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SHORT PAPER

attention that National Standards for solar heating systems are needed. We appreciate the author's scientific integrity when he comments about energy-saving methods: "Although the provision of adequate loft insulation and trying to eliminate draughts by sealing round the edges of windows and doors will not be as interesting or exciting as building a solar water or space heating system, these measures will be far more cost effective at present." The author reports results of an analysis carried out in the UK in 1974 and compares it to those of solar heating over a five-year period. Basic roof insulation (50 mm) has an installation cost of £30 and the estimated value of saved fuel in 5 years is £110, draught prevention costs £10 and saves £50, whereas a practical $6\ m^2$ solar heating would cost £180, a commerical $6\ m^2$ system would cost £500, and both would save £200 over 5 years (with no inflation). The conclusion is clear: one should start by thinking "insulation", then "solar heating" later.

In assessing the viability of solar systems, the author used the payback period criterion, defined as the capital cost of the system divided by the current annual value of the fuel saved. Other more realistic criteria could be suggested; the energy gain of the system: defined as the amount of energy generated by the system during its lifetime, divided by the amount of energy required to manufacture, operate and maintain it during its lifetime; or the energy payback time: defined as the time required for the system to generate sufficient energy to equal the amount of energy expended in manufacturing, as well as operating and maintaining it during its energy payback period. The US energy consumption is about 2500 billion KHW per year: 19% of it is used for heating and cooling of buildings, 25% for industrial process heat, 24% for transportation, 25% for electricity production, 5% for petrochemicals and 2% for exported energy products. The sources of this energy are oil (40%), natural gas (33%), hydropower (4%), coal (20%), nuclear (2%), and synthetic fuel, oil shale, geothermal, wind, and solar energy (1%). The solar contribution will indeed increase but can contribute only to the 19% heating and cooling of buildings sector, unless a major scientific breakthrough is attained in photoelectric cells research. With the supply of oil and natural gas dwindling, coal and nuclear energy have to come into the picture to fill the gap. It seems unrealistic to assume that solar energy alone can satisfy the largest share of energy demand in the near future.

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Reactor Core Fuel Management, by P. Silvennoiem. Pergamon International Library of Science, Technology, Engineering and Social Studies: Oxford, England: Pergamon Press, Ltd., 1976, 257 pages. *Reviewed by Magdi M.H. Ragheb, Department of Nuclear Engineering and Thomas J. Higgins, Department of Electrical and Computer Engineering, The University of Wisconsin, Madison, WI 53706, USA.*

This compactly-written book by P. Silvennoiem, of the Technical Research Centre of Finland in Helsinki, is divided into three parts. The first part comprises elementary concepts of reactor physics, neutron diffusion, reactor-core heat transfer and reactivity, and reactor operation. The second part, titled "Core analysis," defines the variables of core management, reviews the methods of core analysis and the associated computer code modules and epitomizes different reactor concepts. These two parts have, respectively, lengths of 98 and 124 pages. The third part, concerned with methods of optimization and system integration, comprises a very compact 21 pages. The book contains an index; and each chapter entails a pertinent bibliography, updated to 1975.

Reactor-core fuel management, as defined by the author, encompasses: "Determination of the nuclear properties associated with fuel and fuel assemblies whether fresh or burnt.

"Specification of the fuel loaded in the core and strategies used in loading and discharging as well as the patterns of internal shuffling during irradiation.

"Control procedures during operation which are related and parallel to the objectives specified on fuel.

"Consideration of the constraints brought about by other units of the power generation system, by power demand, or by safety.

"Optimization of fuel and control strategies and sequencing the decisions for the purposes of fuel procurement."

These physics, engineering and economical aspects are all aimed at the optimal utilization of the nuclear fuel within the design limits imposed on the reactor core. Even though of great importance for reactor designers and reactor operation personnel, the subject has been treated only superficially in previous Nuclear Engineering texts [1, 2, 3, 4].

The optimal utilization of nuclear fuel is a subject of prime importance for the world energy supply and economy. An over-supply of uranium and national stockpiling at low prices resulted in depression of uranium prices to less than $5 per pound ($U_3O_8$) by 1971. Prices remained low until the October 1973 war, the U.S. arms resupply for Israel, and the ensuing Arab Oil Embargo, with the subsequent rise in oil, coal and uranium prices: the last to $40 per pound in 1976. The future demand for uranium fuel is expected to reach a cumulative total of 2 to 3 million tons of uranium by the year 2000. In the next quarter-century the uranium-producing industry must grow at an unprecedented rate of 12-15% per year, and spend 10 to 20 thousand million dollars to supply an energy-hungry world with a cumulative total of two to four million tons of uranium: knowing that the lead time to bring a uranium deposit into production is about 10 years [5]. This supply problem is accentuated by the unreliability and hazardousness of a coal-based economy: The carcinogens (e.g., benzpyrene), sulphur, and nitrogen oxides that are released in the burning of a fossil fuel pose a formidable environmental problem, strip mining is particularly messy, and the increase of the carbon dixode in the atmosphere at the current rate of one third of one percent per year—which suggests the concentration will double by the middle of next century. The last factor alone has led to scare scenarios of a series of climatic catastrophes: such as the melting of the ice caps that might drown coastal areas of the world [6].

In his article about the "Carbon Dioxide Question," G. Woodwell [8] reports: "The potential hazards associated with a steady increase in the carbon dioxide content of the atmosphere will loom large in the coming decades and will doubtless bear heavily on such decisions as whether to accelerate the development of power plants based on nuclear fuel instead of those base on coal and whether to preserve forest areas instead of encroaching on them (and, if the forests are to be preserved, how to provide the new lands that are almost certain to be needed for agriculture). There is almost no aspect of national and international policy that can remain unaffected by the prospect of global climatic change. Carbon dioxide, until now an apparently innocuous trace gas in the atmosphere, may be moving rapidly toward a central role as a major threat to the present world order." The USA Carter Administration in its National Energy Plan proposes to double domestic coal production in the next decade or so: from 665 million tons in 1976 to 1.2 billion tons by 1985. However, according to a report to Congress prepared by the General Accounting Office (GAO), the prospects are not good. The GAO study entitled "U.S. Coal Development—Promises, Uncertainties," concludes that, "in fact, it will be very difficult to achieve one billion tons annually by 1985" [9]. Over the longer term (beyond the year 2000) it appears to the GAO analyses that coal will be both supply-constrained (particularly with regard to low-sulphur and metallurgical coal) and demand-constrained (in the sense that utility and industrial users are not going to buy coal if they cannot use it). The very-long-term prospects for increased coal demand, "ride on the hope of coal gases and liquids becoming environmentally safe and economical." There is no question, according to the GAO report, that "coal will supply a large part of the nation's energy future." The required "trade-offs" will be costly, however, "particularly in terms of human life and disease." If in the final analysis it is decided that the costs of coal use beyond a certain level are too high, and increased oil importation is not a tenable alternative, then, the report states, the U.S. has only two major alternatives open to it between now and the year 2000: (1) to accelerate the expansion of conventional nuclear power so that nuclear-generated electricity substitutes for oil and gas whereever possible, or (2) to improve energy conservation, through both increased efficiency and decreased consumption. [9].

The situation is made more critical by the U.S. Administration policy of stopping the reprocessing of spent fuel involving plutonium and delaying the introduction of commercial fast breeder reactors. This creates the problem of storing plutonium which is a valuable fuel and should be burned for its energy. At the Iran Conference on Transfer of Nuclear Technology, some of the 109 nations which signed the global nonproliferation treaty said they might withdraw as a consequence of the U.S. nuclear control policy: because they could no longer benefit from the accord, which is designed to prevent the spread of nuclear weaponry around the world, and promote the peaceful uses of nuclear energy [7].

There have been estimates that under the present Light Water Reactors option, and without the Fast Breeders or the Fusion-Fission Hybrids, the fission fuel reserves can only last for 30-50 years. Thus, their optimal use until some other "inexhaustible" option is adopted is of prime importance. According to data from the Federal Power Commission, the leading sources of electricity for the first six months of 1977 were coal-fired plants (46.1 percent); oil-fired plants, (17.8 percent), gas-fired plants (13.2 percent); nuclear plants (12 percent); hydroelectric plants (10.7 percent); other sources (0.2 percent). Thus nuclear plants (12 percent exceeded the contribution of hydroelectric plants (10.7 percent), even though they represent just 9 percent of the total generating capacity. In the UK, "Magnox" nuclear power stations generated more electricity than all the Central Electricity Generating Board oil-fired plants. Nuclear energy currently accounts for approximately 10 percent of the electric-generating capacity and 13 percent of the actual electric output of the U.K. [9].

In Chapter 1 the rudiments of reactor physics are reviewed. These include neutron cross-sections, interactions, fluxes and reaction rates, fission products decay and energy, conversion and breeding, energy spectrum and slowing down, lethargy, the Maxwellian distribution, spatial heterogeneity and unit cell fluxes, the thermal utilization factor and disadvantage factors, and burnup and fuel depletion. This represents a suitable conside introduction to the subsequent chapters.

The stationary neutron transport equation is introduced in Chapter 2 and two types of problems are treated: source problems and eigenvalue or criticality problems, with their associated boundary conditions: vacuum and geometrical periodic and reflective white boundary conditions. The P_1 and diffusion approximations and their underlying assumptions are treated, as well as the multigroup method and the method of modal approximations. The author points-out the dilemma in the multigroup methods: the fact that the group constants appearing in the equation are averages over the fluxes: i.e., over the sought-for solution itself. The problem is iterative in nature and requires the use of previously accumulated flux distributions. Approximate boundary conditions at free and interior surfaces are discussed. To pursue the discussion of the spectral characteristics in fast and thermal reactors, the spatial properties of neutron diffusion are discussed for different reactor concepts. The integral form of the transport equation, which is important for cell calculations, is derived. A major omission here is the Monte Carlo method and its application to resonance escape and cell calculations.

Chapter 3 is devoted to the reactor core heat transfer; since: (1) the power generating capability of the core is constrained by thermohydraulic parameters which have to remain within the ranges designed, (2) the fuel temperature affects the fuel-neutron interaction and cross-sections, and (3) the coolant moderates neutrons and generates a coolant density feedback. Different topics pertaining to the Light Water Reactor (LWR) concept are treated: the temperature profile in fuel pin cell, the loss of heat conductance of the pellet due to cracking within the outer pellet region, and the reduction of heat conductance in the fuel-clad gap due to the accumulation of fission products. The fuel-to-cladding heat transfer, the axial temperature distribution, the coolant flow and change of phase, the void fraction, slip ratio, the boiling or heat transfer crises, the departure from nuclear boiling, the critical heat flux correlations, and the form and Hot Channel Factors are briefly treated.

As reactor criticality is kept by balancing the different reactivity components which separately cause positive or negative changes in reactivity, Chapter 4 is devoted to the reactivity topic. The initial reserve of reactivity stored in the core at the time of refueling, fuel burnup and depletion are explained, as well as means of reactivity control: solid control rods, burnable poisons in fuel assemblies, soluble poisons in coolant, and induced changes in-the neutron moderation and energy spectrum. The Doppler effect is introduced including the Breit—Wigner formula for a Doppler broadened resonance, the concept of the resonance integral, the narrow resonance (NR), wide resonance (WR), and the intermediate resonance (IR) approximations. Reactivity control systems for compensating fuel depletion and for fission products buildup and for changing power levels or other maneuvering action, and fission products poisoning: the X_e^{135} transient and Xenon oscillations, are exposed. Perturbation theory is introduced as a powerful method of analysis: e.g., to control rod worths calculations, since reactivity insertions or withdrawals are localized with a relatively small core region, while the neutron flux distribution remains almost invariable throughout the rest of the core.

Various core dynamic interactions usually incorporated in a time-dependent consideration of the reactor state are treated in Chapter 5. This is exemplified by the compensation of power demand in a PWR. Core surveillance and control—including the checking of core margins and the generation of alarm functions, advanced monitoring and data-processing systems, as well as reactor safety and hypothetical accidents in "PWR"s: loss-of-coolant accidents (LOCA), and the problem of pellet-clad interaction, are briefly analyzed.

Chapter 6 discusses the degrees of freedom one has to depend on in finding out strategies for reactor core fuel management. "Fuel management covers the technical and economic analysis and decisions by which the objective of minimizing the cost of energy production is implemented. The sub-area of reactor core fuel management would involve those tasks immediately related to the core stage." In that respect, radial fuel patterns are discussed and, in order to exploit simultaneously the local and global power flattening as well as the increased discharge burnup, a modified out-in scatter pattern is recommended for LWR's. The approach to equilibrium and typical LWR values of discharge burnup are treated; also the variation of cycle parameters: movement of control rods, batch sizes, enrichment of the fresh batch, the location of the fresh fuel, the shuffling of the partially burnt assemblies and the unexpected change of the capacity or plant load factor. A coarse breakdown of fuel costs and the cost structure of uranium enrichment are discussed (it is known that the fuel cycle costs comprise about 30% or less of the total nuclear power generation cost). The fuel cost is divided into three main components: immediate fuel cost, processing cost, and the fuel inventory cost: and an example calculation is carried out for the fuel cost of a PWR as a function of the discharge burnup.

Chapter 7 is the most detailed and analyzed chapter in the book. It deals with widely-used code systems for reactor-core analysis, particularly for LWR's. The author stresses the impossibility of performing a single reactor calculation that would include all the primary and global effects in the core. He presents an example: "In a LWR with some 50,000 fuel pins in the core a diffusion calculation should require one spatial mesh point per pin. This follows from the thermal diffusion length of neutrons being some 2 cm. Axially one would need at least 50 discretization points. Consequently there would be a total of 2.5 million spatial points in solving the neutron diffusion or transport equation. Moreover, each point would have some five to seven independent cross-section values, fluxes and currents, not to mention the minimum of about a hundred groups. The rank of the ensuing linear transformation would exceed all the limits that the storage capacity of computers can sustain, whether at the present time or in the conceivable future." The computer code systems used for analysis of reactor core fuel management are founded on the principle of condensing the information on the energy variable while simultaneously increasing the detail with which the spatial variables are treated from zero-dimensional to three-dimensional geometry. Fundamental parts of core analysis system are discussed from the nuclear data library microscopic cross-sections, the lattice cell calculation and group condensation, to the global reactor calculation of criticallity, fuel burnup and depletion calculation, power thermohydraulic feedback and fuel-costs optimization. Reactor simulation methods including finite difference, finite element, nodal method, and the numerical iteration techniques used in these methods together with a short section about the computer code libraries, are surveyed. A regrettable omision here is again Monte Carlo codes, which have a large application in that area.

Chapter 8 compares alternative reactor concepts other than the LWR's, with respect to core analysis aspects: the high temperature gas-cooled reader (HTGR), the steam-generating heavy-water reactor (SGHWR), the Canadian CANDU and the Russian WWER's, and the LMFBR.

The methods of optimization are reviewed in Chapter 9. Unfortunately: "The development of applicable optimization routines is lagging behind core analysis methods by a decade at least." The reason is that existing techniques of mathematical programming are faced with the formidable requirement of computer storage and computer time. Fuel cycle economics are treated, and the equation for the present value of a fuel lot is derived, together with its constraints. Also treated are alternative loading and shuffling patterns and control programming.

The final Chapter 10 is very short: wider power system considerations (including grid and load following requirements) and multipurpose applications (such as process heat, ship-propulsion and domestic heating) are listed.

The contents of this book could well and desirably be enfolded in present undergraduate and graduate curricula in nuclear engineering: hence it ought to be on the shelves of all engineering colleges. Yet again it would prove a useful acquisition for the practicing public-utility engineer who desires to keep abreast of energy trends and demands.

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