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"Combining Simulations of the Basic Reactor Experiments with Lectures
in a Nuclear Engineering Course"
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Abstract

Nuclear Engineering Departments were created at most engineering colleges and universities during the 1950s and 1960s. These schools typically procured a research or test reactor which became the centerpiece of the department. It had dual use for research and academic instruction. The author was the Supervisor and Instructor at such a critical facility at which a Nuclear Engineering Laboratory Course was based.

The basic reactor experiments that were performed were quite similar to what the pioneers Enrico Fermi, Leo Szilard, Eugene Wigner and others performed in Chicago in 1942 and subsequently at the plutonium producing reactor in the state of Washington. These experiments remain similar to those done at the electric utility reactors and by the nuclear navy at times of refueling and startup.

The experiments include 1) confirming the ability to measure neutrons and calibrating the instrument channels by testing and calibrating to assure that neutrons and only neutrons are measured, 2) starting with an empty core and then loading fuel and monitoring neutron multiplication as a function of fuel loading with rods in and out, 3) measurement of reactivity vs rod position once the fuel is fully loaded, 4) measurement of reactivity vs temperature to assure hands off stability, 5) measurement of reactivity vs void at various core locations, 6) measurements of reactivity vs boron and 7) mapping the flux for determining power distribution in the reactor.

Unfortunately, many nuclear engineering departments have been eliminated or merged with other departments. Most instructional reactors have been shut down. Furthermore there have been no nuclear engineering text books written in recent years.

However, many graduate students have nuclear industry related employment and opportunities and remain interested in having a nuclear engineering course as part of their program. The challenge is how to effectively structure such a course. Some students may have extensive nuclear industry experience and others with minimal prior knowledge.

The author has developed such a course that combines instruction from an out of print text book and simulated reactor experiments to provide a context for the text book and lecture material. The author will describe this course along with student comments that have been consistently favorable.

1. Introduction

Nuclear Engineering and Technology at Union College is a masters level course in the Mechanical Engineering Department. There continues to a strong interest in this course. The average enrollment has been consistent at about 25 students each year for the last fifteen years. Most are part time students who are employed as engineers in local nuclear or power related industries. Some are high performing undergraduate students.

The challenges in presenting this course result from the nonexistence of an appropriate text book, no nuclear related laboratory equipment, and the fact that some students may have 20 years of nuclear experience or be nuclear training instructors, while other students have virtually no prior knowledge of nuclear principles and practice.

However, the instructor has the benefit of forty years of nuclear experience with the naval reactors program, commercial nuclear power plants and as a supervisor of a university research and teaching reactor. He has also directed and taught a two week program of reactor based experiments on this reactor. This program of ten experiments has been highly effective in providing non nuclear engineers with a fundamental understanding of nuclear theory and technology.

Thus the author decided to develop the Nuclear Reactor and Technology course around a virtual reactor. The students pretend to do a set of reactor based experiments. The experiments include a) neutron measurement, b) loading fuel to the critical condition, c) control rod calibration, d) reactivity vs temperature, e) reactivity vs boron, f) reactivity vs void and g) spatial power mapping.

It is noted that these are the experiments that were devised by Enrico Fermi and Leo Szilard as part of their December, 1942 demonstration of a nuclear chain reaction. They are repeated to confirm satisfactory performance at the time of the initial fuel loading and the refueling for any power plant.

2. Experiments

These experiments also demonstrate nuclear principles at the fundamental and operational level. Students write a lab report for each experiment comprised of theory, measured data, analysis, results and discussion. This paper section will further describe the experiments and demonstrated principles and practices.

a. Neutron Measurement

Fundamental to nuclear control and safety is the monitoring a reactor is to measure the rate of fission which corresponds to heat generation and power. Options include measurement of heat by calorimetric or measurement of the resulting radiation products of alpha, beta, gamma or neutrons. The pros and cons of each method is described. It is

shown that neutron measurement is the best option, but the problem is that neutrons are not ionizing radiation and thus do not produce an electrical signal.

The technique of using neutrons to produce an ionizing transmutation of boron in a BF3 tube is described, and then the design of the corresponding circuit to measure events. The object is to measure neutron events and only neutron events. Adjustments are made in the BF3 voltage and discriminator to establish the settings at which neutrons and only neutrons are measured.

b. Fuel Loading by Subcritical Multiplication

A subcritical reactor is an amplifier of external source neutrons. The amplification factor is 1/(1-keff). The keff is a function of the neutron non leakage and this a function of the amount of fuel.

A reactor core map is provided along with an external source and neutron detectors. Measured neutron rate is measured as a function of the amount of fuel loaded. From these measurements the value of keff is calculated and the critical mass is predicted at each step of the fuel loading process.

c. Control Rod Calibration

An operational reactor must be subcritical with the rods inserted and supercritical with the control rods fully withdrawn, and thus exactly critical at an intermediate rod position. The purpose of this experiment is to determine the value of keff vs rod height and thus the differential and integral control rod worth.

The evaluation of rod worth is obtained from processing neutron measurements as from rods on bottom to fully withdrawn. The neutron data is then processed to rod worth via the Wicks reactor equation (Reference 1). This differential equation is developed from first principles and then solved for the special conditions of subcritical multiplication, supercritical period and scram response.

The one delayed neutron group and single node differential equation is developed from a neutron balance equation and a delayed neutron precursor equation. The neutron multiplication factor, keff, is converted to a diffference from critical and then normalized to the fraction of delayed neutrons, B. The resulting is rho in $ is shown in equation 1. Thus, rho equals 1 $ is the prompt critical condition, which should never be approached.

Rho($)= (Keff-1)/B (1)

The resulting Wicks reactor differential equation that relates neutron population, n(t), reactivity, rho(t), external neutron source strength in neutrons per second, s(t), the decay

rate of delay neutron precursor atoms, r(1/sec) and neutron life time, L(sec), is presented in equation 2.

$$(dn/dt)*(1-rho(t))= r*n(t)*rho(t)+ n(t)*(drho/dt)+L*(r*s(t)+ ds/dt)/B \quad (2)$$

This equation is solve for a variety of conditions representing subcritical multiplication, M, which is the ratio of total neutrons to source neutrons per (equation 3), reactivity as a function of the supercritical steady state period, T(sec), where period is the time for neutrons to increase by a factor of e per (equation 4) and scram response which is the immediate neutron response to a step change in reactivity per (equation 5).

$$M= 1/(1-keff)= -1/(B*rho) \quad \text{(subcritical multiplication)} \quad (3)$$

$$rho=1/(1+r*T) \quad \text{(supercritical with constant rho)} \quad (4)$$

$$n(+)/n(-)= (1- rho(+))/(1-rho(-)) \quad \text{(step neutron response to step change in reactivity)} \quad (5)$$

A scram represents a discontinuous function in time. The rho(-) and rho(+) in equation 5 are the reactivity values immediately before and immediately after the step change in reactivity. The n(-) and n(+) are the neutron populations immediately before and after.

d. Reactivity vs Temperature

Any practical reactor must be self regulated by some internal feedback mechanism. Small to moderate size reactors may be regulated by a negative moderator temperature coefficient. When the water temperature increases the neutron diffusion lengths increase and thus there is more leakage from the reactor and corresponding decrease of the keff, the neutron multiplication factor. Larger and low enriched reactors self regulate by means of the Doppler effect, which results from resonance broadening of the cature cross section in U238.

The reactivity vs temperature experiment is performed by sustaining the reactor at a low power critical condition as the water is heated by adjusting the control rod position. The differential rod worth functions from the prior experience is used to convert these measurements to a temperature coefficient. This is defined as the change of keff vs change of temperature. The subject reactor has a positive temperature reactor which is unstable at low temperatures. The coefficient becomes negative at higher moderator temperatures. The reactor is stable and thus self regulating in this range.

e) Reactivity vs Boron (r)

The Boron10 isotope has a high neutron capture cross section. Thus it is used to

suppress neutron multiplication via control rods or chemical shim in large pressurized water reactors. The sensitivity of keff to Boron10 depends upon both amount and location. The effect is nominally proportional to the product of the neutron flux shape function and the importance function, which is also nominally proportional to neutron shape. Thus, the effect of Boron10 is nominally proportional to the neutron flux squared.

A small sample of Boron10 that looks like electrical tape is placed on a stringer at various points in the reactor. The critical control rod height is compared with the reference with no Boron10. The reactivity effect of Boron10 vs vertical location in the reactor is found to correspond to the differential control rod worth vs height. Students are asked to explain this correspondence.

f) Reactivity vs Void

Water is a neutron moderator. The water increases Keff by slowing the 2 Mev neutrons from fission down to thermal equilibrium of about .05 ev at operating temperature. Keff is increased because of larger atomic cross sections and less leakage. However, water also captures neutrons. Thus some water is good, but more is bad for keff. Optimal moderation or fuel to water ratio is the amount of water that maximizes keff.

A stable or self regulating reactor should be under moderated. Thus, an upward perturbation of power raises the temperature of the water which either expands as a liquid or undergoes local boiling which decreased keff and thus stabilizes power.

If a critical reactor is over moderated the increase in power will increase keff and the reactor can rapidly reach and exceed the prompt critical condition. The 1986 accident at Chernobyl started at a low power level, which corresponded to a positive void coefficient.

Local void effects upon keff can be calculated with only limited confidence. Thus, confirming experiments are important. The experiment is performed by placing increasing amounts of a water displacing material such as styrofoam at various locations and converting the differences in critical rod height to a void effect.

The instructional reactor at room temperature is found to have a small positive void coefficient at the center. Void always has a stabilizing negative effect on the boundary, which can be explained because the increased neutron leakage from the core is more important.

g) Spatial Flux and Power Shape

Nuclear reactors are commercially viable because of the engineer's ability to design small diameter fuel rods and with nucleate boiling enhanced heat transfer from the rod to the cooling water. Power densities of 70 kw thermal per liter of volume are achieved.

A chain is as strong as the weakest link. Similarly, the total power that can be produced by a reactor is limited by the point that is closest to burnout, which happens if the enhanced heat transfer mechanism of nucleate boiling is replaced by bulk boiling. The Departure from Nucleate Boiling Ratio (DNBR) represents the thermal hydraulic safety factor of a reactor.

The thermal hydraulics engineer would prefer a reactor with a uniform heat generation rate throughout. However, any finite size reactor has a power shape nominally like a cosine function with maximum power at the center and low at the boundaries. An accurate knowledge of this shape is important. Experiments supplement the calculations.

The flux shape experiment is performed by placing small samples of an element such as gold. Neutrons are captured and unstable isotopes are produced. The reactor is operated with such samples installed at various locations. They are then removed. The decay rate is measured, and correlated with the amount of flux received, which is then processed to power level at each core location.

3. Conclusions

Student comments and evaluations have been consistently favorable over fifteen years of teaching a Nuclear Engineering and Technology course in this manner which balances lectures with the previously described experiments and lab reports. Students with minimal prior nuclear experience and others with extensive experience are comparable in terms of performance and benefit. The experiments provide the inexperienced with a context. The experienced student attains enhanced insight and understanding.

The structure and content of the course rely heavily upon four decades of nuclear related experience by the instructor in naval, commercial and university reactors. The future challenge for instructors will be teaching such a course without updated text books and without the benefit of experience with educational, test or research reactors.

Reference:

1. Frank Wicks, "Formulation and Application of an Equation for Low Power reactor Operations and Experiments", Transactions of the American Nuclear Society, volume 45, page 32, 1983.

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