Third edition

The elements of nuclear power

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Preface to the third edition

In the sixteen years since the publication of the First Edition of this book, nuclear power has expanded greatly from the relatively few countries in which early developments took place to a large number of countries worldwide. Some of these countries now depend heavily on nuclear power for their energy supplies.

The purpose behind this Third Edition remains the same, to provide an introduction to the theory and technology of nuclear power which is suitable for students of mechanical and electrical engineering, and for engineers working in the field of nuclear power.

The serious reactor accidents at Three Mile Island in 1979 and Chernobyl in 1986, as well as the much publicized concern in the UK over radioactive effluent levels and leukaemia clusters have increased public awareness of the hazards of nuclear power and all aspects of the nuclear fuel cycle. The additional new material in this edition deals with some of these topics, in particular the effects of nuclear radiation on humans, the safety of nuclear reactors and those parts of the nuclear fuel cycle which deal with fuel element manufacture and the reprocessing of irradiated fuel.

The opinions expressed in this book do not necessarily reflect the views of the National Nuclear Corporation.

University of Strathclyde, D. J. BENNET
Glasgow.

National Nuclear Corporation, J. R. THOMSON
Cheshire.

June 1988

Preface to the second edition

In the eight years since the First Edition was published the use of nuclear energy for electricity generation has expanded throughout the industrialized world. This expansion seems set to continue, although in the present economic situation the demand for energy is growing slowly, and the rate of nuclear power growth is also likely to be slow.

At the same time public awareness of nuclear power, and in particular its hazardous aspects, has increased considerably and several pressure groups exist throughout the world whose aims are to oppose the development of this form of energy.

Thus at the present time nuclear power appears to be at a crossroads and it is difficult to predict its future direction and rate of development with any certainty. One thing however is sure, that in the next few decades, until other sources of energy can be exploited, nuclear power has a vital role to play in world energy supply.

With this in mind, the Second Edition contains new material designed to give a better perspective to the study of nuclear power – its history, its potential as an energy source, its benefits and its hazards. Anyone arguing the pros and cons of nuclear power should be aware of these aspects and it is hoped that this new material will be of help in this respect.

University of Strathclyde, D. J. BENNET
Glasgow.

August 1980

Preface to the first edition

With the expanding use of nuclear fission as a source of energy for electricity generation, it seems likely that an increasing number of engineers and engineering students should be familiar with the principles underlying the generation of power from this source.

This book is based on a one-year course given to Final Year students of Mechanical Engineering at the University of Strathclyde. The aim of this course is to give these students an introduction to the principles of power generation from nuclear fission. The course begins with a description of the physical processes which take place in a nuclear reactor and then it develops simplified theory which enables calculations to be made for reactor criticality. Heat transfer in reactors, thermodynamic power cycles, reactor operation and radiation shielding are also dealt with briefly. A certain amount of additional material, notably the contents of Chapter 5, have been included in this book.

In writing this book I have derived much benefit from the co-operation during several years with my colleagues R. G. Tudhope and J. S. Lewis (now at Lanchester Polytechnic), and it is a pleasure to acknowledge my gratitude to them for the contribution they have made to this book by their discussion and opinions.

University of Strathclyde, D. J. BENNET
Glasgow.

May 1972

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List of symbols and subscripts

a	fuel element dimension
A	area, mass number
b	fuel element cladding thickness
B	breeding ratio, build-up factor
B^2	buckling
B_m^2	material buckling
B_g^2	geometric buckling
c	specific heat
C	concentration of delayed neutron precursors, source strength of gamma radiation, cost
d_e	effective diameter
D	dose rate
E	energy
E_A	available energy
f	thermal utilization factor, friction factor
F	neutron reaction rate per unit volume, feed
g	non-$\frac{1}{v}$ factor
h	enthalpy, heat transfer coefficient
H	rate of energy release per unit volume
I	effective resonance integral
J	neutron current density
k	thermal conductivity, multiplication factor, Boltzmann's constant
k_∞	infinite multiplication factor
k_{eff}	effective multiplication factor
l	neutron lifetime
l_p	prompt neutron lifetime
L	length, height, diffusion length
L_s	slowing-down length
L'	extrapolated length
m	mass

$\dot{m}$	mass flow rate
M	molecular weight, migration length
n	neutron density
N	density of atoms or nuclei, number of neutrons in nucleus
p	pressure, resonance escape probability
P	perimeter, product of enrichment
PP	pumping power
q	slowing down density, heat flux
q_L	heat transfer per unit length of fuel element
Q	rate of heat output or heat transfer
R	radius, thermal rating, gas constant
R'	extrapolated radius of core
R^+	extrapolated radius of reflector
s	entropy
S	surface area, source strength
t	time
t_d	diffusion time of thermal neutrons
t_m	mean life of a radioactive isotope
$\bar{t}_m$	average mean life of delayed neutron precursors
T	temperature, reflector thickness, reactor period, tails of enrichment
$T_{1/2}$	half-life of a radioactive isotope
T_d	doubling time
u	speed of neutron in the centre of mass system
U	speed of nucleus in the centre of mass system
v	neutron speed
V	volume, value function for enrichment
W	work, power
x	isotopic fraction in enrichment process
Z	atomic number
α	temperature coefficient of reactivity, maximum fractional loss of energy after an elastic scattering collision
α_r	radial form factor
α_z	axial form factor
β	delayed neutron fraction
γ	fission product yield
δ	reflector savings
δk	excess reactivity
Δ	mass defect
ϵ	fast fission factor
η	eta, efficiency
θ	temperature difference, angle of scattering in the centre of mass system
κ	inverse of the diffusion length
λ	decay constant, mean free path

μ	linear absorption coefficient, viscosity
$\bar{\mu}$	average cosine of the angle of scattering in the laboratory system
ν	average number of neutrons produced per fission
ξ	logarithmic energy decrement
ρ	density, reactivity
σ	microscopic cross-section
Σ	macroscopic cross-section
τ	neutron age, shear stress
ϕ	neutron flux
ψ	angle of scattering in the laboratory system
χ	mass absorption coefficient
ω	reactor period

Subscripts

a	absorption
av	average
b	bulk
c	capture, core, coolant, centre of mass system
C	core (of reactor)
cl	cladding
CS	Compton scattering
D	dose
eq	equilibrium
E	energy
f	fission, film, feed, fuel surface
$\mathrm{f_p}$	fission product decay
F	fuel, flux
G	gap
i	inelastic
l	laboratory system
M	moderator
MP	most probable neutron speed in a Maxwellian spectrum
p	constant pressure, product of enrichment
P	pump
PE	photoelectric
PP	pair production
R	reflector
s	scattering, surface, shutdown
sat	saturation
t	total, tails of enrichment
th	thermal
tr	transport
w	wall

γ	gamma radiation
0	thermodynamic datum, initial conditions, origin of coordinates
1	fast group of neutrons
2	thermal group of neutrons

Modifying symbols

Where a symbol refers to a particular element, compound or isotope, this is indicated thus:

$N(H_2O)$	number of molecules of water per unit volume
$\sigma_c(^{238}U)$	the capture cross-section of ^{238}U

An historical introduction

The story of the discovery and development of nuclear energy, which in the context of this book is the energy released by the fission of uranium and possibly other heavy elements, may be taken as starting in 1932, the year in which Chadwick at the Cavendish Laboratory, Cambridge, identified the neutron.

This discovery was of great importance in several respects. Firstly, it enabled the structure of the atomic nucleus to be explained in a much more satisfactory way than had previously been possible, and it showed the possibility that any particular element might have a number of different isotopes, i.e. species in which the numbers of neutrons in the atomic nucleus may vary, one from another.

Secondly, the neutron provided atomic scientists with a new particle with which they could bombard atomic nuclei in order to induce artificial nuclear reactions. In previous years scientists had used high-energy protons and alpha particles (nuclei of the element helium) for this purpose, but soon after the discovery of the neutron it was realized by many of them, notably the Italian scientist Fermi working in Rome, that the neutron being uncharged (unlike the proton and alpha particle) would more readily penetrate the potential barrier of the atomic nucleus and interact with it.

In the following years Fermi and his colleagues in Rome bombarded many of the naturally occurring elements with neutrons and studied the products of the resulting reactions. In most cases he found that radioactive isotopes of the original elements were produced, and that when these isotopes decayed other elements, slightly heavier than the original elements, were produced. In this way uranium, the heaviest of the naturally occurring elements, was converted by neutron bombardment into heavier transuranium elements which do not exist naturally on the earth. Fermi made two other important discoveries at this time, namely that low energy neutrons are in general more effective than high energy neutrons for causing nuclear reactions, and that high energy neutrons can most effectively be slowed down to low energy by successive scattering collisions with light elements such as hydrogen in compounds such as water or paraffin wax. These two discoveries turned out to be of crucial importance in the development of nuclear energy in the following years.

Fermi's experiments with uranium were repeated by the German chemists Hahn and Strassmann who, in 1938, discovered that one of the products of the interaction between neutrons and uranium was barium, an element near the middle of the Periodic Table. Evidently a reaction had occurred in which the heavy uranium nucleus had, as a result of neutron bombardment, split into elements of intermediate mass. The physicists Meitner and Frisch, hearing of this discovery, evolved an explanation for the process on the basis of the liquid-drop model of the atomic nucleus, and calculated that an enormous amount of energy (far greater than in any previously known reaction) would be released as a result of the process, to which the name fission was given.

Other important features of fission were discovered in the following months. Joliot and his colleagues in France showed that some neutrons were emitted by the fission process, and it was later shown that these neutrons had very high energy. Thus the possibility existed that the fission process, initiated by a single neutron and producing two or three more neutrons, might be continued if these new neutrons caused further fission. The self-sustaining chain reaction so produced would be capable of releasing amounts of energy that were huge by existing standards.

Two distinct types of fission chain reaction were envisaged: one in which the process would proceed at a steady, controlled rate and release energy steadily and continuously; the other in which the fission rate would be so rapid and uncontrolled as to produce, literally, a nuclear explosion of considerable destructive potential. There were, however, many unknowns to be solved before these ideas even approached reality. Among these unknowns was the cross-section of uranium 235 for fission (the measure of the probability that this type of process would occur), and until this quantity was known there was no way of telling if a chain reaction would be possible, and if so how large would be the critical mass of uranium necessary. It was also realized that to achieve a chain reaction in certain types of system designed to give a steady and continuous energy release it would be necessary to reduce the energy of fission-produced neutrons to much lower energies at which, as Fermi had already shown, they would more readily cause further fission. The material to achieve this slowing down process became known as the moderator, and one of the earliest moderators to be used experimentally was heavy water, which at the time in question had only one source in Europe—the Hydro-Electric Company of Norway, from whom the French obtained the entire stock in 1940.

The discovery of fission in 1938 and the further developments of 1939, coming as they did just before the outbreak of the Second World War, could hardly have occurred at a more crucial time in world history. Had Hitler appreciated fully the significance of this discovery and encouraged his scientists to develop it, there is every possibility that Germany would have been the first country to produce atomic weapons and world history in the last thirty or forty years would have been very different. Fortunately, from the British point of view, Hitler was unimpressed by the discoveries of his atomic scientists, many of whom were Jews and were fleeing to Britain and America, and fission research in Germany was pursued with limited resources and priority. Fission research in France came to an abrupt end in June 1940 and two leading French scientists, Halban and Kowarski, came to Britain with France's vital stocks of heavy water.

Thus in the summer of 1940 Britain, already involved in a single-handed struggle with Germany, became the focal point of fission research. There was in the country in that year an impressive collection of the world's leading scientists, many of them refugees from Europe. There was an extraordinary sense of urgency, for it was realized that the first country to produce an atomic bomb would almost certainly win the war, and no one knew exactly what the Germans were doing. In that year the scientists in Britain made impressive progress and showed theoretically that an atomic bomb with a devastating explosive power could be made from uranium 235, which would itself require to be separated from uranium 238 in natural uranium by a process such as gaseous diffusion.

There was, however, still a very long way to go to produce the pure uranium 235 in adequate quantities and manufacture bombs, and in wartime Britain these steps were considered to be impracticable in view of the industrial resources that would be required and the vulnerability of the plant to air attack. It was decided to transfer nearly all the research, development and production work to the United States of America, where work on fission was in progress, though it was not as advanced, nor was it being pursued with the same degree of urgency, as in Britain. America, however, had the necessary industrial resources and, even after the outbreak of war with Japan, was immune from air attack.

The principal aim of fission research in America in the early nineteen-forties was to produce atomic bombs, and once America was involved in the war the sense of urgency increased. Two methods were proposed for obtaining pure fissile material for bombs: first, pure uranium 235 would be obtained from natural uranium by isotopic separation, using the gaseous diffusion process and uranium hexafluoride as the gaseous compound that would diffuse through a series of membranes. Second, the transuranium isotope plutonium 239, which was known to be fissile, would be produced from uranium 238 by neutron bombardment in a controlled chain-reacting system using natural uranium. Fission in the uranium 235 fraction of the natural uranium would sustain the chain reaction, and surplus neutrons would convert some uranium 238 to plutonium 239 which could be separated from the uranium. To these ends the huge gaseous diffusion plant at Oak Ridge, Tennessee, went into production in 1943 to produce uranium 235, and in December 1942 the first controlled chain-reacting system went critical at Chicago under the direction of Fermi, who several years previously had left Italy for the United States. In the following two years bigger, more powerful reactors (as the controlled fission systems came to be called) were built, culminating in the huge plutonium producing reactors at Hanford in Washington.

By the summer of 1945 enough uranium 235 had been produced at Oak Ridge, and enough plutonium 239 at Hanford to make the first atomic bombs. One was tested at Alamogordo in New Mexico, two were dropped on Japan and brought the Second World War to an abrupt end. The destructive power of these bombs confirmed the claims, and the fears, that had been expressed by scientists in the preceding years, and made August 1945 a watershed in human history.

In the years immediately following the Second World War the development of nuclear weapons proceeded apace, not only in America, but also in Britain and Russia who were determined to have their own weapons. Testing of atomic bombs, and the later and much more powerful hydrogen bomb, produced large-scale radioactive pollution in the atmosphere, and in due course these three countries signed an Atmospheric Test Ban Treaty to limit this pollution. The treaty was only partly effective, as France and China, new members of the 'atomic bomb club', did not sign the treaty and atmospheric testing continued, albeit on a reduced scale.

The early development of nuclear energy for electric power generation had its origins in military work. In the United States Admiral Rickover foresaw that naval vessels powered by nuclear reactors would have almost unlimited range, certainly much greater than the range of existing vessels, and this would confer considerable strategic advantages, particularly for submarines which would be able to cruise underwater for prolonged periods. It was, of course, necessary that the nuclear reactors should be as compact as possible to be installed in a ship, and this requirement led to the development of the first Pressurized Water Reactor, in which (as the name implies) water at high pressure is the moderator and coolant, and the fuel is slightly enriched uranium, i.e. uranium in which the uranium 235 content is increased by isotopic separation to 2 or 3 per cent. This type of reactor was much more compact than the huge graphite moderated Hanford reactors. The first nuclear powered ship, the submarine USS Nautilus, sailed in 1955. Two years later a reactor of similar design at Shippingport, Pennsylvania, became America's first commercial nuclear power plant for electricity supply, and in the thirty years since then this type of reactor, progressively enlarged in size and power, has been the basis for nuclear electricity generation in the United States and other countries.

Canada's wartime research had been centred on the development of reactors using heavy water as the moderator. This work was the continuation of the research started in France in 1939 and transferred to Britain between 1940 and 1942. Canada, being the Allies' sole producer of heavy water, was the logical country in which to continue this work when atomic research was transferred from Britain to the other side of the Atlantic. This early work has determined the course of Canadian nuclear energy development ever since, and present-day Canadian power reactors owe much to their original heavy water moderated reactors of the early post-war years.

In Britain at the end of the war the first priority was considered to be the production of plutonium 239 as a weapons material, and the first large British reactors were the two plutonium-producing reactors at Windscale. These reactors were similar to the American plutonium-producing reactors at Hanford in that they used natural uranium as the fuel and graphite as the moderator. This choice of materials was to some extent dictated by the fact that Britain did not at that time have access to large quantities of enriched uranium or heavy water, so the lines of development being followed in the United States and Canada were not then possible in Britain. The next stage was the construction of the combined power and plutonium-producing reactors at Calder Hall (beside Windscale) and when these reactors were commissioned in 1956 they became the world's first large power reactors to supply electricity to the public supply system. (A short time earlier the Russians had commissioned their first power reactor, but its output was very small.) In 1957 there was a serious fire in one of the original Windscale reactors, and both were closed down, however the Calder Hall reactors continued to operate successfully, and have become the prototypes for the subsequent development of gas-cooled, graphite moderated reactors for electricity generation in Britain, a development which has continued to the present day.

Such, then, is the brief history of the early development of nuclear energy in the western world. Similar developments of no less significance have taken place concurrently in Russia, and now many developed industrial countries, particularly western European countries and Japan, have their programmes of construction and use of nuclear power. The one type of reactor which more than any other now dominates the world nuclear energy scene is the American Pressurized Water Reactor which has been sold to, and built under licence, in many other countries.

There can be no doubt that the discoveries of the neutron, fission and plutonium have presented mankind with possibilities and dangers of an unprecedented magnitude. On the one hand there is the possibility of using for peaceful purposes an energy source which is potentially far greater than the world's resources of fossil fuel; on the other hand there are the dangers of the destructive power of nuclear weapons, a power that could destroy humanity. The discoveries of forty years ago cannot be undone or forgotten, and it may well be thought (bearing in mind that these discoveries and developments were made at a time when world war was in progress) that the birth pangs of nuclear energy might have been worse than they were. Two bombs were dropped in anger, and the destruction and death which they caused have given the world a lesson which so far has been heeded. The future use of nuclear energy presents challenges to the scientists and engineers who will be responsible for the design, construction and operation of nuclear reactors reliably and safely for power generation; it presents even greater challenges to mankind, and politicians in particular, to ensure that this source of energy is never again used for war.

Chapter 1