SUB- POWER PLANT ENGINEERING

NUCLEAR POWER PLANT-

10.1 INTRODUCTION There is strategic as well as economic necessity for nuclear power in the United States and indeed most of the world. The strategic importance lies primarily in the fact that one large nuclear power plant saves more than 50,000 barrels of oil per day. At $30 to $40 per barrel (1982), such a power plant would pay for its capital cost in a few short years. For those countries that now rely on but do not have oil, or must reduce the importation of foreign oil, these strategic and economic advantages are obvious. For those countries that are oil exporters, nuclear power represents an insurance against the day when oil is depleted. A modest start now will assure that they would not be left behind when the time comes to have to use nuclear technology. The unit costs per kilowatt-hour for nuclear energy are now comparable to or lower than the unit costs for coal in most parts of the world. Other advantages are the lack of environmental problems that are associated with coal or oil-fired power plants and the near absence of issues of mine safety, labor problems, and transportation bottle-necks. Natural gas is a good, relatively clean-burning fuel, but it has some availability problems in many countries and should, in any case, be conserved for small-scale industrial and domestic uses. Thus nuclear power is bound to become the social choice relative to other societal risks and overall health and safety risks. Other sources include hydroelectric generation, which is nearly fully developed with only a few sites left around the world with significant hydroelectric potential. Solar power, although useful in outer space and domestic space and water heating in some parts of the world, is not and will not become an economic primary source of electric power. Yet the nuclear industry is facing many difficulties, particularly in the United States, primarily as a result of the negative impact of the issues of nuclear safety waste disposal, weapons proliferation, and economics on the public and government The impact on the public is complicated by delays in licensing proceedings, court and ballot box challenges. These posed severe obstacles to electric utilities planning nuclear power plants, the result being scheduling problems, escalating and unpredictably costs, and economic risks even before a construction permit is issued. Utilities had a delay or cancel nuclear projects so that in the early 1980s there was a de fan moratorium on new nuclear plant commitments in the United States. It is, however, the opinion of many, including this author, that despite these difficulties the future of large electric-energy generation includes nuclear energy as a primary, if not the main, source. The signs are already evident in many European and Asian countries such as France, the United Kingdom, Japan, and the U.S.S.R. 308 POWER PLANT ENGINEERING In a power plant technology course, it is therefore necessary to study nuclear energy: systems. We shall begin in this chapter by covering the energy-generation processes in nuclear reactors by starting with the structure of the atom and its nucleus and reactions that give rise to such energy generation. These include fission, fusion, aw different types of neutron-nucleus interactions and radioactivity. 10.2 GENERAL HISTORY AND TRENDS 10.2.1 MAJOR EVENTS 1945 : “Nuclear energy emerged from scientific obscurity and military secrecy.”

1945-55 : “An enthusiastic vision developed of a future in which nuclear power would provide a virtually unlimited solution for the world’s energy needs.” 1955-73 : The pros and cons of nuclear energy were debated; however, the optimists prevailed and nuclear energy grew to become an important source of electricity. Pros : Abundant, clean, and cheap energy. (We now know nuclear energy is not cheap.) Cons : Large amounts of radioactivity are produced in the nuclear reactor, mishaps cannot be totally ruled out, and nuclear energy cannot be divorced from nuclear weapons. (Also, the long-term storage of nuclear wastes is now a very important issue.) 1955-65 : Many reactors designed, built, and put into operation. 1965-73 : Most of the US reactors were ordered during this period. 1973-85 : Many US reactors canceled during this period. 1970-90 : Most US reactors licensed to operate during this period. 1990-present : The number of nuclear reactors operating in the US and in the world leveled off, reaching a plateau. Few new reactors ordered and built. Nuclear reactors started producing electricity in a significant way beginning about 1970 — just before the first international oil crisis in 1973. Thus, many countries saw nuclear energy as a means to reduce dependency on foreign oil. The US government saw nuclear energy as an important key to "energy independence." However, the 1973 oil crisis lead to "side effects," which adversely affected nuclear energy: Attention was focused worldwide on reducing energy consumption, including the consumption of electricity. (During the 1973-86 period, energy growth was erratic. Overall in the US, energy grew about as fast as the population, whereas electricity grew about as fast as the GNP, which means it grew faster than overall energy consumption, though not as fast as it had grown prior to 1973. The oil crises reduced economic growth, thus, decreasing the demand for energy and electricity. These effects reduced the demand for new nuclear plants. By 1973, the cost of nuclear energy was no longer regarded as "cheap," as had been touted in the early days of nuclear energy development, and safety concerns were starting to have an impact on the public view of nuclear energy. Also, nuclear energy was regarded as "establishments," and there were many protests against the establishment and its programs. US nuclear energy capacity has been steady since the late 1980s. Currently, about 22% of US electricity is generated from nuclear energy (7.17 Quads). In 1994, there were 109 operating nuclear reactors in the US, with a total capacity of 99GWe. Currently, nuclear energy represents about 8% of the NUCLEAR POWER PLANT 309 primary energy consumption in the US. However, coal is "king," generating about 55% of US electricity. Hydro generates about 10% of US electricity. The US generates more electricity from nuclear energy than any other nation. However, France generates the greatest percentage of electricity from nuclear energy — about 75-80%. France is followed by Sweden. In 1994, Sweden generated about 50% of its electricity from nuclear energy, but now says it is getting out of nuclear energy electricity generation. The Swedish government claims this move will not increase its greenhouse gas emissions — a claim not believed in all circles. Worldwide, for 1994, nuclear energy accounted for 6% of the primary energy consumption and 18% of the electricity generation. These numbers are just below the values for the US. 424 nuclear reactors operate worldwide, with a total capacity of 338GWe, spread over 30 countries. In all but a few countries, nuclear energy growth was brought to a stop or at least to a crawl in the late 1980s and the 1990s. A summary of the reasons is: • Reduction in oil and gas prices, especially since the late 1980s. • Reduced growth in energy, compared to the pre-1973 period. • Rising cost of nuclear energy. • Increasing fears about nuclear energy. • Campaigns against nuclear energy. Public interest in nuclear energy began about 1944, grew strongly until about 1974, reached its peak then, and by 1994 dropped to a low level. Is the age of nuclear energy over? Outside of a few countries, will more reactors be built? Has the verdict been given on nuclear energy? 10.2.2 WHAT MIGHT CHANGE THE CURRENT SITUATION? Cost. Currently, nuclear energy is regarded as costly, and some costs are surely being passed on to future generations. The euphoric claims of the 1940s and 1950s regarding low cost nuclear energy

have been discounted for at least two decades. The statement of the 1950s that nuclear energy would be "too cheap to meter" has haunted the industry. However, the text states that nuclear energy was cheaper than fossil energy for a period in the 1970s, and today is cheaper than fossil energy in some countries. In the US, the long construction times, of about 10 years, have significantly driven up the cost. During construction period, capital is invested, interest payments occur, but no income from the sale of electricity occurs. The development of factory-built, packaged, nuclear reactors, which could be purchased much as combined cycle combustion turbines are done today, would probably significantly reduce the cost. "From order to operation" within 2 or 3 years would be quite a change. Standardization of nuclear reactor designs would likely significantly reduce the cost, and would likely increase safety. Two things should be noted about US reactors. Many designs were developed and built. And most of the US reactors were ordered over a very short period of time, 1965 to 1973. Thus, during the 1970s and 1980s the opportunity to "get out the bugs," and for the better systems to evolve and win out didn't fully occur. With the benefit now of experience, with standardization, and with reduced ordertostart-up times, the cost of nuclear energy should come down. 310 POWER PLANT ENGINEERING Public Attitude. The public requires assurance that the industry truly has the issues of safety, fuel security, and waste disposal well under control. Perhaps the French experience will be convincing in this regard. Greenhouse Effect. If the public comes to fear greenhouse warming, rather than simply having a concern about it, as currently the case, nuclear energy may be viewed more favorably. Coal is the "real" problem with respect to greenhouse gases. More electricity is produced by the burning of coal than by any other method. If the world continues to produce much of its electricity from coal, the evidence is fairly strong: CO_2 concentrations in the atmosphere will significantly increase, and greenhouse warming will occur (though the level of temperature increase is uncertain). Burning of all of the earth's fossil fuel resources would probably increase the atmospheric CO_2 concentration from the current level of 360 ppmv to about 1300 ppmv. 90% of this increase would be due to coal, since the oil and gas resources are small compared to the coal resources. The calculation assumes 4000 Gte (giga tonnes) of carbon in the earth's fossil fuel resources, an increase of 1ppmv CO_2 in the atmosphere for every 2.13 Gte of carbon burned, and a retention of 50% of the emitted CO_2 in the atmosphere. Since the start of the industrial age in the late 1700s, the CO_2 contention of the atmosphere has increased about 80 ppmv, and the mean temperature of the earth's atmosphere near the surface has increased about 1 degree F. If the temperature rise is assumed to be due to the CO_2 increase (which is debatable), a linear extrapolation implies a temperature increase of 12 degrees F for the 360 to 1300 ppmv CO_2 increase. Demand for Eelectricity. Electricity is a desirable and convenient form of energy. Several factors could influence the demand for its generation, including its generation from nuclear power stations: • Greater use of electricity, relative to heat, for manufacturing processes — a trend likely to continue and to drive up demand for electricity. • Greater use of heat pumps for space heating. Significant growth here is problematic, since gas is cheap, and for many, heating with gas-fired furnaces is cheaper than converting to electric driven heat pumps. • Electrification of transportation systems : Electric vehicles (EVs) and some types of hybrid electric vehicles (HEVs) depend on an external source of electricity. However, other types of HEVs and fuel cell powered vehicles generate electricity on board. It is too early to judge which system will evolve, or whether the internal combustion engine will retain predominance in a new form. Thus, a significant increase in electricity for the transportation sector is difficult to judge at present. See the front page of the Wall Street Journal for Monday, January 5, 1998 for an article on new power plants for automobiles. • Combined cycle combustion turbines, fired on gas, are rapidly gaining popularity for generating electricity. Capital cost is relatively low, first law efficiency is high and will go higher (at least 60%), and order-to-start-up time is short. These systems may diminish the interest in new nuclear energy technology over the next one to two decades. Long term availability and price stability of the natural gas is the concern with respect to these systems. Also, they emit greenhouse gases, though the amount of CO_2 emitted per unit of electrical energy produced is less than one half that of a coal-fired electric power generating station.

• Renewable energy technology : What will be the growth of solar, wind, biomass, and other renewable energy technologies ? Will their cost competitiveness improve ? Are they as environmentally benign as thought ? Will they fill more than niche markets? Will technological breakthroughs occur ? Could they increase from 8% of US primary energy consumption (the current situation) to say the 20 to 30% level within 10 to 20 years ? If "yes," renewable energy may diminish the rejuvenation of the nuclear energy industry. NUCLEAR POWER PLANT 311 10.2.3 TECHNICAL HISTORY AND DEVELOPMENTS Developments Prior to and During WW-2 • 1896: discovery of radioactivity. • 1911: discovery of the nuclear atom. • 1911: Rutherford noted the enormous amount of energy associated with nuclear reactions compared to chemical reactions. • 1932: discovery of neutron. • 1938: discovery of nuclear fission. • 1939: researchers recognized that enough neutrons were released during fission reactions to sustain a chain reaction (in a pile of uranium and graphite). A chain reaction requires the release of two neutrons (or more) for every neutron used to cause the reaction. • 1942 (Dec. 2): demonstration of the first operating nuclear reactor (200 Watts). • 1943 (Nov.): 1 mW reactor put into operation at Oak Ridge, Tennessee. • 1944 (Sept.): 200 mW reactor put into operation at Hanford, Washington—for the production of plutonium. This reactor was built in only 15 months. • 1944 (Sept.): nuclear reactor for electricity generation proposed, using water for both cooling and neutron moderation. Essentially, this is the birth of nuclear energy for civilian use. 10.2.4 DEVELOPMENTS AFTER WW-2 • 1946: AEC (Atomic Energy Commission) established to oversee both military and civilian nuclear energy. • 1953: Putman report/book, a thoughtful analysis of the case for nuclear energy for electricity production. • 1953: US Navy began tests of the PWR (pressurized water reactor). • 1957: 60 mW reactor at Shippingport, PA began to generate electricity for commercial use. The plant was built by the AEC, though Navy leadership played a predominant role. • 1953-60: exploratory period: 14 reactors built, of many different designs, all but 3 under 100 mW size. • 1960-65: only 5 reactors built. • 1965-73: main period of ordering of nuclear reactors in the US. Size was much larger than before, many reactors of 600 to 1200 mW size. • 1974: "honeymoon" over-nuclear energy no longer highly valued by the public. • 1973-78: fall off in orders, with no US orders after 1978. • 1974-85: cancellation of orders, over half of orders were canceled, or construction never brought to completion. Most reactors ordered prior to 1970 were built and brought on line. Many reactors ordered after 1970 never came on line they were canceled. • 1970-90: most of US's reactors brought on line for commercial operation, indicating that most US reactors are 7 to 27 years old, or have 13 to 33 years of operation left, assuming a 40 year operating life. • 1979: Three Mile Island accident. Reactor shut down. 312 POWER PLANT

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10.3 THE ATOMIC STRUCTURE In 1803 John Dalton, attempting to explain the laws of chemical combination, propose his simple but incomplete atomic hypothesis. He postulated that all elements consists of indivisible minute particles of matter, atoms, that were different for different elements and preserved their identity in chemical reactions. In 1811 Amadeo Avo-gadro introduced the molecular theory based on the molecule, a particle of matter composed of a finite number of atoms. It is now known that the atoms are themselves composed of sub particles, common among atoms of all elements. An atom consists of a relatively heavy, positively charged nucleus and a number of much lighter negatively charged electrons that exist in various orbits around the nucleus. The nucleus, in turn, consists of sub particles, called nucleons. Nucleons at primarily of two kinds: the neutrons, which are electrically neutral, and the proton: which are positively charged. The electric charge on the proton is equal in magnitude but opposite in sign to that on the electron. The atom as a whole is electrically neutral the number of protons equals the number of electrons in orbit. One atom may be transformed into another by losing or acquiring some of the above sub particles. Such reactions result in a change in mass Am and therefore release (or absorb) large quantities of energy DE, according to Einstein's law ⊗E = 1 gc ⊗mc2 ...(10.1) where c is the speed of light in vacuum and g,. is the familiar engineering conversion factor. Equation (10.1) applies to all processes, physical, chemical, or nuclear, in which energy is released or absorbed. Energy is, however, classified as nuclear if it is associated with changes in the atomic nucleus. Figure 10.1 shows three atoms. Hydrogen has a nucleus composed of one proton, no neutrons, and one orbital electron. It is the only atom that has no neutrons. Deuterium has one proton and one neutron in its nucleus and one orbital electron. Helium contains two protons, two neutrons, and two electrons. The electrons exist in orbits, and each is quantitized as a lumped unit charge as shown. Most of the mass of the atom is in the nucleus. The masses of the three primary atomic sub particles are Neutron mass mn = 1.008665 amu Proton mass mP = 1.007277 amu Electron mass me = 0.0005486 amu. The abbreviation amu, for atomic mass unit, is a unit of mass approximately equal to 1.66 × 10–27 kg, or 3.66 × 10–2 lb. These three particles are the primary building blocks of all atoms. Atoms differ in their mass because they contain varying numbers of them. NUCLEAR POWER PLANT 313 Atoms with nuclei that have the same number of protons have similar chemical and physical characteristics and differ mainly in their masses. They are called isotopes. For example, deuterium, frequently called heavy hydrogen, is an isotope of hydrogen. It exists as one part in about 6660 in naturally occurring hydrogen. When combined with oxygen, ordinary hydrogen and deuterium form ordinary water (or simply water) and heavy water, respectively. The number of protons in the nucleus is called the atomic number Z. The total number of nucleons in the nucleus is called the mass number A. (a) (b) (c) = neutron = proton = electron Fig. 10.1 As the mass of a neutron or a proton is nearly 1 amu, A is the integer nearest the mass of the nucleus which in turn is approximately equal to the atomic mass of the atom. Isotopes of the same element thus have the same atomic number but differ in mass number. Nucleus symbols are written conventionally as ZXA where X is the usual chemical symbol. Thus the hydrogen nucleus is 1H1, deuterium is 1H2 (and sometimes D), and ordinary helium is 2He1. For particles containing no protons, the subscript indicates the magnitude and sign of the electric charge. The an electron is – e° (sometimes e or) and a neutron is 0n1. Symbols are also often written in the form He-4, helium-4, etc. Another system of notation, written as 7. will not be used in this text. Fig. 10.2 shows, schematically, the structure of H1, He4 and some heavier atoms and the distribution of their electrons in various orbits. Two other particles of importance are the positron and the neutrino. The positron is a positively charged electron having the symbols +1e0, e+ or +. The neutrino (little neutron) is a tiny electrically neutral particle that is difficult to observe experimentally. Initial evidence of its existence was based on theoretical considerations, nuclear reactions where a/3 particle oeither kind is emitted or captured, the resulted energy (corresponding to the lost mass) was not all accounted for by the energy the emitted 13 particle and the recoiling nucleus. It was first suggested by Wolfgai Pauli in 1934 that the neutrino was simultaneously ejected in these reactions and the it carried the balance of the energy, often larger than that carried by the particle itself. The importance of neutrinos is that they carry some 5 percent of the total energy produced in fission. This energy is completely react lost because neutrinos do not rea and are not stopped by any practical structural material. The neutrino is given the symbol u. There are many other atomic sub particles. An example is the mesons, unstable positive, negative, or neutral particles that have masses intermediate between an electron and a proton. They are exchanged between nucleons and are thought to account for the forces between them. A discussion of these and other sub particles is, however beyond the scope of this book. Electrons that orbit in the outermost shell of an atom are called valence electron. The outermost shell is called the valence shell. Thus, hydrogen has one valence electron and its K shell is the valence 314 POWER PLANT ENGINEERING shell, etc. Chemical properties of an element are function of the number of valence electrons. The electrons play little or not part nuclear interactions. e n p (d) e n p e e (c) n p e e (b) p e (a) e p n (e) (f) e 15p 16n (g) 54p 71n e Fig. 10.2 10.4 SUMMARY OF NUCLEAR ENERGY CONCEPTS AND TERMS 10.4.1 SUMMARY OF FEATURES 1. Heat energy source is fission of radioactive material, (U-235) 2. Two typical plant designs: Pressurized water reactor (PWR) (U.S.) Boiling water reactor (BWR) (Russian) 3. Fuel pellets are in a large number of tubes (fuel rods) 4. Water circulates through core 5. Water converted to steam drives turbine 6. Turbine turns generator electricity 10.4.2 FISSION Unstable (radioactive) elements spontaneously split (radioactive decay), emitting high energy particles. Collision of particles with other atomic nuclei can trigger further nuclear decompositions. A small amount of mass is converted into a large amount of energy, when atomic nuclei are split. Einstein equation: E = mc2 Conversion of mass to energy. E = energy, m = mass converted, c = speed of light NUCLEAR POWER PLANT 315

10.4.3 CRITICAL MASS There is a threshold mass of a radioactive isotope at which the flux density of radioactive particles will sustain a chain reaction. If this reaction is uncontrolled the result is an atomic bomb explosion. If the radiation fluxes are controlled and limited, we call it a nuclear reactor, which can be the basis of an electric power plant. Types of Radiation Atomic Weight Charge Alpha radiation (Helium nucleus) 4 +2 Beta radiation (Electron) ~0 – 1 Neutron 1 0 Gamma ray ~0 0 10.4.4 ALPHA RADIATION Alpha is quickly absorbed by matter because the particles have a large probability of collision with nuclei. Sources external to the human body cause radiation absorption within the thickness of the skin. Radiation from airborne particles in the lung are absorbed by surface membranes lining the lung. Alpha emitters ingested with food cause radiation absorption by the lining of the gut. The risk of genetic damage to adult organisms is very small because absorption takes place in surface cells. 10.4.5 BETA PARTICLES Beta particles penetrate to the deepest parts of the body and can cause genetic damage and disrupt the function of cells anywhere in the body. Building walls and earthwork provide substantial shielding. 10.4.6 GAMMA PARTICLES Gamma has the greatest penetration due to their small cross-section. Gamma particles can pass through ordinary materials. Effective shielding requires blankets of lead. Gamma radiation is a danger to all cells in the body. 10.4.7 URANIUM FISSION 92U235 + 0n1 92U236 Fission Products 92U238 + 0n1 92U239 + Gamma Fission Products 92U239 93Np239 94Pu239 Neptunium Plutonium After many steps, (and a long time) the ultimate product is non-radioactive Lead atoms. The neutrons, whose absorbtion is indicated above, come from splitting of later fission products in reactions not shown here. Note that U-235 fission in the presence of U-238 causes the conversion of part of the U- 238 into Plutonium-239 which can be concentrated to make an H-Bomb. Intermediate isotopes of health significance include Cesium-137, Iodine-131, Strontium-90 and many others. 316 POWER PLANT ENGINEERING 10.4.8 HALF LIFE, T Time for half the atomic nuclei to spontaneously split. The amount decays exponentially N = No exp (– t/T) N = Amount of radioactive material, No = Initial amount, t = Elapsed time 10.5 ETHICAL PROBLEMS IN NUCLEAR POWER REGULATION The Atomic Energy Commission (AEC), was formed to create a civilian nuclear energy industry, and had conflicting responsibilities: •• Promoting Nuclear Power —funded research in plant design —subsidized production of nuclear fuel • Regulating Plant Safety —defined safety procedures, poor enforcement —inspecting, certifying plants —certifying operators, poor training As a result of these conflicting interests • No Long Term Waste Dispotal Plan was Completed —wastes are still accumulating in temporary storage —radioactive waste? NIMBY • Future Termination/Cleanup Costs are not Factored into Current Electric Rates • Power Companies are Largely Self-Regulated —avoid reporting radiation release or do not monitor releases. —avoid safety regulations to save money. Internal conflicts of the AEC were supposed to be resolved by splitting the promotional and regulatory duties between the new agencies: Nuclear Regulatory Commission (NRC) – safety and standards Dept. of Energy (DOE) – research, promotion, waste disposal, and fuel rod production. 10.6 CHEMICAL AND NUCLEAR EQUATIONS Chemical reactions involve the combination or separation of whole atoms. C + O2 = CO2 This reaction is accompanied by the release of about 4 electron volts (eV). An electron volt is a unit of energy in common use in nuclear engineering. 1 eV = 1.6021 × 10–19 joules (J) = 1.519 × 10–22 Btu = 4.44 × 10–26 kWh. 1 million electron volts (1 MeV) = 106 eV. In chemical reactions, each atom participates as a whole and retains its identity. The molecules change. The only effect is a sharing or exchanging of valence electrons. The nuclei are unaffected. In NUCLEAR POWER PLANT 317 chemical equations there are as many atoms of each participating element in the products (the right-hand side) as in the reactants (the left-hand side). Another example is one in which uranium dioxide (UO2) is converted into uranium tetra fluoride (UF4), called green salt, by heating it in an atmosphere of highly corrosive anhydrous (without water) hydrogen fluoride (HF), with water vapor (H2O) appearing in the products UO2 + 4HF = 2HzO + UF4 Water vapor is driven off and UF, is used to prepare gaseous uranium hexafloride (UF6), which is used in the separation of the U235 and U238 isotopes of uranium by the gaseous diffusion method. (Fluorine has only one isotope, F9, and thus combi-nations of molecules of uranium and fluorine have molecular masses depending only on the uranium isotope.) Both chemical and nuclear reactions are either exothermic or endothermic, that is, they either release or absorb energy. Because energy and mass are convertible, Eq. (10.1), chemical reactions involving energy do undergo a mass decrease in exothermic reactions and a mass increase in endothermic ones. However, the quantities of energy associated with a chemical reaction are very small compared with those of a nuclear reaction, and the mass that is lost or gained is minutely small. This is why we assume a preservation of mass in chemical reactions, undoubtedly an incorrect assumption but one that is sufficiently accurate for usual engineering calculations. In nuclear reactions, the reactant nuclei do not show up in the products, instead we may find either isotopes of the reactants or other nuclei. In balancing nuclear equations it is necessary to see that the same, or equivalent, nucleons show up in the products as entered the reaction. For example, if K, L, M, and N were chemical symbols, the corresponding nuclear equation might look like Z1KA1 + Z2LA2 ⍰ Z3MA3 + Z4NA4 To balance the following relationship must be satisfied. Z1 + Z2 = Z3 + Z4 A1 + A2 = A3 + A4 Sometimes the symbols y or v are added to the products to indicate the emission of electromagnetic radiation or a neutrino, respectively. They have no effect on equation balance because both have zero Z and A, but they often carry large portions of the resulting energy. Although the mass numbers are preserved in a nuclear reaction, the masses of the isotopes on both sides of the equation do not balance. Exothermic or endothermic energy is obtained when there is a reduction or an increase in mass from reactants to products, respectively. 10.7 NUCLEAR FUSION AND FISSION Nuclear reactions of importance in energy production are fusion, fission, and radioactivity. Infusion, two or more light nuclei fuse to form a heavier nucleus. In fission, a heavy nucleus is split into two or more lighter nuclei. In both, there is a decrease in mass resulting in exothermic energy. The same as in force = 1 g , × mass × acceleration. 318 POWER PLANT ENGINEERING Table 10.1. Mass-energy Conversion factors EnergyMass MeV J Bru kWh mW day amu 931.478 1.4924 × 10–10 1.4145 × 10–13 4.1456 × 10–17 9.9494 × 10–13 kg 5.6094 × 1029 8.9873 × 1016 8.5184 × 1013 2.4965 × 1010 5.9916 × 1014 lbm 2.5444 × 1029 4.0766 × 1016 3.8639 × 1023 1.1324 × 1010 2.7177 × 1014 10.7.1 FUSION Energy is produced in the sun and stars by continuous fusion reactions in which four nuclei of hydrogen fuse in a series of reactions involving other particles that continually appear and disappear in the course of the reactions, such as He, nitrogen, carbon, and other nuclei, but culminating in one nucleus of helium and two positrons resulting in a decrease in mass of about 0.0276 amu, corresponding to 25.7 MeV. 41H1 = 2He4 + 2+1e0 The heat produced in these reactions maintains temperatures of the order of several million degrees in their cores and serves to trigger and sustain succeeding reactions. On earth, although fission preceded fusion in both weapons and power generation. the basic fusion reaction was discovered first, in the 1920s, during research on particle accelerators. Artificially produced fusion may be accomplished when two light atom fuse into a larger one as there is a much greater probability of two particles colliding than of four. The 4-hydrogen reaction requires, on an average, billions of years for completion, whereas the deuterium-deuterium reaction requires a fraction of a second. To cause fusion, it is necessary to accelerate the positively charged nuclei to high kinetic energies, in order to overcome electrical repulsive forces, by raising their temperature to hundreds of millions of degrees resulting in a plasma. The plasma must be prevented from contacting the walls of the container, and must be confined for a period of time (of the order of a second) at a minimum density. Fusion reactions are called thermonuclear because very high temperatures are required to trigger and sustain them. Table

10.2 lists the possible fusion reactions and the energies produced by them. Table 10.2 Fusion reaction Energy per Number Reactants Products reaction, MeV 1 D + D T + p 4 2 D + D He3 + n 3.2 3 T + D He4 + n 17.6 4 He3 + D He4 + p 18.3 n, p, D, and T are the symbols for the neutron, proton, deuterium and tritium respectively. NUCLEAR POWER PLANT 319 Many problems have to be solved before an artificially made fusion reactor becomes a reality . The most important of these are the difficulty in generating and maintaining high temperatures and the instabilities in the medium (plasma), the conversion of fusion energy to electricity, and many other problems of an operational nature. Fusion power plants will not be covered in this text. 10.7.2 Fission Unlike fusion, which involves nuclei of similar electric charge and therefore requires high kinetic energies, fission can be caused by the neutron, which, being electrically neutral, can strike and fission the positively charged nucleus at high, moderate, or low speeds without being repulsed. Fission can be caused by other particles, but neutrons are the only practical ones that result in a sustained reaction because two or three neutrons are usually released for each one absorbed in fission. These keep the reaction going. There are only a few fissionable isotopes U235, Pu239 and U233 are fissionable by neutrons of all energies. The immediate (prompt) products of a fission reaction, such as Xe° and Sry4 above, are called fission fragments. They, and their decay products , are called fission products. Fig. 10.4 shows fission product data for U235 by thermal and fast neutrons and for U233 and Pu239 by thermal neutrons 1841. The products are represented by their mass numbers. Neutron Uranium nucleus Xenon nucleus Neutron lost by escape or consumed in nonfissoin reaction Strontium nucleus Fig. 10.3 10 1.0 0.1 0.010.001 0.0001 70 80 90 100 110 120 130 140 150 U 239 Pu 239 Pu 239 U 239 Pu239 Pu Fission yield per cent Mass number (b) Thermal 4 Mev 10 1.0 0.1 0.01 0.001 0.0001 70 80 90 100 110 120 130 140 150 160 Fission yield per cent Mass number (a) Thermal neutrons 14 Mev neutrons Fig. 10.4 320 POWER PLANT ENGINEERING 10.8 ENERGY FROM FISSION AND FUEL BURN UP There are many fission reactions that release different energy values. Another 92U235 + 0n1 56Ba137 + 36Kr97 + 20n1 ...(1) has the mass balance 235.0439 + 1.00867 136.9061 + 96.9212 + 2 × 1.00867 236.0526 235.8446 ⊗m = 235.8446 – 236.0526 = – 0.2080 amu ...(2) Thus ⊗E = 931 × – 0.2080 = – 193.6 MeV = – 3.1 × 10–11 J ...(3) On the average the fission of a U235 nucleus yields about 193 MeV. The same figure roughly applies to U233 and Pu239. This amount of energy is prompt, i.e., released at the time of fission. More energy, however, is produced because of (1), the slow decay of the fission fragments into fission products and (2) the nonfission capture of excess neutrons in reactions that produce energy, though much less than that of fission. The total energy, produced per fission reaction, therefore, is greater than the prompt energy and is about 200 MeV, a useful number to remember. The complete fission of 1 g of UZ nuclei thus produces 235 Avogadro's number U isotope mass = 200 MeV = 0.60225 1024 235.0439 · × 200 = 0.513 × 1024 MeV = 2.276 × 1024 kWh = 8.190 × 1010 J = 0.948 MW-day. Another convenient figure to remember is that a reactor burning 1 g of fissionable material generates nearly 1 MW-day of energy. This relates to fuel burnup. Maximum theoretical burnup would therefore be about a million MW-day/ton (metric) of fuel. This figure applies if the fuel were entirely composed of fissionable nuclei and all of them fission. Reactor fuel, however, contains other nonfissionable isotopes of uranium, plutonium, or thorium. Fuel is defined as all uranium, plutonium, and thorium isotopes. It does not include alloying or other chemical compounds or mixtures. The term fuel material is used to refer to fuel plus such other materials. Even the fissionable isotopes cannot be all fissioned because of the accumulation of fission products that absorb neutrons and eventually stop the chain reaction. Because of this-and owing to metallurgical reasons such as the inability of the fuel material to operate at high temperatures or to retain gaseous fission products [such as Xe and Kr, in its structure except for limited periods of time-burnup values are much lower than this figure. They are, however, increased somewhat by the fissioning ofsome fissionable nuclei, such as Puz3y, which are newly converted from fertile nuclei, such as U238 (Sec. 10.4.7). Depending upon fuel type and enrichment (mass percent of fissionable fuel in all fuel), burnups may vary from about 1000 to 100,000 MW-day/ton and higher. 10.9 RADIOACTIVITY Radioactivity is an important source of energy for small power devices and a source of radiation for use in research, industry, medicine, and a wide variety of applications, as well as an environmental concern. NUCLEAR POWER PLANT 321 Most of the naturally occurring isotopes are stable. Those that are not stable, i.e., radioactive, are some isotopes of the heavy elements thallium (Z = 81), lead (Z = 82), and bismuth (Z = 83) and all the isotopes of the heavier elements beginning with polonium (Z = 84). A few lower-mass naturally occurring isotopes are radioactive, such as K40, Rb87 and In115. In addition, several thousand artificially produced isotopes of all masses are radioactive. Natural and artificial radioactive isotopes, also called radioisotopes, have similar disintegration rate mechanisms. Fig. 10.5 shows a Z-N chart of the known isotopes. Radioactivity means that a radioactive isotope continuously undergoes spontaneous (i.e., without outside help) disintegration, usually with the emission of one or more smaller particles from the parent nucleus, changing it into another, or daughter, nucleus. The parent nucleus is said to decay into the daughter nucleus. The daughter may or may not be stable, and several successive decays may occur until a stable isotope is formed. An example of radioactivity is 49In115 = 50Sn115 + –1e0 Radioactivity is always accompanied by a decrease in mass and is thus always exothermic. The energy liberated shows up as kinetic energy of the emitted particles and as y radiation. The light particle is ejected at high speed, whereas the heavy one recoils at a much slower pace in an opposite direction. Naturally occurring radio isotopes emit 〈, 3, or y particles or radiations. The artificial isotopes, in addition to the above, emit or undergo the following particles or reactions: positrons; orbital electron absorption, called K capture; and neutrons. In addition, neutrino emission accompanies ? emission (of either sign). Alpha decay. Alpha particles are helium nuclei, each consisting of two protons and two neutrons. They are commonly emitted by the heavier radioactive nuclei. An example is the decay of Pu239 into fissionable U235 94Pu239 = 92U235 + 2He4 Beta decay. An example of ? decay is 82Pb214 = 83Bi214 + –1e0 + ? where ?, the symbol for the neutrino, is often dropped from the equation. The penetrating power of ? particles is small compared with that of y-rays but is larger than that of a particles. 6- and a-particle decay are usually accompanied by the emission of y radiation. Gamma radiation. This is electromagnetic radiation of extremely short wavelength and very high frequency and therefore high energy. ?-rays and X-rays are physically similar but differ in their origin and energy: ?-rays from the nucleus, and X-rays from the atom because of orbital electrons changing orbits or energy levels. Gamma wave-lengths are, on an average, about one-tenth those of X-rays, although the energy ranges overlap somewhat. Gamma decay does not alter either the atomic or mass numbers. 10.10 NUCLEAR REACTOR 10.10.1 PARTS OF A NUCLEAR REACTOR A nuclear reactor is an apparatus in which heat is produced due to nuclear fission chain reaction. Fig. 10.6 shows the various parts of reactor, which are as follows : 1. Nuclear Fuel 2. Moderator3. Control Rods 4. Reflector 5. Reactors Vessel 6. Biological Shielding 7. Coolant. Fig. 10.6 shows a schematic diagram of nuclear reactor. r. 10.10.2 NUCLEAR FUEL Fuel of a nuclear reactor should be fissionable material which can be defined as an element or isotope whose nuclei can be caused to undergo nuclear fission by nuclear bombardment and to produce a fission chain reaction. It can be one or all of the following U233, U235 and Pu239. Natural uranium found in earth crust contains three isotopes namely U234, U235 and U238 and their average percentage is as follows : U238 — 99.3% U235 — 0.7% U234 — Trace Out of these U235 is most unstable and is capable of sustaining chain reaction and has been given the name as primary fuel. U233 arid Pu239 are artificially produced from Th232 and U238 respectively and are called secondary fuel. NUCLEAR POWER PLANT 323 Pu239 and U233 so produced can be fissioned by thermal neutrons. Nuclear fuel should not be expensive to fabricate. It should be able to operate at high temperatures and should be resistant to radiation damage. Uranium deposits are found in various countries such as Congo, Canada, U.S.A., U.S.S.R., Australia. The fuel should be protected from corrosion and erosion of the coolant and for this it is encased in metal cladding generally stainless steel or aluminum. Adequate arrangements should be made for fuel supply, charging or discharging and storing of the fuel. For economical operation of a nuclear power plant special attention should be paid to reprocess the spent: up (burnt) fuel elements and the unconsumed fuel. The spent up fuel elements are intensively radioactive and emits some neutron and gamma rays and should be handled carefully. In order to prevent the contamination of the coolant by fission products, a protective coating or cladding must separate the fuel from the coolant stream. Fuel element cladding should possess the following properties : 1. It should be able to withstand high temperature within the reactor. 2. It should have high corrosion resistance. 3. It should have high thermal conductivity. 4. It should not have a tendency to absorb neutrons. 5. It should have sufficient strength to withstand the effect of radiations to which it is subjected. Uranium oxide (UO2) is another important fuel element. Uranium oxide has the following advantages over natural uranium: 1. It is more stable than natural uranium. 2. There is no problem or phase change in case of uranium oxide and therefore it can be used for higher temperatures. 3. It does not corrode as easily as natural uranium. 4. It is more compatible with most of the coolants and is not attacked by H2, Nz. 5. There is greater dimensional stability during use. Uranium oxide possesses following disadvantages : 1. It has low thermal conductivity. 2. It is more brittle than natural uranium and therefore it can break due to thermal stresses. 3. Its enrichment is essential. Uranium oxide is a brittle ceramic produced as a powder and then sintered to form fuel pellets. Another fuel used in the nuclear reactor is uranium carbide (UC). It is a black ceramic used in the form of pellets. Table indicates some of the physical properties of nuclear fuels. Fuel Thermal con- Specific heat Density kg/m3 Melting pointductivity K- kcal/kg °C (°C) cal/m. hr°C Natural uranium 26.3 0.037 19000 1130 Uranium oxide 1.8 0.078 11000 2750 Uranium carbide 20.6 — 13600 2350 324 POWER PLANT ENGINEERING MODERATOR In the chain reaction the neutrons produced are fast moving neutrons. These fast moving neutrons are far less effective in causing the fission of U235 and try to escape from the reactor. To improve the utilization of these neutrons their speed is reduced. It is done by colliding them with the nuclei of other material which is lighter, does not capture the neutrons but scatters them. Each such collision causes loss of energy, and the speed of the fast moving neutrons is reduced. Such material is called Moderator. The slow neutrons (Thermal Neutrons) so produced are easily captured by the nuclear fuel and the chain reaction proceeds smoothly. Graphite, heavy water and beryllium are generally used as moderator. Reactors using enriched uranium do not require moderator. But enriched uranium is costly due to processing needed. A moderator should process the following properties : 1. It should have high thermal conductivity. 2. It should be available in large quantities in pure form. 3. It should have high melting point in case of solid moderators and low melting point in case of liquid moderators. Solid moderators should also possess good strength and machinability. 4. It should provide good resistance to corrosion. 5. It should be stable under heat and radiation. 6. It should be able to slow down neutrons. MODERATING RATIO To characterize a moderator it is best to use so called moderating ratio which is the ratio of moderating power to the macroscopic neuron capture coefficient. A high value of moderating ratio indicates that the given substance is more suitable for slowing down the neutrons in a reactor. Table 10.3 indicates the moderating ratio for some of the material used as moderator. Material Moderating ratio Beryllium 160 Carbon 170 Heavy Water 12,000 Ordinary Water 72 This shows that heavy water, carbon and, beryllium are the best moderators Table 10.4 Moderator Density (gm/cm3) H2O 1 D2O 11 C 1.65 Be 1.85 Table 10.5 shows some of the physical constants of heavy water and ordinary water NUCLEAR POWER PLANT 325 Table 10.5 Physical constant D2O H2O Density at 293 K 1.1 gm/cm3 0.9982 gm/cm3 Freezing temperature 276.82 273 Boiling temperature 374.5 373 K Dissociation Constant 0.3 × 10–14 1 × 10–14 Dielectric Constant at 293°K 80.5 82 Specific heat at 293°K 1.018 1 Control Rods. The Control and operation of a nuclear reactor is quite different frorn a fossil and fuelled (coal or oil fired) furnace. The furnace is fed continuously and the heat energy in the furnace is controlled by regulating the fuel feed, and the combustion air whereas a nuclear reactor contains as much fuel as is sufficient to operate a large power plant for some months. The consumption of this fueland the power level of the reactor depends upon its neutron flux in the reactor core. The energy produced in the reactor due to fission of nuclear fuel during chain reaction is so much that if it is not controlled properly the entire core and surrounding structure may melt and radioactive fission products may come out of the reactor thus making it uninhabitable. This implies that we should have some means to control the power of reactor. This is done by means of control rods. Control rods in the cylindrical or sheet form are made of boron or cadmium. These rods can be moved in and out of the holes in the reactor core assembly. Their insertion absorbs more neutrons and damps down the reaction and their withdrawal absorbs less neutrons. Thus power of reaction is controlled by shifting control rods which may be done manually or automatically. Control rods should possess the following properties : 1. They should have adequate heat transfer properties. 2. They should be stable under heat and radiation. 3. They should be corrosion resistant. 4. They should be sufficient strong and should be able to shut down the reactor almost instantly under all conditions. 5. They should have sufficient cross-sectional area for the absorption. 10.10.5 REFLECTOR The neutrons produced during the fission process will be partly absorbed by the fuel rods, moderator, coolant or structural material etc. Neutrons left unabsorbed will try to leave the reactor core never to return to it and will be lost. Such losses should be minimized. It is done by surrounding the reactor core by a material called reflector which will send the neutrons back into the core. The returned neutrons can then cause more fission and improve the neutrons economy of' the reactor. Generally the reflector is made up of graphite and beryllium. 10.10.6 REACTOR VESSEL It is a. strong walled container housing the cure of the power reactor. It contains moderator, reflector, thermal shielding and control rods. 326 POWER PLANT ENGINEERING 10.10.7 BIOLOGICAL SHIELDING Shielding the radioactive zones in the reactor roan possible radiation hazard is essential to protect, the operating men from the harmful effects. During fission of nuclear fuel, alpha particles, beta particles, deadly gamma rays and neutrons are produced. Out oil these nc-1utroxrs and gamma rays are of main significance. A protection must be provided against them. Thick layers of lead or concrete are provided round the reactor for stopping the gamma rays. Thick layers of metals or plastics are sufficient to stop the alpha and beta particles. 10.10.8 COOLANT Coolant. flows through and around the reactor core. It is used to transfer the large amount of heat produced in the reactor due to fission of the nuclear fuel during chain reaction. The coolant either transfers its heat to another medium or if the coolant used is water it takes up the heat and gets converted into steam in the reactor which is directly sent to the turbine. Coolant used should be stable under thermal condition. It should have a low melting point and high boiling point. It should not corrode the material with which it comes in contact. The coolant should have high heat transfer coefficient. The radioactivity induced in coolant by the neutrons bombardment should be nil. The various fluids used as coolant are water (light water or heavy water), gas (Air, CO2, Hydrogen, Helium) and liquid metals such as sodium or mixture of sodium and potassium and inorganic and organic fluids. Power required to pump the coolant should be minimum. A coolant of greater density and higher specific heat demands less pumping power and water satisfies this condition to a great extent. Water is a good coolant as it is available in large qualities can be easily handled, provides some lubrication also and offers no unusual corrosion problems. But due to its low boiling point (212 F at atmospheric pressure) it is to be kept under high pressure to keep it in the liquid state to achieve a high that transfer efficiency. Water when used as coolant should be free from impurities otherwise the impurities may become radioactive and handling of water will be difficult. 10.10.9 COOLANT CYCLES The coolant while circulating through the reactor passages take up heat produced due to chain reaction and transfer this heat to the feed water in three ways as follows : (a) Direct Cycle. In this system coolant which is water leaves the reactor in the form of steam. Boiling water reactor uses this system. (b) Single Circuit System. In this system the coolant transfers the heat to the feed water in the steam generator. This system is used in pressurized reactor. (c) Double Circuit System. In this system two coolant are used. Primary coolant after circulating through the reactor flows through the intermediate heat exchanger (IHX) and passes on its hest to the secondary coolant which transfers its heat in the feed water in the steam generator. This system is used in sodium graphite reactor and fast breeder reactor. 10.10.10 REACTOR CORE Reactor core consists of fuel rods, moderator and space through which the coolant flows. NUCLEAR POWER PLANT 327 10.11 CONSERVATION RATIO It is defined as the ratio of number of secondary fuel atoms to the number of consumed primary fuel atoms. A reactor with a conversion ratio above unity is known as a breeder reactor. Breeder reactor produces more fissionable material than it consumes. If the fissionable material produced is equal to or less than the consumed, the reactor is called converter reactor. 10.12 NEUTRON FLUX It is a measure of the intensity of neutron radiation and it is the number of neutrons passing through 1 cm2 of a given target in one second. It is expressed as uv, where u is number of neutrons per cubic centimeter and u is velocity of neutrons in cm/sec. 10.13 CLASSIFICATION OF REACTORS The nuclear reactors can be classified as follows : 1. Neutron Energy. Depending upon the energy of the neutrons at the time they are captured by the fuel to induce fissions, the reactors can be named as follows : (a) Fast Reactors. In such reactors fission is brought about by fast (non moderated) neutrons. (b) Thermal Reactors or Slow Reactors. In these reactors the fast moving neutrons are slowed down by passing them through the moderator. These slow moving neutrons are then captured by the fuel material to bring about the fission of fundamental research. 10.14 COST OF NUCLEAR POWER PLANT Nuclear power plant is economical if used as base load power plant and run at higher load factors. The cost of nuclear power plant is more at low load factors. The overall running cost of a nuclear power plant of large capacity may be about 5 paisa per kWh but it may be as high 15 paisa per kWh if the plant is of smaller capacity. The capital cost of a nuclear power plant of larger capacity (say 250 mW) is nearly Rs. 2500 per kW installed. A typical sub-division of cost is as follows : 328 POWER PLANT ENGINEERING Item Approximate Cost % (a) Capital cost of land, building and 62% equipment etc. (b) Fuel cost 22% (c) Maintenance cost 6% (d) Interest on capital cost 10% The capital investment items include the following : (i) Reactor Plant : (a) Reactor vessel, (b) Fuel and fuel handling system, (c) Shielding. (ii) Coolant system. (iii) Steam turbines, generators and the associated equipment. (iv) Cost of land and construction costs. The initial investment and capital cost of a nuclear power plant is higher as compared to a thermal power plant. But the cost of transport and handling of coal for a thermal power plant is much higher than the cost of nuclear fuel. Keeping into view the depletion of fuel (coal, oil, gas) reserves and transportation of such fuels over long distances, nuclear power plants can take an important place in the development of power potentials. NUCLEAR POWER STATION IN INDIA The various nuclear power stations in India are as follows : (i) Tarapur Nuclear Power Station. It is India's first nuclear power plant. It has been built at Tarapur 60 miles north of Bombay with American collaboration. It has two boiling water reactors each of 200 mW capacity and uses enriched uranium as its fuel. It supplies power to Gujarat and Maharashtra. Tarapur power plant is moving towards the stage of using mixed oxide fuels as an alternative to uranium. This process involves recycling of the plutonium contained in the spent fuel. In the last coupleof years it has become necessary to limit the output of reactors to save the fuel cycle in view of the uncertainty of enriched uranium supplies from the United States. (ii) Rana Pratap Sagar (Rajasthan) Nuclear Station. It has been built at 42 miles south west of Kota in Rajasthan with Canadian collaboration. It has two reactors each of 200 mW capacity and uses natural uranium in the form of oxide as fuel and heavy water as moderator. (iii) Kalpakkam Nuclear Power Station. It is the third nuclear power station in India and is being built at about 40 miles from Madras City. It will be wholly designed and constructed by Indian scientists and engineers. It has two fast reactors each of 235 mW capacity and will use natural uranium as its fuel. The first unit of 235 mW capacity has started generating power from 1983 and the second 235 MW unit is commissioned in 1985. The pressurized heavy water reactors will use natural uranium available in plenty in India. The two turbines and steam generators at the Kalpakkam atomic power project are the largest capacity generating sets installed in our country. In this power station about 88% local machinery and equipment have been used. (iv) Narora Nuclear Power Station. It is India's fourth nuclear power station and is being built at Narora in Bullandshahar District of Uttar Pradesh. This plant will initially have two units of 235 mW each and provision has been made to expand its capacity of 500 mW. It is expected to be completed by 1991. This plant will have two reactors of the CANDUPHW (Canadian Deutrium-Uranium-Pressurised Heavy Water) system and will use natural uranium as its fuel. This plant will be wholly designed and constructed by the Indian scientists and engineers. The two units are expected to be completed by 1989 and 1990 respectively. This plant will use heavy water as moderator and coolant. This plant will provide electricity at 90 paise per unit. Compared to the previous designs of Rajasthan and Madras nuclear power plants the design of this plant incorporates several improvements. This is said to be a major effort towards evolving a standardized design of 235 mW reactors and a stepping stone towards the design of 500 mW reactors. When fully commissioned plant's both units will provide 50 mW to Delhi, 30 mW to Haryana, 15 mW to Himachal Pradesh, 35 mW to Jammu and Kashmir, 55 mW to Punjab, 45 mW to Rajasthan, 165 mW to Uttar Pradesh and 5 mW to Chandigarh. The distribution of remaining power will depend on the consumer’s demands. In this plant one exclusion zone of 1.6 km radius has been provided where no public habitation is permitted. Moderate seismicity alluvial soil conditions in the region of Narora have been fully taken into account in the design of the structure systems and equipment in Narora power plant. Narora stands as an example of a well coordinated work with important contributions from Bhabha Atomic Research Centre, Heavy Water Board, Nuclear Fuel Complex, Electronics Corporation of India Limited (ECIL) and other units of Department of Atomic Energy and several private and public sector industries Instrumentation and control systems are supplied by ECIL. Bharat Heavy Electrical Limited (BHEL) is actively associated with Nuclear Power Corporation of India. It has supplied steam generators, reactor headers and heat exchangers for Narora Atomic Power Plant (NAPP) 1 and 2 (2 × 235 MW). NAPP is the forerunner of a whole new generation of nuclear power plants that will come into operation in the next decade. The design of this reactor incorporates several new safety features ushering in the state of the art in reactor technology. The design also incorporates two fast acting and independent reactor shut down systems conceptually different from those of RAPP and MAPP. Some of the new systems introduced are as follows : 1. Emergency Core Cooling System (ECCS). 2. Double Containment System. 3. Primary Shut off rod System (PSS). 4. Secondary Shut off rod System (SSS). 5. Automatic Liquid Poison Addition System (ALPAS). 6. Post accident clean up system. According to Department of Atomic Energy (DAE) the Narora Atomic Power Plant (NAPP) has the following features. 1. It does not pose safety and environmental problems for the people living in its vicinity. The safety measures are constantly reviewed to ensure that at all times radiation exposure is well within limits not only to the plant personnel but also to the public at large. 2. NAI’P design rneets all the requirement laid down in the revised safety standards. The design of power plant incorporates two independent fast acting shut down systems high pressure, intermediate pressure and low pressure emergency care cooling systems to meet short and long term requirements and double containment of the reactor building. 330 POWER PLANT ENGINEERING Narora Atomic Power Plant (NAPP) is pressurized heavy water reactor (PHWR) that has been provided with double containment. The inner containment is of pre-stressed concrete designed to withstand the full pressure of 1.25 kg/cm2 that is likely to be experienced in the event of an accident. The outer containment is of reinforced cement concrete capable of withstanding the pressure of 0.07 kg/cm2. The angular space between the two containments is normally maintained at a pressure below atmosphere to ensure that any activity that might leak past primary containment is vented out through the stock and not allowed to come out to the environment in the immediate vicinity of the reactor building. The primary and the secondary containments are provided with highly efficient filtration systems which filter out the active fission products before any venting is done. The moment containment gets pressurized it gets totally sealed from the environment. Subsequently the pressure in the primary containment is brought down with the help of the following provisions. 1. Pressure suppression pool at the basement of the reactor building. 2. Special cooling fan units which are operated on electrical power obtainable from emergency diesel generators. The containment provisions are proof tested to establish that they are capable of withstanding the pressures that are expected in the case of an accident. Fig. 5.12 (a) shows primary and secondary containment arrangement. 3. The cooling water to all the heavy water heat exchangers is maintained in a closed loop so that failure in these do not lead to escape of radioactivity very little water from River (Ganga would be drawn for cooling purposes and most of water would be recycled. 4. The power plant has a waste management plant and waste burial facility within the plant area. 5. NAPP is the first pressurized heavy water reactor (PHWR) in the world to have been provided with double containment. 6. No radioactive effluent, treated or otherwise will be discharged into Ganga River. Therefore there will be no danger of pollution of the Ganga water. 7. An exclusion zone of 1.6 km radius around the plant has been provided where no habitation is permitted. 8. A comprehensive fire fighting system on par with any modern power station has been provided at NAPP. 9. NAPP has safe foundations. It is located on the banks of river Ganges an alluvial soil. The foundations of the plant reach upto a depth where high relative densities and bearing capacities are met. The foundations design can cater to all requirements envisaged during life of plant.) It is safe against earthquakes. 10. In the event of danger over heated care of the reactor would be diffused with in a few seconds by two features namely shut down through control rods followed by injection of boron rich water which will absorb the neutrons and stop their reaction in the core. This is in addition to other feature like double containment system provided in the reactor. Above features assure total radiation safety of the plant personnel, general public and the environment during the operation of power plant. With the completion of NAPP it would make a useful contribution to the North-grid thereby accelerating the pace of development in this region. Narora Atomic Power Plant is the fourth atomic power plant to be commissioned in India. This power plant is meant to generate electricity and supply the same to the distribution system (grid) in Uttar Pradesh and other states in the northern region. It has two units each with a capacity of 235 mW of which about seven per cent will be used to run the in house equipment and the rest will be fed into the grid. The net output from the power plant will be about 435 mW. At this power plant all due precautions have been taken in the design, construction, commissioning and operation of the unit with safety as the over-riding consideration. Therefore there appears to be no danger to the public from the operation of this power plant. (v) Kakarpar Nuclear Power Plant. This fifth nuclear power plant of India is to be located at Kakarpar near Surat in Gujarat. This power station will have four reactors each of 235 mW capacity. The reactors proposed to be constructed at Kakarpar would be of the Candu type natural uraniumuelled and heavy water moderated reactors-incorporating the standardised basic design features of the Narora reactors suitably adapted to local conditions. The fuel for the power plant will be fabricated at the Nuclear Fuel complex, Hyderabad. The power plant is expected to be completed by 1991. The Kakarpur unit has two fast shut down systems. The primary one works by cadmium shut off rods at 14 locations which drop down in case of heat build up and render the reactor sub-critical in two seconds. There are 12 liquid shut off rods as a back up, further backed by slow acting automatic liquid poison addition system which absorbs neutrons completely and stop the fissile reaction. In case of sudden loss of coolant, heavy water inside the reactor, there is an emergency core cooling system which also stops the fissile reaction. Lastly, the pressure suppression system in which cool water under the reactor rises automatically to reduce pressure in case it increases and a double containment wall ensures that no radioactivity would be released at ground level even in case of an unlikely accident. The Department of Atomic Energy (DAE) has also evolved emergency preparedness plans for meeting any accident even after all these safety measures. It ensures a high level of preparedness to face an accident including protecting the plant personnel and sur-rounding population. There is no human settlement for five km belt around a nuclear power installation as a mandatory provision. (vi) Kaiga Atomic Power Plant. The sixth atomic power plant will be located at Kaiga in Karnataka. Kaiga is located away from human habitation and is a well suited site for an atomic power plant. It will have two units of 235 mW each. It is expected to be commissioned by 1995. This nuclear power plant will have CANDU type reactors. These reactors have modern systerns to prevent accidents. The plant would have two solid containment walls-inner and outer to guard against any leakage. The inner containment wall could withstand a pressure of 1.7 kg/cm2 and could prevent the plant from bursting. The outer containment walls of the reinforced cement concrete has been design to withstand pressure of 0.07 kg/cm2. The annular space between the two containment walls would be maintained at a lower pressure below that of the atmosphere to ensure that no radioactivity leaked past the primary containments. 10.16 LIGHT WATER REACTORS (LWR) AND HEAVY WATER REACTORS (HWR) Light water reactors use ordinary water (technically known as light water) as coolant and moderator. They are simpler and cheaper. But they require enriched uranium as their fuel. Natural uranium contains 0.6% of fissionable isotope U235 and 99.3% of fertile Lj23 and to use natural uranium in such 332 POWER PLANT ENGINEERING reactors it is to be enriched to about 3%, U235 and for this uranium enrichment plant is needed which requires huge investment and high operational expenditure. Heavy water reactors use heavy water as their coolant and moderator. They have the advantage of using natural uranium as their fuel. Such reactors have some operation problem too. Heavy water preparation plants require sufficient investment and leakage of heavy water must be avoided as heavy water is very costly. Heavy water required in primary circuits must be 99% pure and this requires purification plants heavy water should not absorb moisture as by absorbing moisture it gets degraded. In order to have sufficient quantity of heavy water required for nuclear power plants, the work is fast progressing in our country on four heavy water plant. These plants are situated at Kotah (100 tonnes per year), Baroda (67.2 tonnes), Tuticorin (71.3 tonnes) and Talcher (67.2 tonnes per year). These plants will give our country an installed heavy water production capacity of about 300 tonnes per year. 10.16.1 Importance of Heavy Water The nuclear power plants of Kota in Rajasthan, Kalpakkam in Tamil Nadu and Narora in U.P. use heavy water as coolant and moderator. All these projects have CANDU reactors using natural uranium as fuel and heavy water as moderator. After this enriched uranium natural water reactor at Tarapur, the CANDU reactors are the second generation of reactors in India's nuclear power programme. The CANDU reactor will produce plutonium which will be the core fuel for fast breeder reactor. In fact in breeder reactor heavy water is used as moderator. A CANDU reactor of 200 mW capacity requires about 220 tonnes of heavy water in the initial stages and about 18 to 24 tonnes each year subsequently. Therefore, about one thousand tonnes of heavy water will be required to start the different nuclear power stations using heavy water. The total capacity of different heavy water plants will be about 300 tonnes per year if all the heavy water plant under construction start production. It is expected that heavy water from domestic production will be available from Madras and Narora atomic power plants. The management of the heavy water system is a highly complicated affair and requires utmost caution. Heavy water is present in ordinary water in the ratio 1 : 6000. One of the methods of obtaining heavy water is electrolysis of ordinary water. ADVANTAGES OF NUCLEAR POWER PLANT The various advantages of a nuclear power plant are as follows: 1. Space requirement of a nuclear power plant is less as compared to other conventional power plants are of equal size. 2. A nuclear power plant consumes very small quantity of fuel. Thus fuel transportation cost is less and large fuel storage facilities are not needed Further the nuclear power plants will conserve the fossil fuels (coal, oil, gas etc.) for other energy need. 3. There is increased reliability of operation. 4. Nuclear power plants are not effected by adverse weather conditions. 5. Nuclear power plants are well suited to meet large power demands. They give better performance at higher load factors (80 to 90%). 6. Materials expenditure on metal structures, piping, storage mechanisms are much lower for a nuclear power plant than a coal burning power plant. For example for a 100 mW nuclear power plant the weight of machines and mechanisms, weight of metal structures, weight of pipes and fittings and weight of masonry and bricking up required are nearly 700 tonnes, 900 tonnes, 200 tonnes and 500 tonnes respectively whereas for a 100 mW coal burning power plant the corresponding value are 2700 tonnes, 1250 tonnes, 300 tonnes and 1500 tonnes respectively. Further area of construction site required aired for 100 mW nuclear power plant is 5 hectares whereas was for a 100 mW coal burning power plant the area of construction site is nearly 15 hectares. 7. It does not require large quantity of water. DISADVANTAGES 1. Initial cost of nuclear power plant is higher as compared to hydro or steam power plant. 2. Nuclear power plants are not well suited for varying load conditions. 3. Radioactive wastes if not disposed carefully may have bad effect on the health of workers and other population. In a nuclear power plant the major problem faced is the disposal of highly radioactive waste in form of liquid, solid and gas without any injury to the atmosphere. The preservation of waste for a long time creates lot of difficulties and requires huge capital. 4. Maintenance cost of the plant is high. 5. It requires trained personnel to handle nuclear power plants. SITE SELECTION The various factors to be considered while selecting the site for nuclear plant are as follows : 1. Availability of water. At the power plant site an ample quantity of water should be available for condenser cooling and made up water required for steam generation. Therefore the site should be nearer to a river, reservoir or sea. 2. Distance from load center. The plant should be located near the load center. This will minimise the power losses in transmission lines. 3. Distance from populated area. The power plant should be located far away from populated area to avoid the radioactive hazard. 4. Accessibility to site. The power plant should have rail and road transportation facilities. 5. Waste disposal. The wastes of a nuclear power plant are radioactive and there should be sufficient space near the plant site for the disposal of wastes. Safeguard against earthquakes. The site is classified into its respective seismic zone 1, 2, 3, 4, or 6. The zone 5 being the most seismic and unsuitable for nuclear power plants. About 300 km of radius area around the proposed site is studied for its past history of tremors, and earthquakes to assess the severest earthquake that could occur for which the foundation building and equipment supports are designed accordingly. This ensures that the plant will retain integrity of structure, piping and equipments should an earthquake occur. The site selected should also take into account the external natural events such as floods, including those by up-stream dam failures and tropical cyclones. The most important consideration in selecting a site for a nuclear power plant is to ensure that the site-plant combination does not pose radio logical or any hazards to either the public, plant personnel on the environment during normal operation of plant or in the unlikely event of an accident. The Atomic Energy Regulatory Board (AERB) has stipulated a code of practice on safety inNuclear Power Plant site and several safety guide lines for implementation. 334 POWER PLANT ENGINEERING 10.18 COMPARISON OF NUCLEAR POWER PLANT AND STEAM POWER PLANT The cost of electricity generation is nearly equal in both these power plants. The other advantages and disadvantages are as follows : (i)

The number of workman required for the operation of nuclear power plant is much less than a steam power plant. This reduces the cost of operation. (ii) The capital cost of nuclear power plant falls sharply if the size of plant is increased. The capital cost as structural materials, piping, storage mechanism etc. much less in nuclear power plant than similar expenditure of steam power plant. However, the expenditure of nuclear reactor and building complex is much higher. (iii) The cost of power generation by nuclear power plant becomes competitive with cost of steam power plant above the unit size of about 500 mW. 10.19 MULTIPLICATION FACTOR Multiplication factor is used to determine whether the chain reaction will continue at a steady rate, increase or decrease. It is given by the relation, K = ( ) P A + E where K = Effective multiplication factor. P = Rate of production of neutrons. A = Combined rate of absorption of neutrons. E = Rate of leakage of neutrons. K = 1 indicates that the chain reaction will continue at steady rate (critical) K > 1 indicates that the chain reaction will be building up (super critical) whereas K < 1 shows that reaction will be dying down (subcritical). 10.20 URANIUM ENRICHMENT In some cases the reaction does not take place with natural uranium containing only 0.71% of U235. In such cases it becomes essential to use uranium containing higher content of U335. This is called U235 concentration of uranium enrichment. The various methods of uranium enrichment are as 1. The gaseous diffusion method. This method is based on the principle that the diffusion or penetration molecular of a gas with a given molecular weight through a porous barrier is quicker than the molecules of a heavier gas. Non-saturated uranium hexa-flouride (UF6) is used for gaseous diffusion. The diffusing molecules have small difference in mass. The molecular weight of U235 Fs = 235 + 6 × 19 = 349 and that U238 Fs = 352. The initial mixture is fed into the gap between the porous barrier. That part of the material which passes through the barrier is enriched product, enriched in U235 Fs molecules and the remainder is depleted product. NUCLEAR POWER PLANT 335 2. Thermal diffusion method. In this method (Fig. 10.9) a column consisting of two concentric pipes is used. Liquid UF6 is filled in the space between the two pipes. Temperature of one of the pipes is kept high and that of other is kept low. Due to difference in temperature the circulation of the liquid starts, the liquid rising along the hot wall and falling along the cold wall. Thermal diffusion takes place in the column. The light U235 Fs molecules are concentrated at the hot wall and high concentration of U236 Fs is obtained in the upper part of the column. 3. Electromagnetic Method. This method is based on the fact that when ions moving at equal velocities along a straight line in the same direction are passed through a magnetic field, they are acted upon by forces perpendicular to the direction of ion movement and the field. Let P = force acting on ion e = charge on ion v = velocity of ion H = magnetic field strength m = Ion mass R = radius of ion path P = euH As this force is centripetal 4 P =mv2 R 4 mv2 R = evH 4 R = mv eH This shows that ions moving at equal velocities but different masses move along ng circumferences of different radii (Fig. 10.10). Fig. 10.11 shows an electromagnetic separation unit for uranium isotopes. A gaseous uranium compound is fed into the ion source, where neutral atoms are ionised with the help of ion bombardment. The ions produced come out in the form of narrow beam after passing through a number of silos. This beam enters the acceleration chamber. These ions then enter a separation chamber where a magnetic field is applied. Due to this magnetic field the ions of different masses move along different circumference. 4. Centrifugation Method, This method is based on the fact that when a mixture of two gases with different molecular weight is made to move at a high speed in a centrifuge, the heavier gas is obtained near the periphery. UF6 vapour may be filled in the centrifuge and rotated to separate uranium isotopes. REACTOR POWER CONTROL The power released in a nuclear reactor is proportional to the number of mole fissioned per unit time this number being in turn proportional to density of the neutron flux in the reactor. The power of a nuclear reactor can be controlled by shifting control rods which may be either actuated manually or automatically. Power control of a nuclear reactor is simpler than that of conventional thermal power plant because power of a nuclear reactor is a function of only one variable whereas power of a thermal power plant depends on number of factors such as amount of fuel, its moisture content, air supply etc. This shows that power control of thermal plant requires measuring and regulating several quantities which is of course considerably more complicated. NUCLEAR POWER PLANT ECONOMICS Major factors governing the role of nuclear power are its economic development and availability of sufficient amount of nuclear fuel. It is important to extract as much energy from a given amount of fuel as possible. The electrical energy extracted per unit of amount of fuel or expensive moderator might be called the “material efficiency”. In a chain reactor the high material efficiency as well as high thermal efficiency leads to low over all energy cost. Since the most attractive aspect of nuclear energy is the possibility of achieving fuel costs considerably below that for coal, all nuclear power system being considered for large scale power production involve breeding or regenerative systems. This program includes the development of the technology of low neutron absorbing structural materials such as zirconium, the use of special moderating materials such a D20 and the consideration of special problems associated with fast reactors. In so far as economic factors are concerned it is necessary to consider neutron economy in a general way such as that measured by the conversion ratio of the system. The conversion ratio is defined as the atoms of new NUCLEAR POWER PLANT 337 fuel produced in fertile material per atom of fuel burnt. The conversion ratio varies with the reactor design. Its values for different reactors are indicated in table. Type of reactor Conversion ratio BWR, PWR and SGR 1 Aqueous thorium breeder 1.2 SAFETY MEASURES FOR NUCLEAR POWER PLANTS Nuclear power plants should be located far away from the populated area to avoid the radioactive hazard. A nuclear reactor produces 〈 and (⍰ particles, neutrons and ⍰-quanta which can disturb thenormal functioning of living organisms. Nuclear power plants involve radiation leaks, health hazard to workers and community, and negative effect on surrounding forests. At nuclear power plants there are three main sources of radioactive contamination of air. (i) Fission of nuclei of nuclear fuels. (ii) The second source is due to the effect of neutron fluxes on the heat carrier in the primary cooling system and on the ambient air. (iii) Third source of air contamination is damage of shells of fuel elements. This calls for special safety measures for a nuclear power plant. Some of the safety measures are as follows. (i) Nuclear power plant should be located away from human habitation. (ii) Quality of construction should be of required standards. (iii) Waste water from nuclear power plant should be purified. The water purification plants must have a high efficiency of water purification and satisfy rigid requirements as regards the volume of radioactive wastes disposed to burial. (iv) An atomic power plant should have an extensive ventilation system. The main purpose of this ventilation system is to maintain the concentration of all radioactive impurities in the air below the permissible concentrations. (v) An exclusion zone of 1.6 km radius around the plant should be provided where no public habitation is permitted. (vi) The safety system of the plant should be such as to enable safe shut down of the reactor whenever required. Engineered safety features are built into the station so that during normal operation as well as during a severe design basis accident the radiation dose at the exclusion zone boundary will be within permissible limits as per internationally accepted values. Adoption of a integral reactor vessel and end shield assemblies, two independent shut down systems, a high pressure emergency core cooling injection system and total double containment with suppression pool are some of the significant design improvements made in Narora Atomic Power Project (NAPP) design. With double containment NAPP will be able to withstand seismic shocks. 338 POWER PLANT ENGINEERING In our country right from the beginning of nuclear power programme envisaged by our great pioneer Homi Bhabha in peaceful uses of nuclear energy have adopted safety measures of using double containment and moderation by heavy water one of the safest moderators of the nuclear reactors. (vii) Periodical checks be carried out to check that there is no increase in radioactivity than permissible in the environment. (viii) Wastes from nuclear power plant should be carefully disposed off. There should be no danger of pollution of water of river or sea where the wastes are disposed. In nuclear power plant design, construction, commissioning and operation are carried out as power international and national codes of protection with an overriding place given to regulatory processes and safety of plant operating personnel, public and environment. SITE SELECTION AND COMMISSIONING PROCEDURE In order to study prospective sites for a nuclear power plant the Department of Atomic Energy (DAE) of our country appoints a site selection committee with experts from the following: 1. Central Electricity Authority (CEA). 2. Atomic Minerals Division (AMD). 3. Health and safety group and the Reactor Safety Review group of the Bhabha Atomic Research Center (BARC). 4. Nuclear Power Corporation (NPC). The committee carries out the study of sites proposed. The sites are then visited, assessed and ranked. The recommendations of the committee are then forwarded to DAE and the Atomic Energy Commission (AEC) for final selection. The trend is to locate a number of units in a cluster at a selected site. The highest rated units in India are presently of 500 mW. The radiation dose at any site should not exceed 100 milligram per member of the public at 1.6 km boundary. The commissioning process involves testing and making operational individually as well as in an integrated manner the various systems such as electrical service water, heavy water, reactor regulating and protection, steam turbine and generator. To meet the performance criteria including safe radiationlevels in the plant area and radioactive effluents during operation the stage-wise clearance from Atomic Energy Regulatory Board (AERB) is mandatory before filling heavy water, loading fuel making the reactor critical, raising steam, synchronizing and reaching levels of 25%, 50%, 75% and 100% of full power. The commissioning period lasts for about two years. 10.25 MAJOR NUCLEAR POWER DISASTERS Chernobyl — is near Kiev, Ukraine, in the former Soviet Union. Destroyed by steam and hydrogen explosions followed by fire, it caused many deaths on site, increased cancer rates in the thousands of square miles it contaminated. Three Mile Island — Located 10 miles southeast of Harrisburg PA on the Susquehanna River. The accident, and radiation release, caused no immediate deaths. The cleanup cost more than $1.5 Billion. NUCLEAR POWER PLANT 339 The Three Mile Island accident occurred in 1979 and 1986, Chernobyl occurred essentially killing the expension of nuclear energy. No other nuclear power plants have been ordered in the US since the late 1970's. T.M.I. Aaccount Chronology in Brief 1970's AEC LOFT (Loss of Fluid Test) research canceled as economy measure. September 12, 1978 T.M.I. Unit #2 dedicated. January 1979 TMI #2 began commercial operation. March 26, 1979 Emergency core cooling pumps tested, with diverter valves switched to disconnect ECCS from reactor. Valves not switched back. March 28, 1979, 4 a.m. Three Mile Island Incident began. —Filter in inner loop switched offline to clean —

Pressure transient triggers shutdown sequence. —Core overheats, pressure relief valve sticks open, in manual override —Water in core begins leaking out open relief valve —Emergency cooling pumps don't work ! —After more errors, 1/3 of core exposed, partial meltdown of fuel rods results. —2nd day someone closes relief valve (unrecorded).. situation stabilizes —hydrogen gas bubble forms. —Governor/NRC, order partial evacuation Cleanup/termination cost $1.5+ BILLION. Cleanup after the Three Mile Island Accident. After the Accident it was necessary to dispose of the radioactive gases, water, and contaminated debris from radioactive plumbing etc. The water had to be filtered to separate and concentrate radioactive contaminants for disposal. After these were removed it was possible to begin dismantling the pressure vessel and extract the fuel rods. It was not until then that the inside of the core could be inspected. As the damaged reactor was brought under control, it was known from radiation monitoring that there was a significant amount of radioactive material in the bottom of the pressure vessel. In spite of this, the power company still maintained that the damage to the core had been minimal. When a robot with a video camera was lowered into the pressure vessel, four years after the accident, this is what it saw: 10.26 CHERNOBYL NUCLEAR POWER PLANT Chernobyl is a town of 30,000 people, 70 miles north of Kiev, in the Ukraine. The V. I. Lenin nuclear power plant is located 10 miles from the town of Chernobyl. Adjacent to the plant is the town of Pripyat, which houses and services plant workers. The plant is on the Pripyat River, near its mouth into the Kiev reservoir. The plant had 4 nuclear reactors, each with associated steam turbines and electric generators. Two additional units were under construction at the time of the accident, April 26, 1986. Each of these units was of the same Soviet design, designated RBMK-1000. Chernobyl was the location of the world's worst nuclear power plant disaster. Massive amounts of radioactivity were released, a thousand square mile area will be uninhabitable for many decades. 340 POWER PLANT ENGINEERING 10.26.1 REACTOR DESIGN : RBMK-1000 Boiling Water Reactor Electric generating capacity 1000 Megawatt. Thermal output of core about 2000 Megawatt. 1661 zirconium fuel rods, holding mix of U-238 and U-235; Plutonium-239 is a byproductwhich can be extracted by reprocessing the fuel rod material. Each fuel rod is enclosed in a heat transfer water channel. 211 Boron control rods with 8 fuel rods/control rod Graphite core 1700 tons, made up of graphite bricks 10.26.2 CONTROL OF THE REACTOR 1. Graphite Core, moderates neutron flux from fuel rods 2. Boron control rods to reduce neutron flux for shutdown 3. Thermal transfer control — closed circuit water/steam loop, multiple water pumps Nitrogen/ Helium gas within containment — low thermal conductivity and oxygen exclusion — pressure and gas mixture are controlled. emergency core cooling water system (ECCS) 10.26.3 CHERNOBYL REACTOR OPERATIONS Computer for fine control, operator controls set points of feedback controllers Central power authority dictated operating levels in managing power grid Unnecessary shutdown meant 600,000 ruble revenue loss, firing of person responsible. Plant engineers found the plant unstable at low power levels, Local practice was to manually pull control rods if downward fluctuation threatened spontaneous shutdown. Response time to scram: 18 seconds (theoretically it was claimed to be 3 seconds). Regulations against manual control routinely excepted. 10.26.4 ACCIDENT\SAFETY PLANS Published odds million to 1 against an accident. Authoritarian control staff & engineers do not question safety. Accident planning was around a scenario of 1 or 2 fuel rod/water channels bursting. No plan included a graphite fire. Administration building had emergency bunker under it. Reactor building was a water tight containment building. 10.26.5 EVACUATION Plant director had authority in principle to order evacuation of Pripyat. However a standing order made any nuclear accident a state secret. 10.27 SAFETY PROBLEMS IN CHERNOBYL REACTOR DESIGN 10.27.1 SYSTEM DYNAMICS A problem with RMBK-1000 reactor design is that the time constants for changes in thermal output are short. Control depends on computer regulated feedback control systems. The human operator could not react fast enough to manually control it without the automatic controls. NUCLEAR POWER PLANT 341 Neutron absorption and heat transfer coefficients are very different for water and steam, so neutron flux and thermal output changes rapidly as water in the tubes through the core makes a transition from hot water to steam. 10.27.2 ANOTHER SAFETY PROBLEM WITH THE DESIGN The normal operating temperature of core tubes is greater than the ignition temperature of the graphite blocks of the core (carbon) in an O_2 atmosphere. Its normal environment is an atmosphere with no oxygen. Heat exchange system : One closed loop through reactor core and steam turbines Secondary loop to condense steam to water after turbine Construction problems : Turbine building roof; specification said it should be fireproof. Materials for 1 km × 50 m fireproof roof was not available. Control cable conduits supposed to be fireproof. Material not available. Exception granted. Cement and tiles, etc. Quality control problems. Director had to prioritize uses, discard defective materials. Fittings often required remanufacture to meet specifications. Hazard Potential of Water on Hot Graphite Water Gas Reaction: $C + H_2O$ ⍰ $CO + H_2$ Often used as a H_2 generator in freshman chemistry labs, it has a similar hazard if not carefully controlled: $2\ CO + O_2$ ⍰ $2\ CO_2$ $2\ H_2 + O_2$ ⍰ $2\ H_2O$ OTHER, EARLIER, SOVIET NUCLEAR ACCIDENTS September 1982 — Chernobyl Unit 1, after 5 years service, was shut down for maintenance. Restarted with some valves closed. Result: no water flow in a few channels. Explosion in core, a few fuel rods melted. Some radioactivity escaped plant. No radiation survey was done outside plant. Streets of Pripyat were hosed down. No announcement to population. Emergency core cooling system saved plant. Chief Engineer, his deputy, and chief operator of the shift were all demoted and transferred. 1980 Kursh power station. RBMK-1000 plant had a power outage. Reactor damaged because control rods and circulation driven by electric motors/pumps failed. Time delay to start diesel generators was 40 seconds During which, power surge damaged some fuel rods. Solution : design a special generator to tap turbine power as it spun down during shutdown, to power emergency equipment. Oct. 1982. Armyansk nuclear power station. Explosion. Subsequent fire destroyed turbine building. Fall 1983 Chernobyl Unit 4 startup. Certification team saw anomalous power surge when control rod insertion starts. Considered minor, had been seen in another reactor. No explanation, not documented. June 1985 Balakovsky PWR power station, Valve burst, release of 300 degree C. steam, cooked 14 workmen. Safety regulations viewed as guidelines, chief engineer regularly made exceptions.