34 Nuclear Fission and Fusion

Photo openers feature leading pioneers of nuclear fission and fusion: Lise Meitner, Otto Frisch, Otto Hahn, Enrico Fermi, and Robert J. Oppenheimer. This chapter's personality profile is Lise Meitner.

The material in this chapter is of great technological and sociological importance. Nuclear bombs are not avoided in the applications of nuclear energy, but discussion of other applications emphasize positive aspects of nuclear power and its potential for improving the world. Much of the public sentiment against nuclear power has been due to a distrust of what is generally not understood, and the nuclear disaster in Fukushima, Japan. Fear is also enhanced with the possibility of nuclear fuel falling into groups who seek a nuclear bomb not to safeguard themselves, but to deploy it on others! This IS a frightening scenario. In this climate, we have a responsibility to provide our students with an understanding of the basic physics of nuclear power. In your physics class, an appropriate slogan is "KNOW NUKES."

Note that in this text, the energy release from the opposite processes of fission and fusion is approached from the viewpoint of decreased mass rather than the customary treatment of increased binding energy. Hence the usual binding energy curve is "tipped upside-down" in Figure 34.16, and shows the relationship of the mass per nucleon versus atomic number. I consider this way conceptually more appealing, for it shows that any reaction involving a decrease in mass releases energy in accordance with mass-energy equivalence. Everyone is familiar with the equation $E = mc^2$ and this is where it is best applied.

Mass-energy can be measured in either joules or kilograms (or in ergs or grams). For example, the kinetic energy of a 2-gram beetle walking 1 cm/s = 1 erg, and the energy of the Hiroshima bomb = 1 gram. So we can express the same quantity in essentially different units.

In a uranium mine in Western Africa in the Republic of Gabon, at Oklo, a mining geologist in 1972 discovered evidence of an ancient natural nuclear fission reactor that produced sustained low-level power for several hundred thousand years. The sustained fission reactions occurred about two billion years ago, when concentrations of U-235 were higher than they are now. The byproduct isotopes of this ancient reactor have been found to be almost exactly those found in present day reactors—even with the production of plutonium. So it's interesting to note that the achievement of Fermi and his team of some of the brightest minds in modern physics and engineering duplicated what nature did some two billion year ago. (Go back to "The Workings of an Ancient Nuclear Reactor" in the November 2005 *Scientific American*.)

Nuclear waste need not plague future generations indefinitely, as is commonly thought. Teams of scientists are presently designing devices in which long-lived radioactive atoms of spent reactor fuel can be transformed to short-lived, or nonradioactive, atoms. See the still-relevant article "Will New Technology Solve the Nuclear Waste Problem?" in *The Physics Teacher*, Vol. 35, Feb. 1997, or recent information on the Internet.

One of my general lectures that makes sweeping generalizations about fusion power and an idealized description of a fusion torch is available on the DVD set, *Conceptual Physics Alive*! *The San Francisco*

Years. The 3-disc set is available from Media Solutions (mediasolutions-sf.com) or other vendors. It goes into a speculative and entertaining scenario of a follow-up device to a star-hot flame called the fusion torch—a replicator, similar to that described by Arthur C. Clark in his 1963 book, *Profiles of the Future*.

Practicing Physics Book:
- Nuclear Reactions

Problem Solving Book:
With ample problems on fission and fusion

Laboratory Manual:
- Chain Reaction Nuclear Fission (Activity)

Next-Time Questions:
• Fission and Neutron Count   • Fission Reaction   • Oxygen Decay
• Fusion Reactions   • Fission-Fusion Curve

Hewitt-Drew-It! Screencasts: •*Nuclear Fission* •*Fission Power* •*Plutonium and Breeding*
•*Nuclear Fusion* •*Controlled Fusion*

SUGGESTED LECTURE PRESENTATION

Nuclear Fission

Briefly discuss the world atmosphere back in the late 1930s when fission was discovered in Germany, and how this information was communicated to American physicists who urged Einstein to write his famous letter urging President Roosevelt to consider its potential in warfare. The importance of the fission reaction was not only the release of enormous energy, but the ejected neutrons that could stimulate other fissions in a chain reaction. In the practice of writing equations from the previous chapter, write on the board (or its equivalent) the reaction shown that accompanies the art at the beginning of the chapter (page 639) and discuss its meaning. To give some idea as to the magnitude of the 200,000,000 eV of energy associated with one fission reaction, state that New York City is powered by water falling over Niagara Falls, and that the energy of one drop over the falls is 4 eV; the energy of a TNT molecule is 30 eV, the energy of a molecule of gasoline oxidizing is 30 eV. So 200,000,000 eV is impressive. (Spelling it out like this rather than saying 200 Mev underscores the comparison of fission and conventional energy sources.) Discuss the average 3 neutrons that are kicked out by the reaction and what a chain reaction is (Figure 34.2). Discuss critical mass, and a nuclear device, simplified in Figure 34.5.

Nuclear Reactors

A piece of uranium or any radioactive material is slightly warmer than ambient temperature because of the thermal activity prodded by radioactive decay. Fission reactions are major nuclear proddings, and the material becomes quite hot—hot enough to boil water and then some. Make clear that a nuclear reactor of any kind is no more than a means to heat water to steam and generate electricity as a fossil fuel plant does. The principle difference is the fuel used to heat the water. You could quip that nuclear fuel is closer to the nature of the Earth than fossil fuels, whose energies come from the Sun.

Discuss how scaling (Chapter 12) plays an important role in critical mass (Figure 34.4). There’s much more surface area compared to mass or volume for small pieces of material. And neutron escape is through surface, which if is small compared with the piece, means a chain reaction soon spends itself. For larger pieces, a chain reaction can build up and initiate an explosion.

Discuss the mechanics of a reactor via Figure 34.9. Just as the early automobiles mimicked horse-drawn buggies, energy output by today’s reactors is by turning water into steam.

Plutonium

Show the production of plutonium via the equation suggested by Figure 34.10. Make this two steps, from U-238 + n —> Np-239. Then by beta decay Np-239 to Pu-239. Neptunium's half-life of 2.3 days quickly produces plutonium, with a half-life of 24,000 years. Acknowledge that to some degree all reactors produce plutonium.

Breeder Reactors

Reactors designed to maximize the production of plutonium are the breeder reactors. Make clear that they don't make something from nothing, but merely convert a nonfissionable isotope of uranium (U-238) to a fissionable isotope of plutonium (Pu-239).

Mass-Energy Equivalence

A brief discussion of what $E= mc^2$ says and what it doesn't say should be understood. This is the most important part of your lecture—the *why* of nuclear power.

Begin by supposing that one could journey into fantasy and compare the masses of different atoms by grabbing their nuclei with bare hands and shaking the nuclei back-and-forth. Show with hand motion, holding an imaginary giant nucleus, how the difference might appear in shaking a hydrogen atom and a lead atom. State that if you were to plot the results of this investigation for all the elements, that the relationship between mass and atomic number would look like Figure 34.15, (which you draw on the board). Ask if this plot is a "big deal?" The answer is "no," it simply shows that mass increases with the number of nucleons in the nucleus. No surprise.

Distinguish between the mass of a nucleus and the mass of the nucleons that make up a nucleus. Ask what a curve of mass/nucleon versus atomic number would look like—that is, if you divided the mass of each nucleus by the number of nucleons composing it, and compared the value for different atoms. If all nucleons had the same mass in every atomic configuration, then of course the graph would be a horizontal line. But the masses of nucleons differ. The interrelationship between mass and energy is apparent here, for the nucleons have "mass-energy," which is manifest partly in the "congealed" part, which is the material matter of the nucleons, and the other part which we call binding energy. The most energetically bound nucleus has the least mass/nucleon (iron). Go into the nucleon shaking routine again and demonstrate how the nucleons become easier to shake as you progress from hydrogen to iron. Do this by progressing from the student's left to right the full length of your lecture table. Indicate how they become harder to shake as you progress beyond iron to uranium. Then draw the curve that represents your findings, and you have Figure 34.16 on the board. Announce that this is the most important graph in the book! Note that it is followed up by the same graph emphasizing fission, then fusion (Figures 34.17 and 34.19).

From the curve you can show that any nuclear reaction that produces products with less mass than before reaction, will release energy, and any reaction in which the mass of the products is increased will require energy. Further discussion will show how the opposite processes of fission and fusion release energy.

> CHECK QUESTIONS: Will the process of fission or fusion release energy from atoms of lead? Gold? Carbon? Neon? (Be careful in selecting atoms too near atomic number 26 in this exercise—for example, elements slightly beyond 26 when fissioned will have more massive products, that extend "up the hydrogen hill"; elements near 26 when fused will combine to elements "up the uranium hill." Acknowledging this point, however, may only serve to complicate the picture—unless, of course, a student raises the subject in class.)

State how the graph can be viewed as a pair of "energy hills" on both sides of a valley, and that to progress "down" the hill is a reaction with less mass per nucleon and therefore a gain in energy.

Nuclear Fusion

By way of the energy-hill-valley idea, there are two sides of the valley that go downward. Going from hydrogen down to iron is more steep—more mass "defect" in combining light nuclei than splitting heavy ones. This combining atomic nuclei is nuclear fusion—the energy releasing process of the Sun and the stars.

CHECK QUESTION: Will the process of fission or fusion release energy from the nucleus of iron? [Neither! Iron is the nuclear sink; either process results in “going up the hill,” gaining rather than losing mass.]

In effort to keep page count down, this edition does not feature the **Fusion Torch and Recyling**, as in previous editions. Nor does it discuss the various developments in *inertial confinement fusion*, induced by lasers, electron beams, and ion beams. None of these schemes has shown the promise expected in past years.

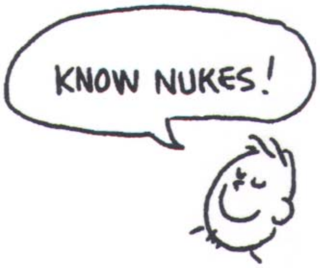
This is a period of transition—in some ways characterized by tough times, but overall, an interesting time to be alive. Particularly for those who are participating in the transition for positive change—for those who have not lost patience and retreated from knowledge into irrationality in its many generally-respected forms. Past centuries are often romanticized. Ask how many of your students would prefer living, say before the time of Galileo, during the Dark Ages. Too often the future is degraded. Back in the late 90s I saw an impressive I-Max 3-D movie, *L-5*. In this movie the future is seen in a positive light, a triumph of problem solving in a future space habitat. But, unfortunately, not the usual diet for movie goers.

Here’s some recommended reading:

Bodansky, D, *Nuclear Energy: Principles, Practices, and Prospects*, 2nd ed., Springer, NY (2004).

Hannum, W. H., and G. E. Marsh, G. S. Stanford, *Physics and Society* 33(3), 8 (July 2004); see http://www.aps.org/units/fps.

Vandenbosch, R, and S. E. Vandenbosch, *Physics and Society* 35((3), 7 (July 2006); see http://www.aps.org/units/fps.



Answers and Solutions for Chapter 34

Reading Check Questions

1. Very little uranium in mines is the fissionable isotope U-235.
2. In a large piece of uranium neutrons are less able to reach beyond the surface, which increases the chances of fission.
3. Critical mass is the amount beyond which spontaneous fission occurs.
4. More leakage occurs for the two separate pieces because they have more surface area per volume than two pieces stuck together.
5. The two methods were gas diffusion and centrifuge separation.
6. (1) Cause fission, (2) escape, (3) be absorbed.
7. Nuclear fuel, control rods, a moderator, and a fluid to extract heat.
8. Control rods and the presence of U-238 are safeguards to escalation in a reactor.
9. The isotope is U-239.
10. The isotope is Np-239.
11. The isotope is Pu-239.
12. Both U-235 and Pu-239 are fissionable.
13. The effect is the production of plutonium.
14. Both U-235 and Pu-239 undergo fission.
15. U-238 breeds to become Pu-239.
16. Both a nuclear reactor and fossil-fuel plant boil water to become steam that drives a generator.
17. Advantages: (1) Plentiful electricity, (2) saving fossil fuels for materials, (3) no atmospheric pollution. Drawbacks: (1) Waste storage, (2) danger of weapons proliferation, (3) release of radioactivity, and (4) risk of accident.
18. The celebrated equation is $E = mc^2$.
19. Yes, yes, with the form of energy as increased mass.
20. Least deflected are the massive ions (inertia).
21. Figure 34.35 shows mass vs atomic number, while Figure 34.16 shows mass *per nucleon* vs atomic number.
22. Mass per nucleon is greatest for hydrogen; least for iron.
23. Mass per nucleon decreases in fission fragments.
24. Reduced mass is manifest as released energy.
25. Progressing toward iron means less mass per nucleon.
26. Helium has less mass than the sum of the hydrogen masses.
27. Helium would have to be fused to release energy.
28. Deuterium and tritium fuse best at relatively moderate temperatures.
29. Deuterium is abundant, found in ordinary water. Tritium is scarce and must be created.
30. Thermonuclear fusion is responsible for sunshine.

Think and Do

31. Open ended.

Think and Solve

32. The energy released by the explosion in kilocalories is (20 kilotons)(4.2×10^{12} J/kiloton)/(4,184 J/kilocalorie) = 2.0×10^{10} kilocalories. This is enough energy to heat 2.0×10^{10} kg of water by 1 °C. Dividing by 50, we conclude that this energy could heat 4.0×10^8 kilograms of water by 50 °C. This is nearly half a million tons.

33. When Li-6 absorbs a neutron, it becomes Li-7, made of 3 protons and 4 neutrons. If this Li-7 nucleus splits into two parts, one of which is a nucleus of tritium containing one proton and two neutrons, the other must be made of two protons and two neutrons. That is an alpha particle, the nucleus of ordinary helium. It is the tritium, not the helium, that fuels the explosive reaction.

34. The neutron and the alpha particle fly apart with equal and opposite momenta. Since the neutron has one-fourth the mass of the alpha particle, it has four times the speed. Also consider the kinetic-energy equation, KE = $(1/2)\, mv^2$. For the neutron, KE = $(1/2)\, m(4v)^2 = 8\, mv^2$, and for the alpha particle, KE = $(1/2)\,(4m)v^2 = 2\, mv^2$. The KEs are in the ratio of 8/2, or 80/20. So we see that the neutron gets 80% of the energy, and the alpha particle 20%. (Alternative method: The formulas for momentum and KE can be combined to give KE = $p^2/2m$. This equation tells us that for particles with the same momentum, KE is inversely proportional to mass.)

Think and Rank

35. A, B, C, D.
36. A, B, C, D.

Think and Explain

37. Fission.

38. Non-enriched uranium—which contains more than 99% of the non-fissionable isotope U-238—undergoes a chain reaction only if it is mixed with a moderator to slow down the neutrons. Uranium in ore is mixed with other substances that impede the reaction with no moderator to slow down the neutrons, so no chain reaction occurs. (There is evidence, however, that several billion years ago, when the percentage of U-235 in uranium ore was greater, a natural reactor existed in Gabon, West Africa.)

39. Electric repulsion between protons reaches across the whole nucleus, affecting all protons, whereas the attractive nuclear force reaches only from one nucleon to nearer neighbors. So the greater the number of protons in a nucleus, the greater the likelihood that mutual electrical repulsion will overcome the attractive nuclear forces and lead to fission.

40. A neutron makes a better “bullet” for penetrating atomic nuclei because it has no electric charge and is therefore not electrically repelled by an atomic nucleus.

41. In a large piece of fissionable material a neutron can move farther through the material before reaching a surface. Larger volumes of fissionable material have proportionally less area compared to their greater volumes, and therefore lose less neutrons.

42. No. The flattened shape has more surface area, and therefore more neutron leakage, making it subcritical.

43. Critical mass is the amount of fissionable mass that will just sustain a chain reaction without exploding. This occurs when the production of neutrons in the material is balanced by neutrons escaping through the surface. The greater the escape of neutrons, the greater the critical mass. We know that a spherical shape has the least surface area for any given volume, so for a given volume, a cube shape would have more area, and therefore more “leakage” of the neutron flux. So a critical-mass cube is more massive than a critical-mass sphere. (Look at it this way: A sphere of fissionable material that is critical will be subcritical if flattened into a pancake shape—or molded into any other shape—because of increased neutron leakage.)

44. The process of assembling small pieces of fission fuel into a single big piece increases average traveling distance, decreases surface area, reduces neutron leakage, and increases the probability of a chain reaction and an explosion.

45. Because plutonium releases more neutrons per fission event, plutonium can stand more neutron leakage and still be critical. So plutonium has a smaller critical mass than uranium in a similar shape.

46. Only trace amounts of plutonium can occur naturally in U-238 concentrations. When U-238 captures a stray neutron it becomes U-239 and after beta emission becomes Np-239, which further transforms by beta emission to Pu-239. Because of its relatively short half-life (24,360 years) it doesn’t last long. Any plutonium initially in Earth’s crust has long since decayed.

47. Plutonium builds up over time because it is produced by neutron absorption in the otherwise inert U-238.

48. The resulting nucleus is ${}_{92}U^{233}$. The mass number is increased by 1 and the atomic number by 2. U-233, like U-235, is fissionable with slow neutrons. (Notice the similarity to the production of ${}_{94}Pu^{239}$ from ${}_{92}U^{238}$.)

49. One purpose of a separate water cycle is to restrict radioactive contamination of the reactor water with the reactor itself and to prevent interaction of the contaminants with the outside environment. Also, the primary water cycle can operate at higher pressure and therefore at higher temperature (well above the normal boiling point of water).

50. When a neutron bounces from a carbon nucleus, the nucleus rebounds, taking some energy away from the neutron and slowing it down so it will be more effective in stimulating fission events. A lead nucleus is so massive that it scarcely rebounds at all. The neutron bounces with practically no loss of energy and practically no change of speed (like a marble from a bowling ball).

51. The mass of an atomic nucleus is less than the sum of the masses of the separate nucleons that compose it. Consider the work that must be done to separate a nucleus into its component nucleons, which according to $E = mc^2$, adds mass to the system. Hence the separated nucleons are more massive than the original nucleus. Notice the large mass per nucleon of hydrogen in the graph of Figure 34.16. The hydrogen nucleus, a single proton, is already “outside” in the sense that it is not bound to other nucleons.

52. If the difference in mass for changes in the atomic nucleus increased tenfold (from 0.1% to 1.0%), the energy release from such reactions would increase tenfold as well.

53. Fission and fusion are alike in that both are energy-releasing nuclear reactions that involve transformation of one or more elements into other elements. However, they differ in important ways: Fission doesn’t require high temperatures; fusion does. Fission involves heavy nuclei; fusion involves light nuclei. As the names imply, fission is the splitting apart of a nucleus while fusion is the joining together of nuclei. The concept of critical mass applies to fission, but not to fusion.

54. Both chemical burning and nuclear fusion require a minimum ignition temperature to start and in both the reaction is spread by heat from one region to neighboring regions. There is no critical mass. Any amount of thermonuclear fuel or of combustible fuel can be stored.

55. Copper, atomic number 29, fused with zinc, atomic number 30, becomes the rare earth element praseodymium, atomic number 59.

56. The fusion of 2 hydrogen nuclei with an oxygen nucleus would produce a nucleus of neon, atomic number 10.

57. Aluminum. (Two carbons fuse to produce manganese, atomic number 12. Beta emission would change it to aluminum, atomic number 13.)

58. Although more energy is released in the fissioning of a single uranium nucleus than in the fusing of a pair of deuterium nuclei, the much greater number of lighter deuterium atoms in a gram of matter than the heavier uranium atoms in a gram of matter, results in more energy liberated per gram for the fusion of deuterium.

59. If enough fission fuel is localized, it will spontaneously undergo a chain reaction when triggered by a single neutron. Fusion fuel, on the other hand, is like combustible fuel, not a chain-reacting substance. It has no “critical mass,” and can be stored in large or small amounts without undergoing spontaneous ignition.

60. A hydrogen bomb produces a lot of fission energy as well as fusion energy. Some of the fission is in the fission bomb “trigger” used to ignite the thermonuclear reaction and some is in fissionable material that surrounds the thermonuclear fuel. Neutrons produced in fusion cause more fission in this blanket. Fallout results mainly from the fission.

61. A major potential advantage of fusion power over fission power has to do with the fuel for each: Fusion fuel (heavy hydrogen) is plentiful on Earth, especially in the world’s oceans, whereas fission fuel (uranium and plutonium) is a much more limited resource. (This imbalance holds in the universe as well.) A second advantage of fusion power has to do with the byproducts: Whereas fission produces appreciable radioactive wastes, the chief byproduct of fusion is nonradioactive helium (although neutrons released in fusion can cause radioactivity in surrounding material).

62. You don’t get something for nothing. There is great misunderstanding about hydrogen. To release it from water or other chemicals costs more energy than you recover when you burn it. Hydrogen represents stored energy, like a battery. It’s made in one place and used in another. It burns without pollution, a big advantage, but it should be regarded as a storage and transport medium for energy, not as a fuel.

63. Ruthenium. (U with atomic number 92 splits into palladium, atomic number 46, which emits an alpha particle with atomic number 2. This results in an element having atomic number 44, ruthenium.)

64. The KE of the fission products is converted into heat energy for boiling water to turn a turbine.

65. No. U-235 (with its shorter half-life) undergoes radioactive decay six times faster than U-238 (half-life 4.5 billion years), so natural uranium in an older Earth would contain a much smaller percentage of U-235, not enough for a critical reaction without enrichment. (Conversely, in a younger Earth, natural uranium would contain a greater percentage of U-235 and would more easily sustain a chain reaction.)

Think and Discuss

66. A fission reactor has a critical mass. Its minimum size (including moderator, coolant, etc.) is too large to power a small vehicle (although it is practical as a power source for submarines and ships). Indirectly, fission can be used to power automobiles by making electricity that is used to charge electric car batteries.

67. To predict the energy release of a nuclear reaction, simply find the difference in the mass of the beginning nucleus and the mass of its configuration after the reaction (either fission or fusion). This mass difference (called the “mass defect”) can be found from the curve of Figure 34.16 or from a table of nuclear masses. Multiply this mass difference by the speed of light squared: $E = mc^2$. That’s the energy release!

68. Each fragment would contain 46 protons (half of 92) and 72 neutrons (half of 144), making it the nucleus of Pd-118, an isotope of palladium, element number 46.

69. Fusing heavy nuclei (which is how the heavy transuranic elements are made) costs energy. The total mass of the products is greater than the total mass of the fusing nuclei.

70. Splitting light nuclei (which happens in particle accelerators) costs energy. As the curve in Figure 34.16 shows, the total mass of the products is greater than the total mass of the initial nucleus.

71. Energy would be released by the fissioning of gold and from the fusion of carbon, but by neither fission nor fusion for iron. Neither fission nor fusion results in a decrease of mass for iron.

72. If uranium were split into three parts, the segments would be nuclei of smaller atomic numbers, more toward iron on the graph of Figure 34.16. The resulting mass per nucleon would be less, and there would be more mass converted to energy in such a fissioning.

73. If the mass per nucleon varied in accord with the shape of the curve of Figure 34.15 instead of the curve of Figure 34.16, then the fissioning of all elements would liberate energy and all fusion processes would absorb rather than liberate energy. This is because all fission reactions (decreasing atomic number) would result in nuclei with less mass per nucleon, and all fusion reactions (increasing atomic number) would result in the opposite; nuclei of more mass per nucleon.

74. Whereas a pair of hydrogen nuclei collectively weigh more when apart than when locked together, a pair of nuclei half as heavy as uranium nuclei would weigh more when fused together than when apart.

75. The initial uranium has more mass than the fission products.

76. The initial hydrogen nuclei have more mass than the fusion products.

77. Energy from the Sun is our chief source of energy, which itself is the energy of fusion. Harnessing that energy on Earth has proven to be a formidable challenge.

78. Radioactivity in the Earth’s core provides the heat that keeps the inside molten, and warms hot springs and geysers. Nuclear fusion releases energy in the Sun that bathes Earth in sunshine.

79. Such speculation could fill volumes. The energy and material abundance that is the possible outcome of a fusion age will likely prompt several fundamental changes. Obvious changes would occur in the fields of commerce. Also, global warming by humans would be greatly reduced. Regional wars based on oil scarcity would be reduced. More development would likely reach undeveloped parts of the world. A fusion age would likely see changes that would touch every facet of human life.

80. The comparisons are many. Foremost are these: Conventional fossil-fuel power plants consume our natural resources and convert them into greenhouse gases and poisonous contaminants that are discharged into the atmosphere, producing among other things, global climate change and acid rain. A lesser environmental problem exists with nuclear power plants, which do not pollute the atmosphere. Pollution from nukes is concentrated in the radioactive waste products from the reactor core. Any rational discussion about the drawbacks of either of these power sources must acknowledge that *both* are polluters—so the argument is about which form of pollution are we more willing to accept in return for electrical power. (Before you say “No Nukes!,” rational thinking suggests that you first be able to say that you “Know Nukes!.”)

81. In 1 billion years U-235 on Earth would be in short supply and fission power would likely be a thing of the past.