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REACTOR PHYSICS FOR NON-NUCLEAR ENGINEERS

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ABSTRACT

A one-term undergraduate course in reactor physics is described. The instructional format is strongly influenced by its intended audience of non-nuclear engineering students. In contrast to legacy treatments of the subject, the course focuses on the physics of nuclear power reactors with no attempt to include instruction in numerical methods. The multi-physics of power reactors is emphasized highlighting the close interactions between neutronic and thermal phenomena in design and analysis. Consequently, the material's sequencing also differs from traditional treatments, for example treating kinetics before the neutron diffusion is introduced.

Key Words: Education, reactor physics, multi-physics.

1. INTRODUCTION

This one-term course is aimed at a diverse audience, consisting primarily of undergraduate mechanical engineering students, but with other engineering disciplines also represented along with a sprinkling of physics majors and graduate students. Since Northwestern University no longer has a nuclear engineering degree program the students have no previous exposure to nuclear engineering, and with the exception of the few who will pursue graduate nuclear engineering degrees, it may be their only formal exposure to reactor physics. The nature of the student body and the need to compress the material into a one-term course has had a strong impact of the pedagogical approach which I have taken in organizing the course and in authoring the text derived from it.[1] It is an approach with differs significantly from the legacy treatment of the subject which has roots going back to the earliest days of nuclear energy.

The course in focused on the physics of nuclear reactors, and is almost entirely divorced from the teaching of the numerical methods needed to obtain highly accurate solutions to reactor problems. While this omission is in part a time-saving mechanism, I believe it is also well justified. For when the earlier texts were written students needed to do their own programming, usually in FORTRAN, at an elemental level to do such things as applying finite differencing and then solving tridiagonal matrix equations, or numerically integrating the point kinetics equations. But now students are already familiar with the use the numerical packages in high-level languages, such as Matlab or MathCAD, and can use these for solving nonlinear equations, integrating systems of ordinary differential equations and so on, without diverting the course's narrative away from the physics at hand. Thus problems assigned are focused those analytical solutions that provide physical insight, spreadsheet problems to parameter variation, and where needed the use of the aforementioned high-level language.

The course also attempts to integrate early-on the multi-physics of power reactors. Here my effort is colored by nearly fifteen years of organizing and teaching in a week-long industrial short coarse titled, "Safety of Light-Water Cooled Nuclear Power reactors." There it was necessary to give a holistic overview of reactor physics to engineers who were involved in the design and operation of power reactors in one long day! In that course it was imperative to relate neutronics to thermal-hydraulic phenomena, and to give a great deal of emphasis to prompt critical, reactivity feedback and other topics that all too often get short shrift in the final days of reactor theory courses of limited duration. And while the academic reactor physics course in not nearly so compressed that one must rely primarily on graphical explanations, the emphasis is nevertheless changed, and the topics arranged in a somewhat different order than has traditionally been the norm. Even though this must be done at the expense of de-emphasizing some of the topics typically covered in the traditional sequence of development: homogeneous reactors, reflector savings and the like.

2. COURSE OUTLINE

The emphasis on a holistic treatment of reactor physics is implemented in the outline summarized in Table I. Here I would like to draw attention to those aspects that differ significantly from the "classic" sequencing and emphasis of the material. The lattice structure and composition of power reactor cores is introduced early-on immediately following the necessary preliminaries covering nuclear reactions, neutron cross sections, scattering and slowing down. This allows relating thermal and neutronic considerations. Explaining the four factor formula for lattices provides an excellent tool for comparing the properties of various moderators and the effect that the slowing down decrement, power and ratio have on the choice of fuel to moderator ratios other core parameters. A table of typical values of the four factors and related parameters for different reactor classes, and a graph of multiplication vs. fuel to moderator ratio for various enrichments for a PWR provides insight into the effects of over- and under-moderation on reactor stability.

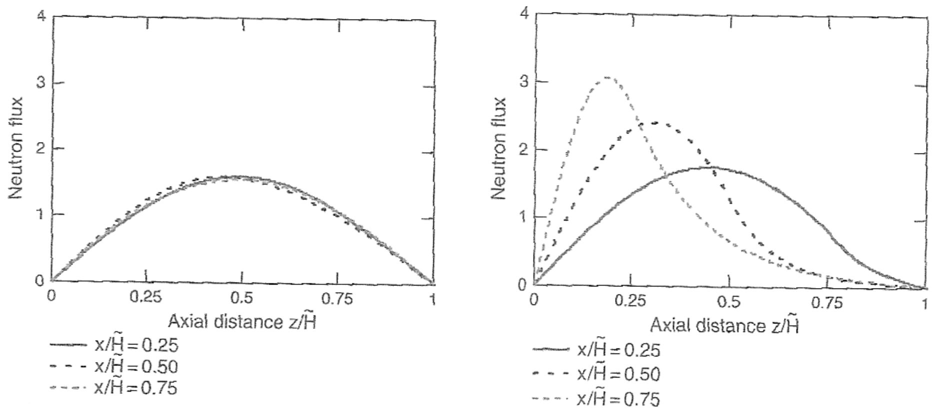
TABLE I. Sequence of Topics.

1. Nuclear Reactions
2. Neutron Interactions
3. Neutron Distributions in Energy
4. The Power Reactor Core
5. Reactor Kinetics
6. Spatial Diffusion of Neutrons
7. Neutron Distributions in Reactors
8. Energy Transport
9. Reactivity Feedback
10. Long Term Core Behavior

The treatment of neutron leakage is deferred. In the treatment of reactor lattices, it is included as a non-escape probability. More, importantly including leakage simply as a nonleakage probability allows the all important time-dependent behavior of reactors to be taken up before delving into the intricacies of neutron diffusion. In my view criticality, the reactor period, the importance of delayed neutrons and prompt critical should be introduced early and built upon, rather than being put off until late in the course. The student readily accept that leakage is diminished as the size of the core is increased, and are willing to wait for the concept to be treated quantitatively later in the course. In a similar manner reactivity feedback is introduced qualitatively as a prolog to what will be detailed later.

Diffusion theory, of course, must be treated to describe the spatial distributions of neutrons. Following derivation of the equations and boundary conditions and solutions for simple non-multiplying configurations, we proceed to the treatment of a simple subcritical sphere with a uniform source. Increasing the value of *k* until the denominator vanishes. This re-enforces the point made in the treatment of kinetics that only subcritical systems with sources and source-free critical systems have time-independent solutions. Moreover, the criticality equation, along with an expression for the non-leakage probability follows directly from setting the denominator equal to zero.

Further treatment of the spatial distributions of neutrons focuses on cylindrical reactor cores, beginning by explaining the standard *k* formulation of the diffusion equation. Emphasis is placed on neutron coupling as expressed as the ratio of the reactor's characteristic dimension to the neutron migration length: *D/M*. The effect of the diminished effect of reflector savings in neutronically loosely-coupled cores is examined. The increased tendency to power peaking in loosely-coupled cores is then illustrated by displaying the axial power distributions in cores with small and large values of *D/M* as control rod banks with the same reactivity worth are inserted. This is shown in Figure. 1 The axial offset of reactivity decrease with bank insertion in large *D/M* cores can likewise be illustrated.



(a) *H/M* = 10 (b) *H/M* = 50

Figure 1. Normalized Axial Flux Distributions for Three Control Bank Insertion Depths.

We return to the importance of integrating neutronics with energy transport considerations by developing a simple model for steady state fuel and coolant temperatures. We then show how they are integrated in reactor design by performing a simple PWR scoping calculations. At first pass, once the fuel to coolant ratio and the axial and radial power peaking factors are specified, the maxima in linear heat rate, surface heat flux and outlet coolant temperature determine the core volume, with enrichment then being adjusted to obtain criticality. We then proceed to develop a simple transient model for the fuel and coolant temperatures, which is later combined with reactivity coefficients and neutron kinetics to treat dynamic behavior. Throughout the course typical parametric values are presented for various classes of existing power reactors to provide the students with an appreciation for the differences in magnitude. For example Table II makes apparent the differences between fast and thermal reactors and the effects of different moderators on fuel to coolant ratio's, nonescape probabilities and related parameters.

TABLE II. 3000 MW(*th*) Power Reactor Approximate Core Properties.

	PWR	*BWR*	*CANDU*	*HTGR*	*LMFR*	*GCFR*
Mean Power Density (MW/m^3)	102	56	7.7	6.6	217	115
Mean Linear Heat Rate (kW/m)	17.5	20.7	24.7	3.7	22.9	17
Core Volume (m^3)	29.4	53.7	390	455	13.8	26.1
Height & Diameter in Migration Lengths	43.9	55.0	40.8	68.8	13.5	12.6
Number of Fuel Pins	51,244	35,474	15,344	97,303	50,365	54,903
Nonleakage Probability	0.956	0.972	0.950	0.982	0.676	0.644

The treatment of temperature coefficients is combined with the foregoing thermal models to formulate prompt, isothermal and power reactivity coefficients. The use of temperature and power defects then allows excess reactivity – and hence control requirements – to be displayed for various reactor states as a function of time. Combining the two transient heat transfer equations with fuel and coolant temperature coefficients and the kinetics equations, then allows the solution of simple transient problems. For example the “startup accident” is illustrated in Fig 2 by showing the effect of initial power on the power transient for the same ramp reactivity insertion rate, kinetics parameters and feedback coefficients. The final chapter details longer term core behavior, filling in the reasons behind the time dependence of the curves in Figure 3. After treating Xenon poisoning, and actinide buildup, brief discussions of burnable poisons and nuclear waste bring the course to an end.

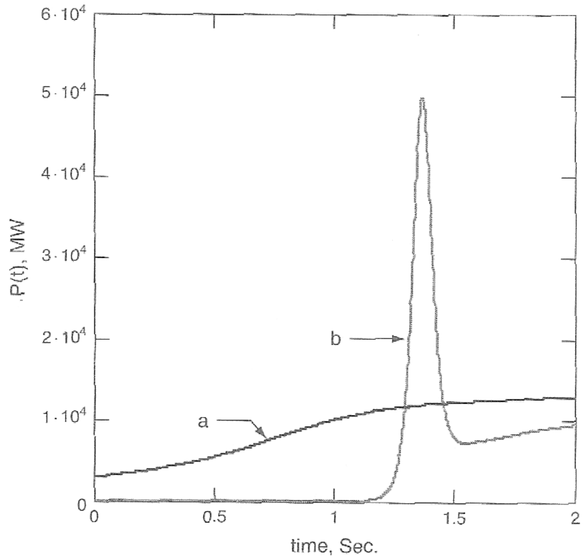


Figure 2. Power Transients for a Reactivity Insertion Rate of 1.0$/s.

(a) Initiated from Full Power (b) Initiated from Low Power

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