large-scale synfuel production by greatly expanded nuclear power, desert cities like Las Vegas and Phoenix will become ghost-towns. Originally the US had planned to have 200–300 reactors at 1 GWe each by the year 2000, but instead there are only 105 today. After the Three-Mile-Island (TMI) reactor meltdown in 1979 in the US (with zero casualties), and Russia's Chernobyl accident in 1986 with 45 fatalities, public hysteria fanned by fear-mongering antinuclear activists caused cancellations and moratoria on construction of new nuclear plants. While the USA was once the leader, most US businesses with reactor manufacturing know-how closed. Instead France, Russia, Japan, South-Korea, India, and China are now in charge. Anti-nuclear lobbyists, a mal-informed government, and suffocating regulations/taxations have driven out and are still expelling US technical capabilities in nuclear and related fields. They are directly responsible for the looming energy crisis. We are entering a war-like energy-deprivation period as serious as WW-II or Al-Qaida. Strong Manhattan-project-like leadership is now needed to reverse the short-sightedness and follies of prior administrations.

9.2 Action Items

To avoid a disastrous energy crisis after 2030 (Briefs 43–45) and minimize excessive global warming, high-tech developments based on proven science must take place concurrently on four fronts:

(I) Synfuel Selections, Testing, Mass-Production, Storage, and Distribution
(II) New Propulsion Engines (Fuel Cells and Combustion Engines) – Testing and Mass Production
(III) Nuclear Breeder Introduction – Selection, Testing, Deployment; Fueling, and Burner Conversions
(IV) Coal Use Reassignments; Organic Chemicals Syntheses; Coal → Nuclear Plant Modifications

In previous chapters we explored what possibilities exist in the above listed areas based on known science and restrictions imposed by well-established proven physical laws and economics. New discoveries or inventions sometimes break conventional wisdom, but so far none have broken the conservation laws of physics for example. Innovations, improvements, and new inventions will certainly help us but we cannot rely on physics-violating hope-laden dreams or "may-be"s. Based on the given surveys, I believe that research and development (R&D) in the next 20 years must include the following:

9.2.1 Development of Synthetic Fuel (Synfuel) Manufacture, Storage, and Distribution

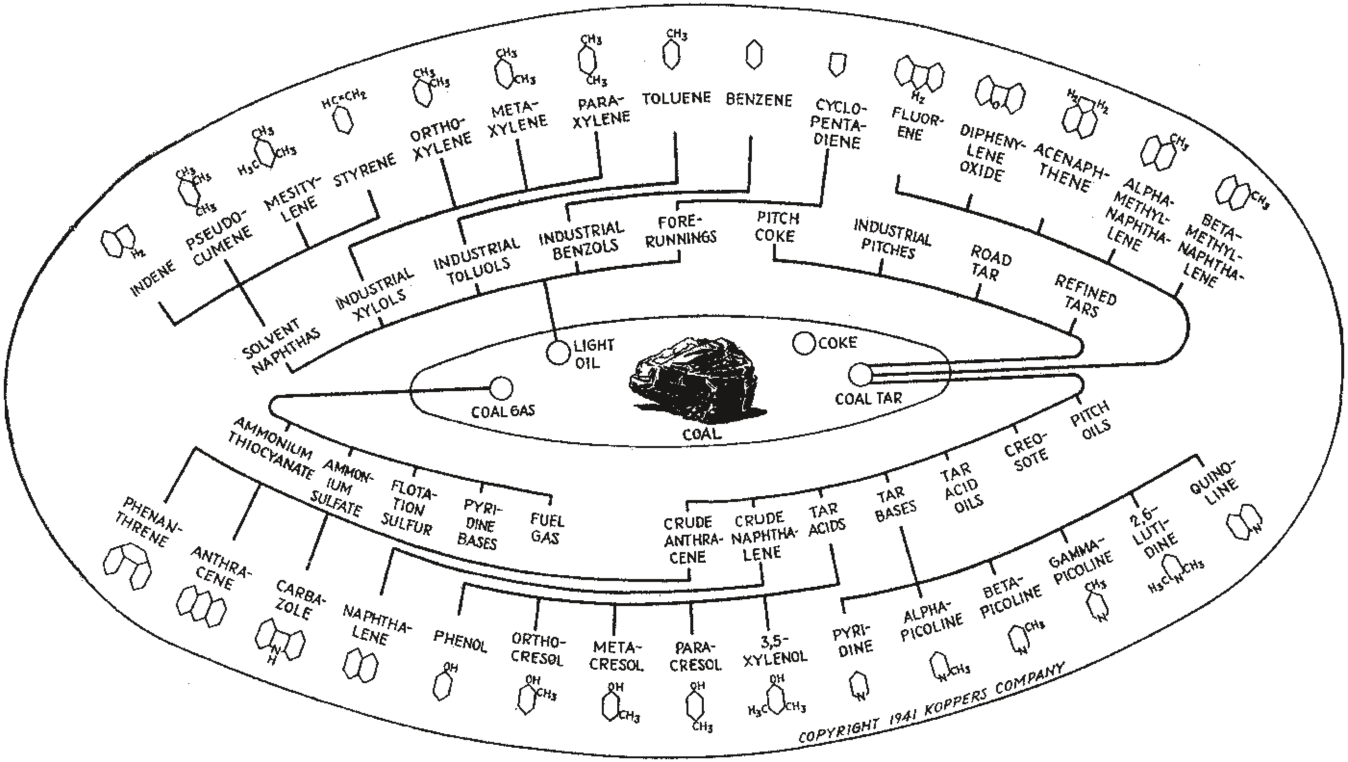
(a) Large-scale synfuel production of hydrogen (H_2) from water (H_2O) + nuclear heat or electricity: by sulfur-iodine catalysis; by electrolysis, by other economic methods.
(b) Synfuel production of ammonia (NH_3) and hydrazine (N_2H_4) from water (H_2O) + air (N_2) + nuclear heat or electricity. Stabilization of N_2H_4 (e.g. hydration).
(c) Biofuel production from agri-crops (e.g. corn) + sunshine + nuclear heat or electricity. Production of ethanol (C_2H_5OH), methanol (CH_3OH), etc. to replace petrol or electricity.
(d) Hydrocarbon synfuel production from coal (C) + water (H_2O) + nuclear heat or electricity. Production of synpetrols propane (C_3H_8), butane (C_4H_{10}), (C_mH_n), and acetylene (C_2H_4) by SASOL process to bridge interim period between petrol- and uranium-consumption eras.
(e) Porous adsorption materials ("bladders") for storage of gaseous synfuels H_2, NH_3, CH_4, etc.
(f) Development of improved high-pressure tanks for hydrogen (H_2) synfuel storage in automobiles and aircraft.
(g) Distribution of hydrogen and ammonia gas; synfuel filling stations and transfer techniques.

While pure hydrogen would be the preferred synfuel in automotive fuel-cell engine applications, hydrogen's compactibility problem, requiring liquefaction to extremely low temperatures or storage in high-pressure tanks to reduce hydrogen volume, makes this gaseous fuel somewhat problematic. Research on adsorptive storage of hydrogen in porous bladders has also been disappointing. In addition, countrywide distributions of hydrogen fuel pose problems. Unless storage and distribution difficulties for hydrogen can be solved in the next decade, liquid ammonia, which has been called "second" hydrogen, looks more attractive as a portable synfuel for automobiles. It is produced by compressing nitrogen (air) with hydrogen obtained from electrolyzed water and can be safely confined as a liquid under a modest pressure of 12 atm in a fuel tank. It has been used in agriculture for decades.

Hydrogen and ammonia for use as fuels in ICEs has been technically proven and tested. Liquid-ammonia-burning engines are already being marketed for farm operations (tractors and standby power generators). Possible NOx formation from atmospheric nitrogen and oxygen due to high-temperature combustion can be negated by modern catalytic converters, but has been found unnecessary for ammonia-burning ICEs. To run fuel-cell engines (FCEs), ammonia (NH_3) can also be used as fuel but it must first be catalytically decomposed to hydrogen (H_2) and nitrogen (N_2) on an FCE proton exchange membrane (PEM) to allow passage of pure hydrogen through it. Liquid hydrazine (N_2H_4) can similarly be used in a fuel-cell after catalytic decomposition into hydrogen and nitrogen. However hydrazine is less stable than ammonia and less desirable for public use, unless a good stabilizing agent can be found. Catalytic decomposition of ammonia or hydrazine by ruthenium alloys to provide hydrogen on fuel-cell PEMs has been demonstrated. There is virtually no generation of NOx in low-temperature-operated FCEs. Ammonia can be used directly in solid oxide fuel-cells (SOFs) without prior reduction to hydrogen (Refs. III-8–III-11). After some operational problems in present SOF technology are solved, ammonia can be used as a future fuel for both SOF/FCEs as well as ICEs.

Bio-alcohol, which is liquid and more similar to petrol, might be preferred for internal combustion engines (ICEs) if it were not for the extremely large areas of farm land needed for continuous biomass cultivation to satisfy the demands of our vast transportation fleets. Together with the availability of adequate amounts of nuclear electricity or heat, bio-alcohol production may still be an affordable partial solution for oil replacement in countries with large areas of thinly populated arable lands, such as Brazil and the USA. Brazil has apparently chosen this path to overcome the pending out-of-oil crisis by expanding both nuclear power generation and bio-alcohol production. As discussed earlier, emissions of carbon-dioxide by burning bio-alcohols is exactly balanced by the intake of carbon-dioxide during bio-fuel plant growth, so there is no net atmospheric increase of this greenhouse gas. During the petroleum → uranium era transition period, it may be prudent to convert coal to petrol or propane/butane fuels for a decade or so using Fischer–Tropsch or other SASOL synthesis techniques (Section 5.1.1). This would allow uninterrupted fueling of our fleets of long-haul transportation systems for a while until sufficient added nuclear power generation can supplant coal as a prime energy source, and new green synfuels like ammonia can be mass-produced sustainably. After new green synfuels for long-haul transportation become widely available, production of portable transport fuels from coal should be halted and synthesis of plastics and other organics from coal should be phased in (Brief 46 and Section 9.2.6).

Coal conversion fuels produced under item 9.2.1(d) would irreversibly add carbon-dioxide to our biosphere from engine exhausts. If continued, science-based calculations predict this will overburden the atmosphere and cause excessive global warming by mid-century (Section 1.2). Nevertheless, item 9.2.1(d) is important to provide an interim source of long-haul propulsion fuels till new synfuels are mass-produced. SASOL-type synfuels can assist in overcoming near-future oil shortages by bridging the critical period between present and pending expansions of nuclear power plants that are needed to enable mass-manufacture of new synfuels and introduction of new engine technologies. Also under 9.2.1(d) new pathways for making hydrocarbons, plastics, and other organics from coal should be advanced after oil is gone as raw material (Brief 46).



COPYRIGHT 1941 KOPPERS COMPANY

Brief 46 Derivative organic compounds obtainable from a lump of coal

9.2.2 Portable Energy Storage Devices

(a) Low-weight portable electric storage batteries and super-capacitors for vehicular propulsion
(b) Improved low-weight portable flywheel devices (mechanical batteries) for vehicular propulsion

Electrical and mechanical batteries look quite attractive at first glance. Unfortunately nature does not allow electrochemical energy stored in a given mass and volume to exceed that obtainable from the combustion of a portable synfuel or petrol of the same mass and storage volume. To achieve a given travel range for an automobile (e.g. 600 km), one needs 10–30 times more mass if the vehicle is powered by a freshly charged battery than if it is propelled by a portable synfuel-consuming engine. This restricts the use of electric battery devices to short-range (inter-city) applications in mass transportation (Section 5.1.2). To accommodate long-distance driving, it is important to develop automotive batteries with the lightest possible weights, and such that they can be exchanged or rapidly recharged every 100 km with wall-plug electricity. In Section 5.1.2, the best (i.e. lightest) automotive lithium battery was reported to have an energy/weight ratio of 200 Wh(e)/kg = 0.72 MJ/kg. Assuming that it takes 0.72 GJ(e) of electric energy to move an average car 600 km (373 mi), one would need 1,000 kg = 2,200 lb of battery to achieve this goal. Even if one assumes that the overall efficiencies of electricity-to-mechanical-to-road-distance conversions can be improved by 50%, for example with a small light-weight stripped-down car and optimum tire pressure, the required electric battery weight to drive 600 km would still be 500 kg = 1,100 lb, the weight of five heavy passengers! Mechanical flywheel batteries (Section 5.1.3) don’t fare much better and are even worse at 0.3 MJ/kg assuming that the highest tensile-strength material can be used to hold a heavy rotating mass together. Nevertheless they may be used for city buses and rail transport and possible improvements should be investigated.

For a typical automobile driving range of 100 km (60 miles), the required electric battery weight is about 160 kg (370 lb). This can be accommodated for commuter driving if battery recharging can be done in home garages and workplace parking lots. It is expected that within the next 20 years most commuter transportation will be via plug-in battery-powered vehicles. It is difficult to see how the Wh(e)/kg ratios of electric batteries could be improved much, given that lithium is already the lightest electrolyte element that nature can provide. Only nuclei have much higher captured energy densities than atomic electrons. But except in nuclear reactors and space vehicles, presently the controlled release of their energy can not be safely handled in the format of an automobile. An unexpected discovery based on a new phenomenon to provide more portable electricity for automobiles is of course not entirely impossible but very unlikely. At this point in time (2009), the optimum solution for future (post-2030) versatile automobiles appears to be a plug-in hybrid vehicle powered by a lithium battery for short-haul duties, and a synfuel-burning ICE for long-haul travels. Work to improve, lighten, and “ruggedize” lithium batteries for automotive applications should be vigorously pursued in the coming years even though physics indicates it will be difficult to increase the energy/weight ratios much above 1 MJe/kg (= 700 Wh(e)/kg). Using super-capacitors instead of batteries to draw off stored electric energy should also be investigated. But so far they appear incapable of doing better than electro-chemical batteries.

9.2.3 Development of Advanced Automotive and Aircraft Engines

(a) New ICEs burning H_2, NH_3, N_2H_4, C_2H_5OH synfuels with N_2, H_2O, or CO_2 exhausts (no NO_x)
(b) FCEs consuming hydrogen (H_2), ammonia (NH_3), alkanes (C_mH_{2m+2}), or hydrazine (N_2H_4)

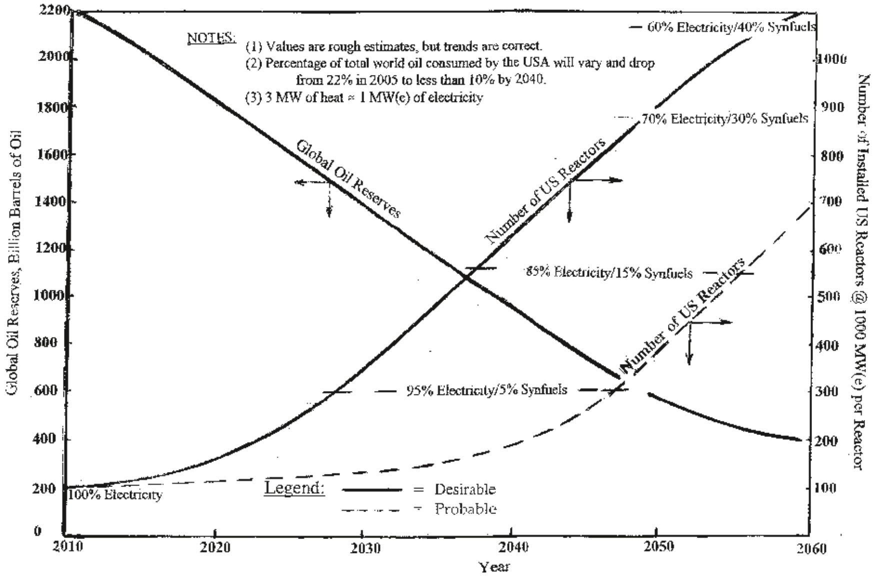
Besides providing long-haul land and sea transport vehicles with new sustainable synfuels and engines, our current fleets of aircraft must also be retro-fitted with new engines and synfuels to keep on flying after 2030/2040. Portable synfuels with a high energy-content/volume ratio are particularly of interest. An intensive program is needed to evaluate jet engines that burn bio-alcohol, ammonia, and stabilized hydrazine synfuels or derivatives to establish whether these fuels are suitable for air commerce when aviation fuels (kerosene, etc.) are no longer available. Costs and field-tested operational performances should be closely examined and compared. If bio-alcohols prove to be superior, the 10–15% of agricultural harvests that could sustainably produce oil-replacing bio-fuels should be used exclusively for weight- and volume-sensitive aircraft propulsion. Land- or sea-borne vehicles should then concentrate on perfecting hydrogen, ammonia, and stabilized hydrazine fuels for locomotion. Otherwise pure or mixtures of bio-alcohol and ammonia synfuel should be explored for all types of engines. In the interim, before oil fields are totally exhausted, (jet) engines that can burn coal-derived liquid synfuels produced via SASOL-like processes might be developed to replace present oil-based aviation fuels for aircraft propulsion.

The development of new ICEs should go hand in hand with new synfuel developments. Different materials for engine blocks and fuel handling may be needed than those used heretofore with petrol or diesel fuels. Tests are also needed to explore the possibility of propelling aircraft with fuel-cell engines (FCEs) instead of internal combustion engines (ICEs). Small private aircraft might be checked out first to see if a light-weight FCE can propel them affordably.

9.2.4 Breeder Reactor Development, Testing, Deployment, and Burner-to-Breeder Conversions

(a) Uranium → plutonium breeders
(b) Thorium → uranium breeders

As discussed in Section 1.4, the biggest challenge will be to have 900 breeder reactors deployed in the USA and 8,000 world-wide by mid-century. Within the next 10 years, one or two basic GEN-IV breeder reactor designs must be selected for mass deployment. Both uranium/plutonium and thorium/uranium breeders should be explored and tested (Section 6.2.2) and an optimum design selected. They must be built and fielded on a scale comparable to the WW-II mass-production of transport ships in the USA, but with stringent safety and durability features. After selection of optimum designs for uranium- and thorium-based breeders, a comprehensive fast-track construction and deployment program must be formulated and integrated together with introduction of new synfuel engines and synfuel mass-production technologies. It will be necessary to determine early on whether nuclear heat or electricity (or a mix) is preferred for manufacturing hydrogen-based synfuels (Section 5.1.1). This can be investigated in pilot plant operations with electricity or heat from non-nuclear sources. Heat-generating breeder reactors could probably be built more quickly than electricity generating units which require large steam turbines and sophisticated electrical components. A strong government leader must be appointed to conduct this war-like effort. Brief 47 illustrates the US nuclear expansion program necessary to stave off a collapse of Western civilization. The horizontal tags on the "desirable" and "probable" curves for US nuclear reactor fleet expansions show a gradual increase in how much of the generated nuclear energy is converted to electricity and how much is used for manufacturing synfuels. Ultimately approximately 40% of all nuclear energy should be applied to making bio-farmed and hydrogen-based synfuels for the transport sector of our economy.



Brief 47 Required growth of nuclear power to balance oil depletion

Breeder reactors can consume depleted uranium which has been accumulating over the last 30 years at uranium enrichment plants that presently serve burners. Thus initially there is little need to increase uranium mining activities until these reserves are depleted. This is a bonus not available to the coal-burning option (Section 1.4) which would have to vastly expand mining operations. Also the final nuclear waste produced by breeders is much less than that created by burner reactors, so underground nuclear waste storage facilities can be utilized for much longer periods of time (hundreds of years) before they are filled.

Comprehensive studies should also be initiated to assess the changes and costs of converting present and near-future-built burner reactors into breeders. While reactor cores and primary cooling systems and their controls require total replacement, the steam and electricity generation components are the same and could be integrated into a new breeder plant. Even more important, the entire infrastructure of a nuclear plant such as safety, security, cooling towers, facilities, site preparations, etc. need not be redone. Entry into the reactor containment structure to allow future installation of a new breeder core and coolant system should be considered in design and construction of near-term “new-build” burners.

9.2.5 Reprocessing, Enrichment, and Fabrication of Reactor Fuels

Although separate enrichment, element fabrication, and fuel reprocessing operations may continue to be the modus operandi for the fuel cycle for a while, for the longer term a GNEP or similar concept discussed in Section 6.3.2 will probably prove to be more economic and proliferation-proof in spite of opposition by some stubborn anti-nuclears. Integration of these three functions in the nuclear fuel cycle allows optimum design of fuel compositions that can extend reactor re-loading intervals to decades instead of years and greatly reduce final fission wastes for disposal. New dry pyro-processing and more versatile laser techniques to enrich and separate fuel isotopes or mixtures of different chemical fuel species should be investigated to improve the reactor performance and proliferation resistance of future breeder fuels (Refs. II-18, II-22, II-23). Integrated GNEP installations could also provide reactor fuels and fabricate fuel elements for U-233 and U-235 burner reactors for a few decades until all reactors are converted into breeder types.

9.2.6 Coal Usage Reassignment Programs

(a) Conversion of coal power plants to nuclear power plants with retention of existing steam turbines.

(b) Synthesis of organic compounds from coal, for plastics and other organics-dependent industries.

Coal-burning electric power plants might be converted into uranium-burning plants since steam generators are similar and usually housed in separate parts of the plant.

Because many coal-burning power plants already exist, it would be worthwhile to explore the cost and feasibility of such a conversion when it is deemed essential to limit globe-warming carbon-dioxide emissions. Many coal power plants may not be suitable for such conversions because sites for nuclear power plants are subject to more stringent requirements. Nevertheless a number of coal power plants might be on suitable sites for nuclear power generation and a conversion might be economically worthwhile.

When oil is no longer available, organic chemicals presently extracted from crude oil must be synthesized from coal as the major feed material (Brief 46). Programs to provide new pathways for providing such organics must be ramped up and be ready to go into mass production by the year 2030. Some coal-burning power plants may be converted into electricity- and heat-providing sources for the manufacture and synthesis of coal-derived organics and synfuels. They already have railroads in place that transport and supply coal from the mines. Eventually heat and electricity for operating these plants would be provided by nuclear reactors instead of by burning coal.

9.3 Anticipations

All R&D programs listed under 9.2 should receive continuous government funding for at least the next three decades to be effective.[1] Government labs, universities, and industries must all be engaged, and students must be trained to build and maintain a solid knowledge base. New educational programs must also be initiated to increase public understanding and acceptance of nuclear energy (Chapters 6–8).

It is important to re-emphasize that we are *not* considering a mere expansion or improvement in clean electric power generation. We are faced with the necessity to have petrol substitution started by 2030, and to supply *all* of man's future energy needs after 2050, that is electricity + portable fuels, without the use of oil, natgas, or coal. This leaves us with only uranium as a non-renewable prime energy provider. Proposals to expand renewable energy sources such as solar, wind, and biomass, and the introduction of strict energy conservation laws, can only be supplemental in providing adequate urban and rural electric power. If pushed too far and if done at the exclusion of nuclear power expansion, such measures will impoverish and severely diminish present-day comforts in the general population. Although domestic electricity represents only 35% of the total energy pie (see Brief 2), it can affect all other energy sectors.

Denmark recently claimed to have reached its maximum capacity for wind-power generation, which supplies 20% of its electric grid. However this is only 8% of its *total* energy consumption if one includes its use of petrol, diesel, and natural gas.

---

[1] Under the leadership and foresight of William Magwood, the US Department of Energy launched several initiatives in 2004 for R&D on advanced (breeder) reactors and synfuel production (hydrogen, etc.) from nuclear heat and electricity. While encouraging, the US House and Senate need to expand such funding considerably and (re)start advanced breeder reactor development as a national priority.

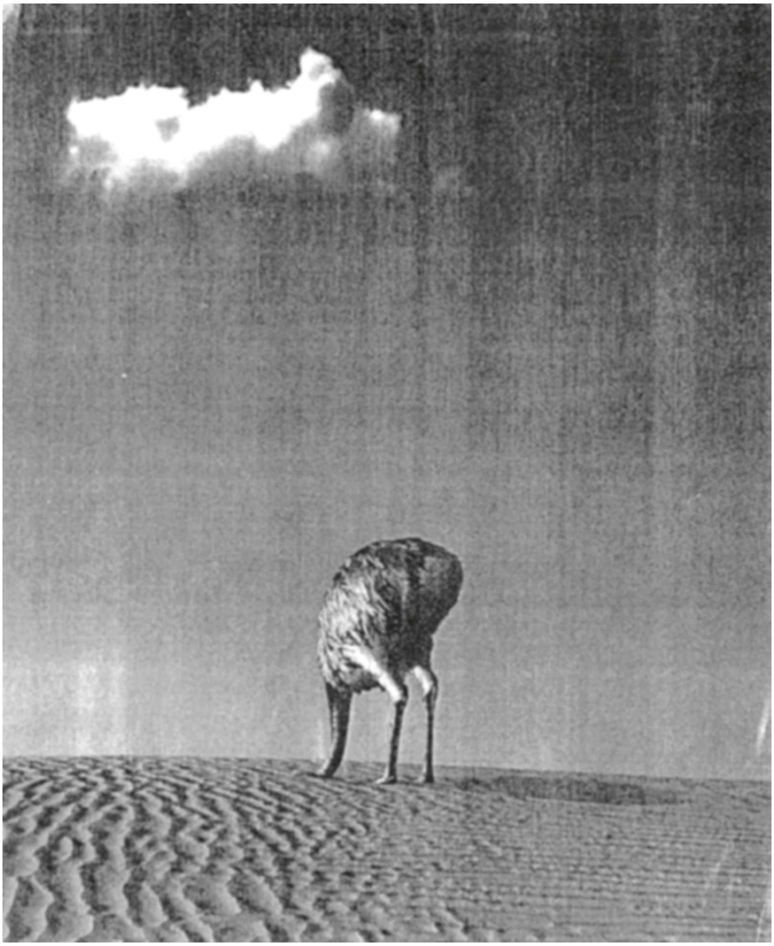
Clearly when the latter energy sources are gone, it must find other means of replacing them to empower its transportation fleets and heavy industries. The only sources for additional prime energy are then coal or uranium whose production of electricity or heat allows the manufacture of synfuels, or the charging of portable energy units (storage batteries) on a Joule for Joule basis. The laws of energy conservation and energy inter-conversions first enunciated by Sir James Prescott Joule and Nicolas Sadi Carnot are immutable: nothing comes for nothing. In summary, preferably by the year 2035 but not later than 2055, the entire energy pie shown in Brief 2 must be accommodated by nuclear fission (available for at least 3,000 years), if one wants to avert an energy catastrophe and minimize global warming (i.e. no burning of coal).

Whether we can pass by the year 2035 unscathed without serious economic upheavals will depend on how forward-looking our future government leaders will be. They must distance themselves from the political influence of myopic extremists who insist that we slow or terminate nuclear power development and replace it entirely with solar cells and wind mills. Government leaders must heed warnings of the nuclear energy engineering profession. Otherwise disastrous energy shortages will surely develop resulting in similar finger-pointing as with the 9/11/01 terrorist attacks on New York's World Trade Center, or the dam breaches around New Orleans from hurricane Katrina on August 29, 2005. Many early warnings were ignored. History shows time and time again that people and government bureaucracies tend to keep their heads in the sand till jolted. Unless remedied on time, oil depletion will produce a downward spiral of rapidly escalating shortages of food and goods, collapse of the economy, serious impoverishment of the majority of people, and an increase of war-provoking world tensions. Desert cities like Las Vegas, Nevada and Phoenix, Arizona which are totally dependent on a cheap-oil economy, will become ghost-towns (Ref. I-19). A forerunner of this occurred in 2008, when oil prices escalated to \$147/barrel and petrol at the pump in the USA exceeded \$4/gal. At the time of this writing (2009) oil prices have retracted to \$45/barrel and \$3/gal, but US oil experts like Boone Pickens predicts \$300/barrel and \$8.00/gal by 2020 (Section 1.1). Before it generates the first kilowatt, construction of a nuclear power plant in the US requires a minimum of 8 years (two presidential terms!) from the moment a decision is made to build it. Besides construction, it includes years of planning, designing, and safety reviews by the NRC.

We can not afford the luxury of meditation until catastrophe hits. But if history repeats itself, we probably will suffer great losses first before corrective action is taken. Too many wrong decisions are being made and bad regulations are enacted into law by "technologically-challenged" environmental zealots. They are opposing new nuclear power development, asserting they can solve the approaching energy crisis entirely by instituting energy savings, windmills, and solar power. They are "bad-mouthing" and distorting everything related to nuclear power and have infiltrated state and federal governments. If strictly followed, these neo-luddites are helping the upcoming no-oil era turn into an economic disaster, forcing the public to suffer avoidable quality-of-life losses and impoverishment due to seriously flawed and unnecessary oppressive edicts. Former US-EPA secretary Dixie Lee Ray called some of the new environmental laws that neo-luddites pushed through, "environmental overkill" (Ref. I-10). James Lovelock, a renowned British naturalist, and Patrick Moore a former co-founder of Greenpeace, who were formerly hesitant to endorse nuclear energy, are now much in favor of greatly expanded nuclear power to support man's need for energy when fossil fuels are depleted. Unfortunately Greenpeace, once a noble pacifist organization promoting the protection of nature and wildlife (e.g. whales) has been taken hostage by anti-nuclear commanders who rally their troops to protest anything related to nuclear energy. The same has happened to some other ossified pacifist groups who mistakenly equate nuclear power with nuclear weapons. As the editor of Nuclear News (Ref. II-10) wrote recently tongue-in-cheek: "Green energy, non-air-polluting, available 24/7 for millennia at an affordable cost? – There has to be something wrong with it if it has the word "nuclear" in it!".

As mentioned, to design, obtain approval, and build a nuclear reactor in the USA takes 8–10 years. Unfortunately the government in the USA changes every 4 years and the two-party system of Democrats and Republicans causes wild fluctuations between obstructing and promoting the development of more green nuclear energy to rescue the nation from a pending economic collapse. A culture of "what the other party recommends, we shall automatically disapprove" has been the infantile attitude of both Democrats and Republicans, to the detriment of the country. While major energy decisions should be in the hands of knowledgeable engineers and be non-partisan, mal-informed biased politicians and lobbyists in the USA often prevail and continue to lead the USA towards the precipice of a deep out-of-energy ravine. They believe they can edict technology by demanding that utilities provide for example 20–30% of power generation from "renewable" sources, a very expensive if not impossible goal (I am waiting for them to pass a law that the sun must shine 24/7). Some wind or solar energy development is helpful, but if pursued at the exclusion of badly needed base-load nuclear power, it will positively bankrupt and impoverish the USA. Many have come to believe the fraudulent anti-nuclear propaganda preached during the 1960s through 1980s, and have outlawed new nuclear construction in some States. Anti-nuclear bigots have also obstructed such common-sense programs as the GNEP and reprocessing of nuclear fuels (Section 6.3.2), the establishment of a national radio-waste repository (Section 6.3.3), and have opposed adequate financing for new nuclear power plants. As many US citizens have proclaimed in one way or another: "Our quixotic government always manages to find the costliest and worst solution to solve a problem. Only after calamity strikes and often when it is too late, does it finally look at the most sensible remedy which usually was right in front of their nose all the time." While anti-nuclear activists may believe they are promoting a just cause, they can be certain that future generations will accuse them of sabotaging the one sure affordable solution to the forthcoming energy crisis. Because of their irresponsible shenanigans, my fear is that in Brief 47 the most probable reactor expansion curve will be the dotted one. It lags the most desirable solid curve by 15 years, when it is practically too late to affect an economic energy recovery without great impoverishment of most US citizens, the same goal sought by terrorists and anarchists.

The escalating energy shortages that we face can be overcome with very modest loss of comfort provided the public better understands, appreciates, and accepts nuclear power generation. The discovery of nuclear energy came just in time to rescue mankind. We don't have to return to living in caves or in the middle-ages and abandon all modern conveniences which previous generations invented and toiled to develop. Wise governments must provide continuous support and invest in the synfuel development programs listed above. Concurrently they must support the design, development, and construction of advanced Gen-IV breeder reactors together with integrated fuel handling, reprocessing, and enrichment facilities monitored by the IAEA. Expansion of wind and solar power generation is only supplemental and useful as long as it does not interfere with the much more effective development of nuclear power. As a bonus, it brings many new high-tech jobs and reduces unemployment like President Franklin Roosevelt accomplished with his national hydro-electric and roadwork programs during the great depression of the 1930s. Environmentalists should join nuclear engineers to demand expansion of non-air-polluting nuclear energy. Benjamin Franklin said at the signing of the Declaration of Independence in 1776: “We must all hang together or assuredly we shall all hang separately”.



No more oil!!??

Abbreviations

AC	Alternating Current (electricity)
AEC	Atomic Energy Commission (USA)
ALARA	As Little As Reasonably Achievable
AVLIS	Atomic Vapor Laser Isotope Separation
BTU	British Thermal Unit
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium Uranium reactor (heavy water moderated and cooled reactor)
CF	CentriFuge
CTBT	Comprehensive Test Ban Treaty
DC	Direct Current (electricity)
DIF	Diffusion, process for uranium enrichment
DOE	Department of Energy (USA)
DOT	Department of Transportation (USA)
DNA	Desoxyribo Nucleic Acid (biomolecule)
ECCS	Emergency Core Cooling System
EPA	Environmental Protection Agency (USA)
FP	Fission Product
GDP	Gross Domestic Product
GE	General Electric (Corporation)
GEN-I,II, III, IV	Generation I, II, III, IV
GHG	Green House Gas
GM	Geiger Müller (radiation counter)
GNEP	Global Nuclear Energy Partnership
HP	Horse Power (unit for energy consumption rate = 746 W)
HP	Health Phycists (monitors radiation levels around nuclear reactors)
IAEA	International Atomic Energy Agency
IC	Internal Combustion
ICE	Internal Combustion Engine
ICF	Inertial Confinement Fusion
IFR	Integral Fast Reactor

IN(E)L	Idaho National (Engineering) Laboratory (USA)
IR	Infra-Red
ITER	International Thermonuclear Experimental Reactor
KWI	Kaiser Wilhelm Institute (discovery of uranium fission)
LANL	Los Alamos National Laboratory
LED	Light Emitting Diode
LIS	Laser Isotope Separation
LLNL	Lawrence Livermore National Laboratory (USA)
LPG	Liquefied Petroleum Gas
MLIS	Molecular Laser Isotope Separation
MCA	Maximum Credible Accident
MPD	Maximum Permissible Dose
MPE	Maximum Permissible Exposure
NASA	National Aeronautics and Space Administration (USA)
NEI	Nuclear Energy Institute (USA)
NPT	Non Proliferation Treaty
NRC	Nuclear Regulatory Commission (USA)
OPEC	Organization of Petroleum Exporting Countries
OSEC	Organization of Synfuel Exporting Countries
PEM	Proton Exchange Membrane
PF	Pons-Fleischman
ppb, ppm	Parts per billion, parts per million
PWR	Pressurized Water Reactor
RNA	Ribo Nucleic Acid (biomolecule)
RBE	Relative Biological Effectiveness
SASOL	South Africa Synthetic Oil Ltd
SOFC	Solid Oxide Fuel Cell
TBP	Tributyl Phosphate
TMI	Three-Mile-Island
UCF	UltraCentriFuge, for uranium enrichment
URENCO	Uranium Enrichment Company
USEC	United States Enrichment Corporation
UV	Ultra-Violet

Chemical Symbols of Selected Elements and Isotopes

B	Boron ($Z = 5$); B-10 = Boron ($M = 10$, $Z = 5$); B-11 = Boron ($M = 11$, $Z = 5$)
C	Carbon ($Z = 6$); C-12 = Carbon ($M = 12$, $Z = 6$); C-13 = Carbon ($M = 13$, $Z = 6$)
H	Hydrogen ($Z = 1$); H-1 ($M = 1$, $Z = 1$); H-2 = D = Deuterium ($M = 2$, $Z = 1$); H-3 = T = Tritium ($M = 3$, $Z = 1$)
He	Helium ($Z = 2$); He-4 = Helium ($M = 4$, $Z = 2$); He-3 = Helium ($M = 3$, $Z = 2$)
K	Potassium or Kalium ($Z = 19$); K-39 ($M = 39$, $Z = 19$); K-40 ($M = 40$, $Z = 19$); K-41 ($M = 41$, $Z = 19$)
Li	Lithium ($Z = 3$); Li-6 = Lithium ($M = 6$, $Z = 3$); Li-7 = Lithium ($M = 7$, $Z = 3$)
N-14	Nitrogen ($M = 14$, $Z = 7$); N-15 ($M = 15$, $Z = 7$)
O-16	Oxygen ($M = 16$, $Z = 8$); O-18 ($M = 18$, $Z = 8$)
Sr-88	Strontium ($M = 88$, $Z = 38$); Sr-90 = Strontium ($M = 90$, $Z = 38$)
I-127	Iodine ($M = 127$, $Z = 53$); I-126 ($M = 126$, $Z = 53$)
Cs-133	Cesium ($M = 133$, $Z = 55$); Cs-137 ($M = 137$, $Z = 55$)
Hg-200	Mercury ($M = 200$, $Z = 80$)
Th-232	Thorium ($M = 232$, $Z = 90$)
U-233	Uranium ($M = 233$, $Z = 92$); U-235 = Uranium ($M = 235$, $Z = 92$)
Pa-233	Protactinium ($M = 233$, $Z = 91$)
U-238	Uranium ($M = 238$, $Z = 92$)
Np-239	Neptunium ($M = 239$, $Z = 93$)
Pu-239	Plutonium ($M = 239$, $Z = 94$)

NOTE:

M = Atomic mass number = (number of protons + number of neutrons) in nucleus of atom
Z = Atomic charge number = number of protons in nucleus = number of electrons in atom

International MKS Units & Prefixes

m	meter, unit of length; kg = kilogram, unit of mass; s = second, unit of time
J	Joule, unit for energy
W	Watt (= J/s), unit for rate of energy consumed/produced per second
Gr	Gray, unit for radiation dose = 1 J deposited radiation energy per kg bio-matter
Sv	Sievert, unit for man-effective radiation dose = 1 Gray × Biological Effectiveness

Atomic/Molecular Units

1 eV (electron-Volt) = 1.6021×10^{-19} Joule per atom or molecule = $9.65 \times 10^{4}/M$, Joule per gram

1 MeV = 10^{6} eV = 1.6021×10^{-13} Joule per atom or molecule = $9.65 \times 10^{10}/M$, Joule per gram

1 gram of an element with mass number M contains N = $6.0247 \times 10^{23}/M$ atoms
1 mole = 6.0247×10^{23} atoms or molecules

Prefixes

z	zepto = 10^{-21}, sextillionth part
a	atto = 10^{-18}, quintillionth part
f	femto = 10^{-15}, quadrillionth part
p	pico = 10^{-12}, trillionth part
n	nano = 10^{-9}, billionth part
μ	micro = 10^{-6}, millionth part
m	milli = 10^{-3}, thousandth part
c	centi = 10^{-2}, hundredth part
k	kilo = 10^{3}, thousand-fold
M	mega = 10^{6}, million-fold
G	giga = 10^{9}, billion-fold
T	tera = 10^{12}, trillion-fold
P	peta = 10^{15}, quadrillion-fold
E	eta = 10^{18}, quintillion-fold

About the Author

Jeff W. Eerkens is an adjunct research professor at the University of Missouri in Columbia. He has a doctorate in Engineering Science (1960) and a masters degree in Nuclear Engineering (1957) from the University of California at Berkeley, and is a registered nuclear engineer in the State of California. His doctoral dissertation was a study of the chemical effects in fluids produced by fission fragments of uranium. His Ph.D. work included graduate studies in biochemistry and the origin of life.

Dr. Eerkens has had extensive "hands-on" experience with nuclear reactors, isotope separation systems, and various aspects of the nuclear fuel cycle. Prior to research on laser separation of medical isotopes in Missouri, he spent 30 years in California working in staff positions for several aerospace companies. He participated there in the design and testing of nuclear and solar energy systems for space applications. This included the preparation of reactor hazards analysis reports and the execution of reactor experiments.

In 1957, as a student at UC-Berkeley's Engineering Field Station, Eerkens measured molecular (isotope) separations in annular shock regions of free jets, a variant of a nozzle isotope enrichment method developed earlier by Becker in Germany. In 1959/1960 he carried out critical mass assemblies of two research reactors, one at the University of Oklahoma, and one at Rice University in Texas. In 1964/1965 Eerkens designed and operated the world's first nuclear-pumped gas laser by exciting lasable noble gases directly with uranium fission fragments in a laser tube placed inside a pulsed TRIGA reactor at the Norhtrop Space Laboratories. In 1972/1973 he initiated experiments to study isotope enrichment of gaseous uranium hexafluoride using a molecular laser. This ultimately led to a new laser isotope separation technique called CRISLA (Condensation Repression Isotope Separation by Laser Activation) which employs a supersonic free jet and laser-activated condensation repression of selected isotopomers.

Eerkens holds the first patent on a gamma-ray laser or "graser", and is a co-patent-holder of the first green Helium-Neon laser sold commercially. In addition to experience in the nuclear and laser fields, he performed studies on rocket plume infrared radiation signatures for the US Air Force, and participated in designing infrared optical systems and space power units for aerospace satellites. He also designed and built high-power lasers, and investigated radiation hardening of optical materials.

Dr. Eerkens is of Dutch descent and was born in Indonesia (formerly the Dutch East Indies), where his father was a physician. As a child during World War II, he spent 3 years in a Japanese concentration camp on Java. The atomic bomb that ended WW-II saved his life (and of half a million others in Asia). It later spurred his interest in nuclear physics and engineering. After enrolling at the University of California in Berkeley as a foreign student in 1950, he obtained his Ph.D. degree in 1960 and became a US citizen in 1961. He lived in California till 1994, in Missouri till 2005, and returned to California after that. He is married and the father of four children.

Acknowledgments

I am grateful to my wife Els and my children Laura, Jelmer, Mieke, and Boukje, who stood by me during some difficult years in my professional and academic career. My daughter Mieke, who is an accomplished writer with a degree in English literature, edited and improved the readibility of some sections in the book. It was also with great pleasure to work with Nathalie Jacobs and Anneke Pot of SpringerNL, who were very helpful and professional in helping to publish this book.

To Dick R. Griot, my former business partner and long-time friend, I am indebted for helping me stay the course in the promising and fascinating field of nuclear energy which I had chosen to devote my life to. Further I wish to express my gratitude to Jay F. Kunze, Dean of Engineering at Idaho State University, who encouraged me and kept me going. Finally I wish to express my appreciation for valuable discussions with colleagues Bill H. Miller, Sudarshan Loyalka, Mark Prelas, Tushar Gosh, and Bob Tompson at the Nuclear Science and Engineering Institute of the University of Missouri, Columbia. Others who saw rough drafts of my book and made specific suggestions to improve the book were: professors Tom Marrero and Allen Hahn of the University of Missouri; Dr. Bob Gordon, retired president of SCI, Inc., and a former nuclear engineering class-mate (now deceased); Steven Barnholtz a former science teacher from Pacific, Missouri; Dr. Bertus de Graaf, vice-president of Geodynamics in Australia; Dr. Piet Borst, professor of molecular biology, Netherlands Cancer Institute, Amsterdam; and Ir C. Eerkens, former agricultural consultant to the EU Agriculture Mission in Brussels, and staff engineer at Unilever, Rotterdam, and UNDP, NewYork.

Annotated Bibliography

I. Nuclear and Other Energy Sources; History, and Needs of Man

I-1. Gueron, J., Lane, J.A., Maxwell, I.R., Menke, J.R. (eds.): The Economics of Nuclear Power. McGraw-Hill, New York (1957)
I-2. Ellis, C.T.: A Giant Step – History of Rural Electrification in the USA. Random House, New York; Lib Cong Cat No 66-11991 (1966)
I-3. Blair, J.M.: The Control of Oil. Random House, New York; ISBN 0-394-72532-8 (1976)
I-4. Teller, E.: Energy from Heaven and Earth. W.H. Freeman, San Francisco, Oxford; ISBN 0-7167-1064-1 (1979)
I-5. Cheney, M.: Tesla, Man Out of Time. Dell Publ., New York; ISBN 0-440-39077-X (1983)
I-6. Rhodes, R: The Making of the Atomic Bomb. Simon & Schuster, New York; ISBN 0-671-44133-7 (1986)
I-7. Cohen, B.L.: The Nuclear Energy Option. Plenum, New York; ISBN 0306435675 (1990)
I-8. Bethe, H.A.: The Road from Los Alamos – The Necessity of Fission Power. Simon & Schuster, New York; ISBN 0671-740121 (1991)
I-9. Rhodes, R.: Nuclear Renewal; Common Sense About Energy. Whittle Books/Viking Penguin, New York; ISBN 0-670-85207-4 (1993)
I-10. Ray, D.L.: Environmental Overkill; Whatever Happened to Common Sense. Harper Perennial; ISBN 0-06-09758-9 (1993)
I-11. Waltar, A.E.: America the Powerless; Facing Our Nuclear Energy Dilemma. Cogito Books (Medical Physics Publishing), Madison, WI; ISBN 0-99483-58-8 (1995)
I-12. Ahn, J., Kastenberg, W.E. (eds.) Energy future and the nuclear fuel cycle in the Asia/Pacific region. In: Proceedings of Nuclear Energy Section of 19th Annual ILP Conference, University of California, Berkeley, College of Engineering and College of Chemistry (1997)
I-13. Deffeye, K.S.: Hubbert's Peak; The Impending World Oil Shortage. Princeton University Press; ISBN 0- 691-116253 (2001)
I-14. 2002 World Almanac and Book of Facts, Primedia; ISBN 0-88687-848-10 (2001)
I-15. Heaberlin, S.W.: A Case for Nuclear-Generated Electricity. Batelle Press, Columbus, OH; ISBN 1-57477-1361 (2003)
I-16. Goodstein, D.: Out of Gas: The End of the Age of Oil. W.W. Norton, New York, London; ISBN 0-393-05857-3 (2004)
I-17. Roberts, P.: The End of Oil; On the Edge of a Perilous New World. Houghton Mifflin Co., Boston, MA; ISBN 0-618-23977-4 (2004)
I-18. Cooke, R.C.: Oil, Jihad, and Destiny. Opportunity Analysis; ISBN 1-930847-62-9 (2004)
I-19. Kunstler, J.H.: The Long Emergency; Surviving the Converging Catastrophies of the Twenty-First Century. Atlantic Monthly Press, New York; ISBN 0-87113-888-3 (2005)

I-20. Nuttall, W.J.: Nuclear Renaissance; Technologies and Policies for the Future of Nuclear Power. Institute of Physics, London; ISBN 0750309369 (2005)
I-21. White, R.S.: Energy for the Public: The Case for Increased Nuclear Fission. Book Surge Pub.; ISBN 0-938711-85-7 (2005)
I-22. Sweet, W.: Kicking the Carbon Habit – Global Warming and the Case for Renewable and Nuclear Energy. Columbia University Press, New York; ISBN 978-0-321-13710-2 (2006)
I-23. Eerkens, J.W.: The Nuclear Imperative – A Critical Look at the Approaching Energy Crisis, 1st edn. Springer, Dordrecht; ISBN 1-4020-4930-7 (2006)
I-24. Suppes, G.J., Storvick, T.S.: Sustainable Nuclear Power. Academic Press, New York, London; ISBN-10:0-12-370602-5 (2007)
I-25. Lovelock, J.: The Revenge of Gaia – Earth's Climate Crisis and the Fate of Humanity. Basic Books, New York; ISBN 13: 978-0-465-04168-8 (2006)
I-26. McGrayne, S.B.: Nobel Prize Women in Science. Joseph Henry Press, Washington, DC, Fourth Printing; ISBN 0-309-07270-0 (2006)
I-27. Cravens, G.: Power to Save the World – The Truth About Nuclear Energy. Random House, New York; ISBN 978-0-307-26656-9 (2007)
I-28. Shuster, J.M.: Beyond Fossil Fuels – The Roadmap to Energy Independence by 2040. Beaver's Pond Press; ISBN 10:1-59298-235-2 (2008)
I-29. Smil, V.: Energy in Nature and Society – Energetics of Complex Systems. MIT Press, Cambridge, MA; ISBN 978- 0-262-19565-2 (2008)
I-30. Olson, S., Fri, R.W. (eds.): The National Academies Summit on America's Energy Future – Summary of a Meeting. National Academic Press; ISBN-13: 978-0-309-12478-2 (2008)
I-31. Blees, T.: Prescription for the Planet, Tom Blees; ISBN 1-4196-5582-5 (2008)
I-32. Muller, R.A.: Physics for Future Presidents – The Science Behind the Headlines. Norton, New York; ISBN 978-0-393-06627-2 (2008)
I-33. Rhodes, R.R.: Arsenals of Folly – The Making of the Nuclear Arms Race. Alfred A. Knopf, New York; ISBN 978-0-375-41413-8 (2007)
I-34. Nuclear Age Peace Foundation: The Comprehensive Test Ban Treaty. Nuclear Files.org (2009)
I-35. Seife, C.: Sun in a Bottle – The Strange History of Fusion and the Science of Wishful Thinking, Viking; ISBN 978-0-670-02033-1 (2008)

II. Technical Books, Reports, Articles on Nuclear Reactor Design & Engineering: Neutronics, Radiation, Fuels, Safety, Accidents, Nuclear Materials and Nuclear Medicine

II-1. Riegel, E.R.: Industrial Chemistry, 5th edn. Reinhold, New York (1949)
II-2. Glasstone, S.: Principles of Nuclear Reactor Engineering. Van Nostrand, Princeton, NJ/ Toronto/ London/New York; Lib Cong No 55-8832 (1955)
II-3. United Nations. Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, vols. 1–16, Geneva, August 1955. UN Publications, New York (1956)
II-4. Nucleonics. McGraw-Hill, New York, Monthly Journal (1957–1967)
II-5. Tammaro, A. (ed.): The Shippingport Pressurized Water Reactor. Addison-Wesley, Reading, MA; Lib Cong No 58-12595 (1958)
II-6. Kramer, A.W. (ed.) Boiling Water Reactors. Addison-Wesley, Reading, MA; Lib Cong No 58-12603 (1958)
II-7. Starr, C., Dickinson, R.W.: Sodium Graphite Reactors. Addison-Wesley, Reading, MA; Lib Cong No 58-12598 (1958)
II-8. Weinberg, A.M., Wigner, E.P.: The Physical Theory of Neutron Chain Reactors. University of Chicago Press, Chicago, IL; Lib Cong No 58-8507 (1958)
II-9. Claus, W.D. (ed.): Radiation Biology and Medicine. Addison-Wesley, Reading, MA; Lib Cong No 58-12599 (1958)

II-10. ANS (American Nuclear Society): Nuclear News. Monthly Issues (1961–2004)

II-11. Shreve, R.N.: Chem Process Industries, 3rd ed. McGraw-Hill, New York; Lib Cong No 68-20721 (1967)

II-12. Van Thoor, T.J.W.: Chemical Technology: An Encyclopedic Treatment, vol. I. Barnes & Noble, New York; Lib Cong No 68-31037 (1968)

II-13. Physics Today. Journal of AIP (Am. Inst. of Physics): Selected Issues on Nuclear Topics (1970–2004)

II-14. ACS (Am. Chem. Society): Chemical & Engineering News. Selected Issues on Nuclear Topics (1970–2004)

II-15. Levine, S. (ed.): Reactor Safety Study. WASH-1400 Rasmussen Report, US-ERDA (Oct 1975)

II-16. Lucky, T.D.: Hormesis with Ionizing Radiation. CRC Press, Boca Raton, FL (1980)

II-17. Benedict, M., Pigford, T., Levi, H.: Nuclear Chemical Engineering, 2nd edn. McGraw-Hill, Boston, MA; ISBN 0-07-004531-3 (1981)

II-18. Waltar, A.E., Reynolds, A.B.: Fast Breeder Reactors. Pergamon, New York; ISBN 0-08-80259820 (1981)

II-19. Leclercq, J.: The Nuclear Age. Published by Le Chêne, distributed by Hachette (France), Sodel (1986)

II-20. Rippon, V: Chernobyl: The Soviet Report. Nuclear News, Oct 1986, pp 59–66, Monthly Publication of American Nuclear Society (1986)

II-21. Waltar, A.E.: Radiation and Modern Life; Fulfilling Marie Curies Dream. Prometheus Books, Amherst, NY; ISBN 1-59102-250-9 (2004)

II-22. Prelas, M.K., Peck, M.S.: Nonproliferation Issues for Weapons of Mass Destruction. Taylor & Francis (CRC Press), New York; ISBN 0-8247-5339-9 (2005)

II-23. Koch, L.: Experimental Breeder Reactor-II, an Integrated Experimental Fast Reactor Nuclear Power Station. American Nuclear Society; ISBN 0-89448-042-1 (2008)

II-24. Chandrasekhar, S.: Introduction to the Study of Stellar Structure. University of Chicago (1939); Dover, New York (1957)

III. Books, Reports, and Articles on Chemical Fuel-Cells and Synfuels

III-1. Liebhafsky, H.A., Cairns, E.J.: Fuel Cells and Fuel Batteries. Wiley, New York; Lib Cong No 68-22892; SBN 47153420X (1968)

III-2. Bockris, J.O'M., Srinivasan, S.: Fuel Cells: Their Electrochemistry. McGraw-Hill, New York; Lib Cong No 68-1475306345 (1969)

III-3. Braker, W., Mossman, A.L.: Matheson Gas Data Book, 6th edn. Matheson, East Rutherford, NJ; Lib Cong No 80-83159 (1980)

III-4. Hail, S.M.: Materials for Fuel Cells. Materials Today (Elsevier), p. 24 (March 2003)

III-5. Marsh, G.: Membranes fit for a revolution. Materials Today (Elsevier), p. 38 (March 2003)

III-6. Sammes, N. Hot-Bed of Fuel Cell R&D. Materials Today (Elsevier), p. 44 (March 2003)

III-7. Pinkerton, F.E., Wicke, B.G.: Bottling the Hydrogen Genie. The Industrial Physicist, p. 20 (Feb/Mar 2004)

III-8. Gutschi, C., Stigler, H.: Ammoniak als Energieträger; eine Alternative zu Wasserstoff. ACCEPT proposal No NNE5-2001-00209, Institut für Elektrizitätswirtschaft und Energieinnovation (IEE), Graz, Austria (2006)

III-9. Fournier, G.G.M., Cunning, I.W., Hellgardt, K.: High Performance Direct Ammonia Solid Oxide Fuel Cell. J. Power Sources (2006)

III-10. Dekker, N., Rietveld, R.: Highly efficient conversion of ammonia into electricity by solid oxide fuel cells. In: ECN Petten, the Netherlands; 6th European Solid Oxide Fuel Cell Forum, 6/28-7/2, 2004, Lucerne, Switzerland

III-11. Coenen, P., Mulder, G., Gutschi, C.: The ACCEPT Program: Fueling a 2 kW Fuel Cell System with Ammonia. VITO Report, Mol, Belgium, 10/10/2004

IV. Reports and Articles on Coal, Oil, and Natural Gas

IV-1. Johnson, J.: Getting to clean coal. Chemical and Engineering News, p. 20ff (Feb 23 2004)
IV-2. Appenzeller, T.: The end of cheap oil. National Geographic, p. 84ff (June 2004)
IV-3. Forest, C., Webster, M., Reilly, J.: Narrowing uncertainty in global climate change. The Industrial Physicist, pp. 20–23 (Aug/Sept 2004)
[See also Ref. I-18. R.C. Cooke, Oil, Jihad, and Destiny]

V. Reports and Articles on Solar, Wind, and Geothermal Energy

V-1. Daniels, F., Duffie, J.A. (eds.): Solar Energy Research. University of Wisconsin Press, Madison, WI (1955)
V-2. Douglas, L.W., Kastens, M.L. (eds.): Proceedings of the World Syposium on Applied Solar Energy, Phoenix, Arizona, November, 1955. SRI, Menlo Park, CA (1956)
V-3. Prospectus of Geodynamics, Ltd., Power from the Earth, ABN 55 095 006 090, PO Box 2046, Milton, QLD 4064, Australia (August 2002)
V-4. Winters, J.: Alternative power systems. American Society of Mechanical Engineers (ASME). Mech. Eng. **125(**1), 36–39 (Jan 2003)
V-5. Johnson, J.: Blowing green. Chemical and Engineering News, pp. 27–30 (Feb 24, 2003)
V-6. Kazmerski, L., Surek, T.: Power from the sun. Society of Photo Instrumentation Engineers (SPIE). OEM Magazine, pp. 24–27 (April 2003)
V-7. Weisz, P.B.: Basic choices and constraints on long-term energy supplies. American Physical Society (APS), Physics Today, pp. 47–52 (July 2004)

VI. Reports and Articles on Bio-Mass Energy

VI-1. Faaij, A.P.C.: Energy from biomass. Ph.D. thesis, University of Utrecht (Sept 29, 1997)
VI-2. Eerkens, C.: An holistic approach to evaluate the potential productivity of unconventional crops. In: Raymond, W.F., Larvor, P. (eds.) Alternative Uses for Agricultural Surpluses, pp. 104–114. Elsevier Applied Science, London (1986)

VII. Books on Risk Analysis

VII-1. Stern, P.C., Fineberg, H.V. (eds.): Understanding Risk, Informing Decisions in a Democratic Society. National Academic Press, Washington, DC; ISBN 0-309-08956-5 (1996)
VII-2. Daniel, D., Applegate, J. (eds.): Risk and Decisions About Disposition of Transuranic and High-Level Radioactive Waste. National Academic Press, Washington, DC; ISBN 0-309-09549-2 (2005)
VII-3. Vignial, C., Monti, A., Dehouck, C., Smiley, E. (eds.): Terrorism Risk Insurance in OECD Countries. OECD Publishing, Paris; ISBN 92-64-00872-1 (2005)

Index