NEW REACTOR EXPERIMENTS COURSE AT THE UNIVERSITY OF MASSACHUSETTS LOWELL

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ABSTRACT

A new graduate-level Reactor Experiments course is currently under development at UMass-Lowell. This is a laboratory-based course that uses the UMass-Lowell Research Reactor (UMLRR) to illustrate, validate, and expand upon a mix of topics from reactor core physics, reactor operations, and balance-of-plant/energy removal considerations in nuclear systems. Typical experiments include an approach-to-critical demo, reactivity measurements, generation of blade worth curves, analysis of various reactor kinetics and dynamics scenarios (including temperature and xenon effects), measurement of temperature/void coefficients and axial flux profiles, analysis of loss of flow and other pump transients, etc. MATLAB is used extensively for data analysis and for reactor simulation. Comprehensive analysis reports and student oral presentations that compare/contrast experimental and simulation data are required. Although the topical coverage within the new course is rather traditional in scope, the format and delivery take full advantage of the modern digital instrumentation and control system within the UMLRR and standard web-based communications technology so that all educational users (both local and remote) can have easy access to both real-time and archived sensor data from the reactor. After working out many of the course details during the first offering in Spring 2013, we hope to make the course available via web-based access for use at other universities and organizations involved in training the next generation of nuclear engineers.

Introduction

The University of Massachusetts Lowell owns and operates a 1 MW MTR-fuelled pool-type research reactor that serves as a general teaching and training centre, and as a neutron and gamma source for a variety of materials testing and general research activities. The UMass-Lowell Research Reactor (UMLRR) has operated safely since 1975, with the use of HEU uranium-aluminide fuel until the summer of 2000 and with LEU uranium-silicide fuel since that time. The UMLRR staff offer a formal Reactor Operator Training course whose main focus is to train students to become licensed UMLRR operators, and many Nuclear Engineering (NE) and Radiological Sciences (RS) undergraduate and graduate students over the years have done their project or thesis work related to the reactor in some way. However, it has been nearly 20 years since a formal Reactor Experiments course has been taught at UMass-Lowell (since the retirement of a senior faculty in the mid 1990s), and the re-integration of this type of course within the NE curriculum has been long overdue. In addition, it should be noted that there have been many significant improvements within the facility over the last 10-15 years, including the addition of a modern digital control and data acquisition system about 10 years ago and the addition of online accessibility in recent years. In addition, there has been increased student interest and enrollment in our UML NE programs in the last few years after several very lean years. Thus, it is within this context that we have undertaken the development of a new Reactor Experiments course for the graduate NE curriculum at UMass-Lowell.

This paper overviews the general structure, technical content, and delivery mechanisms for the new course, highlights some key aspects from the lab modules completed thus far during the first offering in Spring 2013, and summarizes the future availability of such a course for use at other universities and organizations.

Course Structure and Delivery

The new laboratory-based course, although quite traditional in scope, uses the reactor's web-accessible data acquisition system as a key resource for the course, so that both the on-campus or online student has full access to whatever data that may be needed for a particular lab module. The experiments will cover both basic and advanced concepts and include both normal and off-normal core operation, reactivity control considerations, and the interaction of core operation with the energy removal and auxiliary systems within the UMLRR. At present, we plan to offer the course each year during the Spring semester (late January to early May), and each lab will be an essentially autonomous educational module. Each lab module will contain appropriate topical background material, pre-lab preparation guidelines, and questions/tasks for the post-lab analyses and discussions, as well as the actual lab experience.

The plan is to have six formal labs each semester. The course structure assumes that 13 classes will be offered each semester with one nominal 3-hr meeting per week. After the first orientation class and pre-lab discussion for Lab #1, the reactor experiments occur every other week, In the non-lab weeks, a set of formal student presentations take place at the beginning of class as wrap-up for the previous week's lab. Then, the remainder of the class focuses on the description, background theory, and any other preparations that may be needed for the following week’s lab. Homework assignments occur every week, alternating between preparations for the upcoming experiment and post-processing and analysis of the data collected from the most recent lab. This schedule keeps the students consistently engaged within the course throughout the semester. However, the overall workload is quite reasonable and well distributed, with only a "light effort" needed for the pre-lab assignments followed by a "relatively heavy load" for the weeks requiring a formal lab report. The students are encouraged to work together in two-person teams when collecting and analyzing data, for the post-lab work, and for the student presentations -- and this team approach seems to be working quite well so far this semester.

Note that considerable flexibility has been built into the course structure to accommodate the distance learner as well as the local on-campus student. Everyone will be encouraged to participate live in the actual lab sessions to interact with the session moderator, the reactor staff, and their fellow classmates, while observing actual real-time reactor behaviour. However, for those who cannot participate live, the full session and the reactor data are recorded and archived so that the asynchronous distance learner will have access to many of the same experiences and actual process data as those who actively participated during the actual lab. The post-lab student presentations and subsequent discussions are also recorded for the online student who cannot synchronously attend the session. However, each team, whether online or on-campus, will be expected to give at least one live presentation at the scheduled class time. Thus, everyone will be encouraged to actively participate, at some point, in these live sessions.

The web-based UMLRR Online application (see description below) and the live chat capability within the Blackboard Learn course management system are used for primary communication for all the in-class activities. The reactor control room and most of the classrooms at UMass-Lowell already have sufficient smart technology to accommodate web-based learning and communications and, for the online student to actively participate, they will only need to have routine web access and an inexpensive web-cam and microphone. Thus, the infrastructure needed to implement this course for both the on-campus and online student is already in place, with only modest computer and communications requirements placed on the individual student.

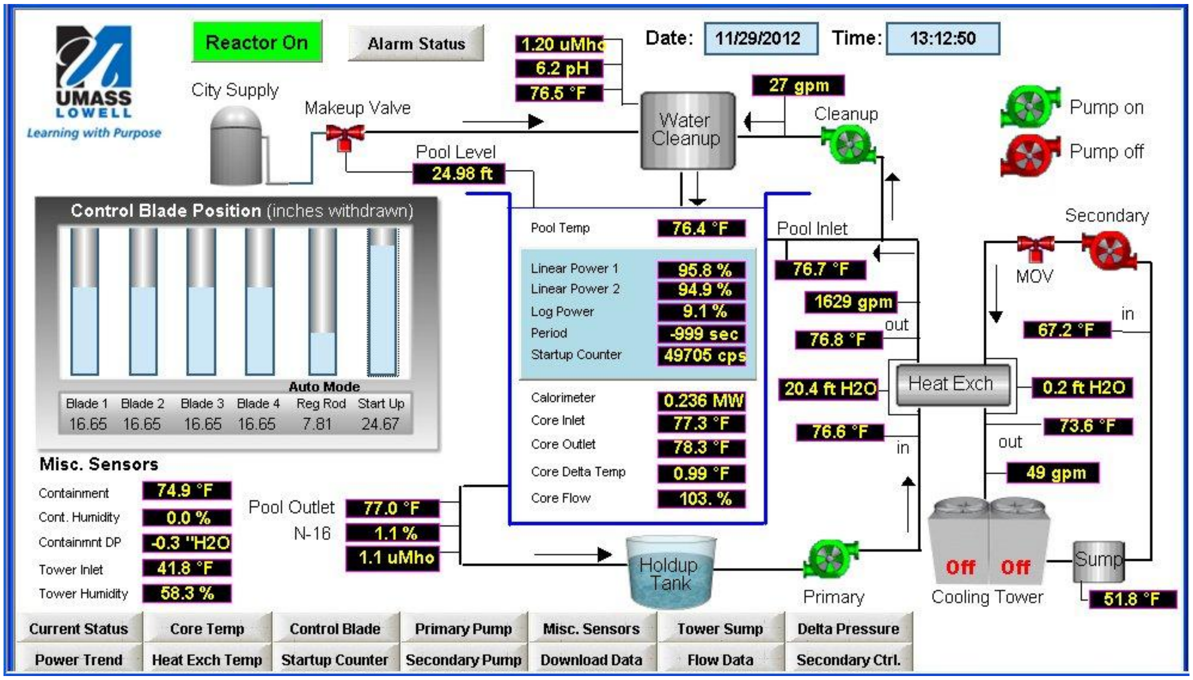
The Reactor, Online User Interface, and Offline Data Processing Tools

The UMass-Lowell research reactor (UMLRR) is a 1 MW pool-type research reactor with plate-type fuel that is moderated and cooled with demineralized water. The UMLRR core contains 21 fuel elements, each consisting of sixteen fuel plates with low-enriched uranium-silicide fuel as the meat material inside Al cladding. Control for the reactor is provided by four large control blades and one low-worth regulating rod for fine power/reactivity adjustment. Cooling for the UMLRR can be achieved by forced or natural convection. The data acquisition system for the UMLRR has a large number of sensors for neutron level, temperature and flow, pressure drop, on/off status, etc., that give a good indication of the overall system status on a continuous basis.

In particular, the UMLRR has a modern digital instrumentation and control system that fully integrates all sensor inputs and outputs for the facility through a proven industrial control system. Almost all the process variables within the UMLRR are available for real-time display, data trending, and archival storage. In addition, over the last several years, the UMass-Lowell Nuclear Program, in collaboration with the staff of the UMLRR, has developed a system for making this real-time and archived research reactor data available to educational users via a standard web browser. This capability is available online to facilitate various remote learning activities and training exercises via the nuclear101.com website and the UMLRR Online application. [1–3]

The remote accessibility was accomplished using a standard personal computer to act as a web server along with the use of a special purpose software package that receives data from the control room computers and then distributes it in a web-based format. This real-time web-based remote communications and control capability is made possible by InduSoft Web Studio (IWS), a supervisory control and data acquisition (SCADA) package donated to UMass-Lowell by InduSoft Ltd. [4] This software tool was used to create a series of screens that allow a remote user to observe most of the same real-time and historical information that is accessible to the reactor operators within the UMLRR control room. The main screen from a recent version of the UMLRR Online application is given in Fig. 1 and this illustrates the type of information available to the student and the layout of the general user interface -- where the buttons at the bottom of the screen open additional windows for displaying historical trends of the various process variables that are recorded.

In addition to the UMLRR Online interface, an offline data processing tool was also developed to assist in the visualization and analysis of the large amounts of recorded data from the reactor. This MATLAB-based GUI actually consists of two screens as shown in Fig. 2 -- with the window on the left showing the primary user interface with a plot of the information selected within the Plot Group menu, and the screen on the right showing the various sensor readings available for plotting within the given plot groups. In addition to the visualization capability, there are also several processing features built into the **umlrr_data** GUI such as a simple averaging capability, the ability to "magnitude adjust" the raw sensor data for power vs. time data into a smooth P(t) profile, an inverse kinetics routine to convert the P(t) data into reactivity vs. time, the capability to generate blade worth curves, and the ability to select only a portion of the data for plotting and for writing a separate data file containing only the information from the time period of interest -- and this capability is of particular interest for the more specialized processing tasks that may be needed for a particular lab exercise.



Date: 11/29/2012 Time: 13:12:50

1.20 uMho
6.2 pH
76.5 °F
27 gpm

Pool Level 24.98 ft

Control Blade Position (inches withdrawn)

Auto Mode

Blade 1	Blade 2	Blade 3	Blade 4	Reg Rod	Start Up
16.65	16.65	16.65	16.65	7.81	24.67

Misc. Sensors

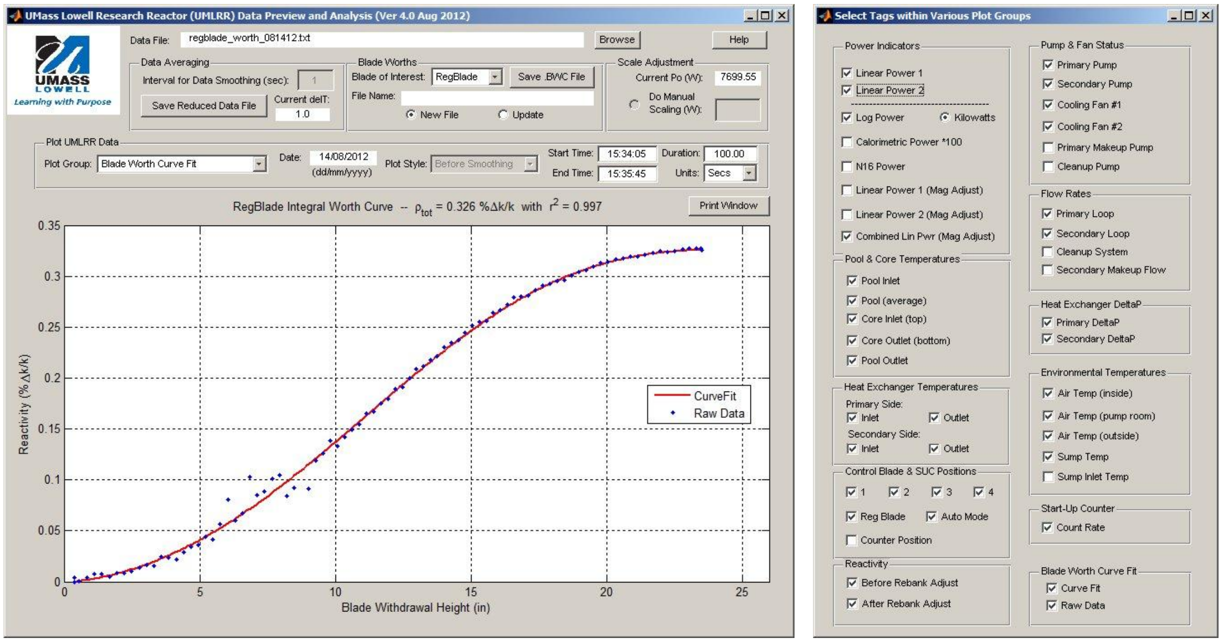
Containment	74.9 °F
Cont. Humidity	0.0 %
Containmnt DP	-0.3 "H2O
Tower Inlet	41.8 °F
Tower Humidity	58.3 %

Pool Outlet 77.0 °F
N-16 1.1 %
1.1 uMho

Pool Temp	76.4 °F
Linear Power 1	95.8 %
Linear Power 2	94.9 %
Log Power	9.1 %
Period	-999 sec
Startup Counter	49705 cps
Calorimeter	0.236 MW
Core Inlet	77.3 °F
Core Outlet	78.3 °F
Core Delta Temp	0.99 °F
Core Flow	103. %

Pool Inlet 76.7 °F
1629 gpm
76.8 °F
20.4 ft H2O
76.6 °F
67.2 °F
0.2 ft H2O
73.6 °F
49 gpm
51.8 °F

Fig. 1 Snapshot of the Current Status screen for the UMLRR Online application.



Data File: regblade_worth_081412.txt

Data Averaging
Interval for Data Smoothing (sec): 1
Current delT: 1.0

Blade Worths
Blade of Interest: RegBlade
File Name:
● New File ○ Update

Scale Adjustment
Current Po (W): 7699.55
○ Do Manual Scaling (W):

Plot UMLRR Data
Plot Group: Blade Worth Curve Fit
Date: 14/08/2012 (dd/mm/yyyy)
Plot Style: Before Smoothing
Start Time: 15:34:05
End Time: 15:35:45
Duration: 100.00
Units: Secs

RegBlade Integral Worth Curve -- ρ_{tot} = 0.326 %Δk/k with r^2 = 0.997

Power Indicators
☑ Linear Power 1
☑ Linear Power 2
☑ Log Power ● Kilowatts
☐ Calorimetric Power *100
☐ N16 Power
☐ Linear Power 1 (Mag Adjust)
☐ Linear Power 2 (Mag Adjust)
☑ Combined Lin Pwr (Mag Adjust)

Pool & Core Temperatures
☑ Pool Inlet
☑ Pool (average)
☑ Core Inlet (top)
☑ Core Outlet (bottom)
☑ Pool Outlet

Heat Exchanger Temperatures
Primary Side:
☑ Inlet ☑ Outlet
Secondary Side:
☑ Inlet ☑ Outlet

Control Blade & SUC Positions
☑ 1 ☑ 2 ☑ 3 ☑ 4
☑ Reg Blade ☑ Auto Mode
☐ Counter Position

Reactivity
☑ Before Rebank Adjust
☑ After Rebank Adjust

Pump & Fan Status
☑ Primary Pump
☑ Secondary Pump
☑ Cooling Fan #1
☑ Cooling Fan #2
☐ Primary Makeup Pump
☐ Cleanup Pump

Flow Rates
☑ Primary Loop
☑ Secondary Loop
☐ Cleanup System
☐ Secondary Makeup Flow

Heat Exchanger DeltaP
☑ Primary DeltaP
☑ Secondary DeltaP

Environmental Temperatures
☑ Air Temp (inside)
☑ Air Temp (pump room)
☑ Air Temp (outside)
☑ Sump Temp
☐ Sump Inlet Temp

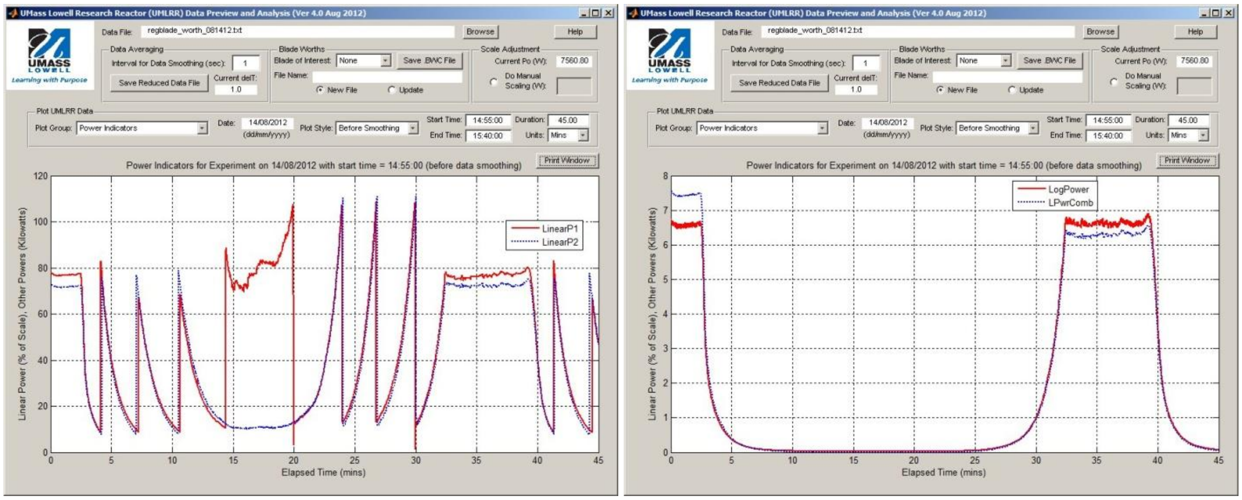
Start-Up Counter
☑ Count Rate

Blade Worth Curve Fit
☑ Curve Fit
☑ Raw Data

Fig. 2 Screen shots of the two user interface windows within the offline umlrr_data GUI.

As an illustration of some of this data analysis processing capability, Fig. 2 shows an example of a blade worth curve that was generated from data for a particular reactor sequence by processing the P(t) data through the inverse kinetics routine to generate ρ(t), correlating this with the available blade position information to create ρ(z) vs. z, and then doing a curve fit to the data to get the desired integral worth curve.

As another example, it should be noted that, in practice, the reactor operators utilize the auto-ranging Linear Power 1 and Linear Power 2 signals from a pair of compensated ion chambers (CIC detectors) as the primary signals to adjust the power level of the reactor during routine operation of the UMLRR. However, the raw detector signals are very difficult to interpret and to analyze quantitatively because they show "percent of scale" and auto-range whenever the power level changes by a factor of ten (either up or down). To remedy this issue, a "magnitude-adjust algorithm" was developed and implemented within the data processing GUI, as illustrated in the before and after power profiles displayed in Fig. 3. Clearly, the discontinuous behaviour of the auto-ranging detectors make it difficult to really visualize the transient power level but, after a little processing, the actual P(t) profiles become quite apparent. In the example shown here, the regulating blade is ramped in at about the 2 minute mark, then, after about 10 minutes, the system is brought back to a power level of between 6-7 kW, and the blade insertion process is repeated again at about 39 minutes into the experiment (with a different regulating blade speed this time). The purpose of this test experiment was to develop the regulating blade integral worth curve using inverse kinetics with two different blade insertion speeds (one of which is shown in Fig. 2) -- and clearly, the "Mag Adjust" capability within the data processing GUI made this test much easier to interpret.



Data File: regblade_worth_081412.txt
Interval for Data Smoothing (sec): 1
Current delT: 1.0
Blade of Interest: None
File Name:
● New File
Current Po (W): 7560.80
Plot Group: Power Indicators
Date: 14/08/2012
Plot Style: Before Smoothing
Start Time: 14:55:00
End Time: 15:40:00
Duration: 45.00
Units: Mins

Power Indicators for Experiment on 14/08/2012 with start time = 14:55:00 (before data smoothing)

Data File: regblade_worth_081412.txt
Interval for Data Smoothing (sec): 1
Current delT: 1.0
Blade of Interest: None
File Name:
● New File
Current Po (W): 7560.80
Plot Group: Power Indicators
Date: 14/08/2012
Plot Style: Before Smoothing
Start Time: 14:55:00
End Time: 15:40:00
Duration: 45.00
Units: Mins

Power Indicators for Experiment on 14/08/2012 with start time = 14:55:00 (before data smoothing)

Fig. 3 Screen shots showing the transient power levels before (left) and after (right) application of the magnitude-adjustment algorithm.
(the LPwrComb signal represents an average of the LinearP1 and LinearP2 sensor outputs and the LogPower signal is another measure of P(t) from a separate high power monitor that does not auto-scale)

Some Example Experiments

The long-term plan is to generate about ten different experiments for this course, of which only six labs would be run in any one semester. Probably 3 or 4 of the labs will become the foundation for every semester, but the additional modules will add some flexibility to cater to the needs/interests of the students in a particular class -- and also allow "mixing things up" a bit so that the course stays fresh from year to year. For the first offering in Spring 2013, the following six labs were used (only Labs 1-4 have been completed as of the date of this writing):

Lab #1: Understanding Subcritical Multiplication via an Approach to Critical Experiment
Lab #2: Reactivity Measurements Lab
Lab #3: Measuring Integral Blade Worths Curves within the UMLRR
Lab #4: Measuring and Interpreting Feedback Effects within the UMLRR -- Part I
Lab #5: Measuring and Interpreting Feedback Effects within the UMLRR -- Part 2
Lab #6: Comparing Calculated and Measured Axial Flux Profiles with the UMLRR

A significant amount of material has been generated for each of these labs (background theory, specific reactor procedures, sample MATLAB simulations, actual experimental data with post-lab analyses, etc.), but only a few illustrative results from Labs 1-4 will be given here.

Lab #1: Approach to Critical Experiment: The purpose of this experiment was to use the concept of the subcritical multiplication factor to predict the critical height of a control blade within the UMLRR. Performing an Approach to Critical experiment by plotting the traditional 1/M curves is an excellent means for illustrating the behaviour of subcritical systems, for highlighting the importance of the subcritical multiplication factor, and for showing how knowledge of the detector count rate in different configurations can give an experimental methodology for predicting when a system will reach the critical state. This procedure, using a control blade to approach critical, was used instead of the traditional critical loading of fuel assemblies, since it was much easier to accomplish, yet it still nicely illustrates all the same concepts of interest.

The experiment was performed on January 31, 2013 with Blade #3 as the blade of interest (BOI). The BOI was moved outward from its fully inserted location towards its critical position in a systematic fashion until the system was close to critical. Then, as a test of the prediction, the reactor staff were asked to take the system to just critical. The blade positions and the startup counter signal recorded during the experiment are shown on the left side of Fig. 4, and the 1/M plot generated from the count rate vs. position data is shown on the right side of the figure. The predicted critical height during the experiment was about 18.6 inches withdrawn and the actual critical height was about 18.9 inches out -- not a bad estimate!

Student response to this lab was good and, from their formal reports, it was clear that the lab was indeed successful in achieving its goals -- they actually did a very nice job here!

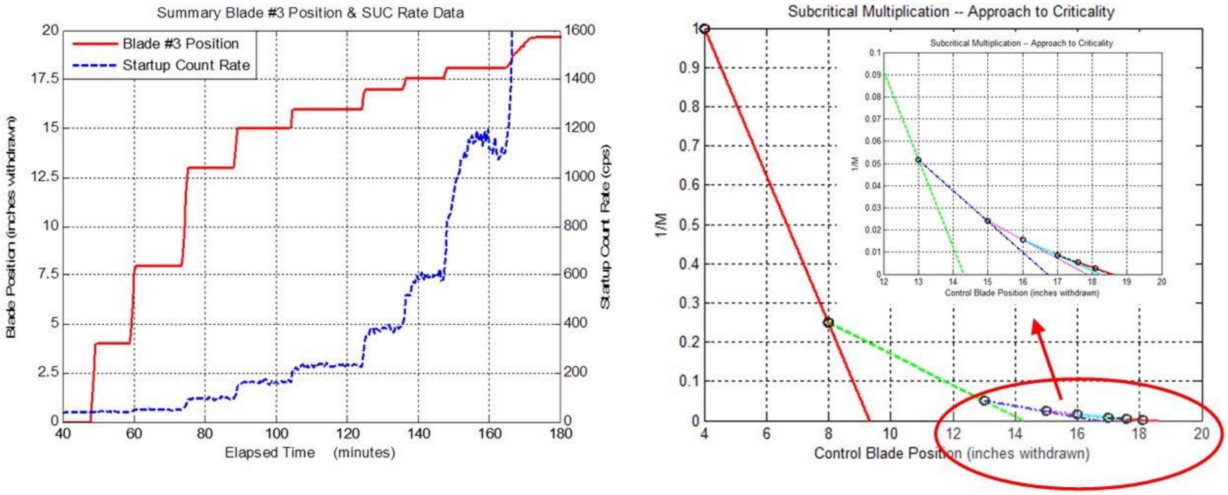
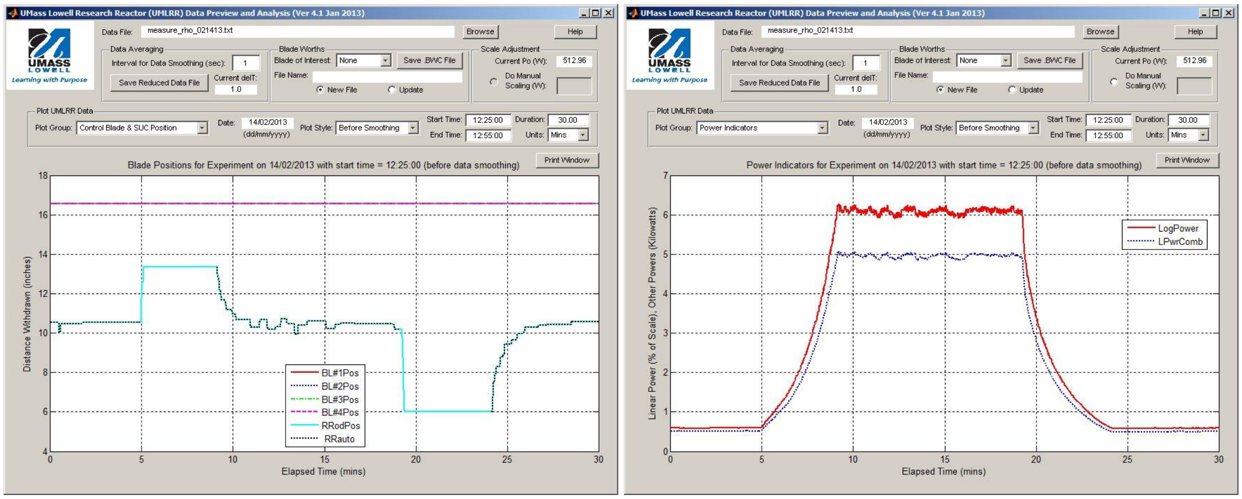


Fig. 4 Results from the Approach to Critical experiment.

Lab #2: Reactivity Measurements Lab: The goal of this lab was to become familiar with various techniques for measuring reactivity changes and reactivity levels within a variety of reactor configurations. This lab exercise addressed four different experimental techniques and showed that a combination of these methods will allow the measurement of a range of reactivity changes, $\Delta\rho$, during both critical and subcritical operations, as well as the determination of the absolute reactivity level, ρ_o, of a subcritical configuration. In particular, the Asymptotic Period Technique and Rod Drop Method were used within the context of measuring the magnitude of a reactivity insertion within a critical system, and the Source Jerk Method and Subcritical Multiplication Factor Approach were used for application within subcritical systems. Four separate reactor sequences or phases were performed during the lab, with each phase highlighting one of the four methods noted here.

For illustration purposes, only the asymptotic period (or stable period) method is discussed in further detail here. In particular, with the reactor at a low power critical condition with no source present, the regulating blade can be withdrawn a small amount to add positive reactivity to initiate a power increase. From analysis of the point kinetics equation (with no feedbacks), after a short transient time, the reactor power should increase as $P(t)/Po = e^{t/\tau}$, where τ is the stable reactor period. Thus, via observation of the P(t) profile, one can easily determine the reactor period and, with the reactivity equation or inhour equation [5], determine the amount of reactivity that was used to initiate the transient. This same approach can be used for small negative reactivity additions to the system.

This sequence of operations was performed on February 14, 2013 as Phase I of the full lab, and the resultant blade positions and power level vs. time profile are displayed in Fig. 5. Initially the blade is withdrawn a few inches to initiate the positive power transient and, after roughly 4.5 minutes, the blade is returned to auto mode to maintain the power level at roughly 5 kW. After a short time to allow the class to discuss the transient and to do some calculations, a similar negative reactivity perturbation was made. After about 5 minutes the power had reached its initial level of 500 W and the regulating blade was again returned to auto mode to stabilize the system. During the periods of positive and negative reactivity states, the observed power level increased and decreased, as expected, in a pure exponential fashion, and the "measured" reactivity values that were obtained agreed within about 5-7% of the values obtained from the available blade worth curves.



Data File: measure_rho_021413.txt
Interval for Data Smoothing (sec): 1
Current delT: 1.0
Blade of Interest: None
File Name:
● New File ○ Update
Current Po (W): 512.96
○ Do Manual Scaling (W):
Plot Group: Control Blade & SUC Position
Date: 14/02/2013 (dd/mm/yyyy)
Plot Style: Before Smoothing
Start Time: 12:25:00
End Time: 12:55:00
Duration: 30.00
Units: Mins

Data File: measure_rho_021413.txt
Interval for Data Smoothing (sec): 1
Current delT: 1.0
Blade of Interest: None
File Name:
● New File ○ Update
Current Po (W): 512.96
○ Do Manual Scaling (W):
Plot Group: Power Indicators
Date: 14/02/2013 (dd/mm/yyyy)
Plot Style: Before Smoothing
Start Time: 12:25:00
End Time: 12:55:00
Duration: 30.00
Units: Mins

Fig 5 Measured data used in illustrating the Stable Period Method for measuring $\Delta\rho$.

The other three portions of this experiment also gave generally expected results and the reactivity measurements as compared to the blade worth curves were quite good, except for the case of the Rod Drop Method (which had about 10-20% error). For this case, Blade 3 was dropped nearly instantaneously from about 16.6 inches withdrawn to its full insertion depth ($z = 0$). This caused a large prompt drop with an exponential decrease after the initial transient. However, the power detectors within the UMLRR for this scenario of events (i.e. a rapidly decreasing power level for an extended period) give a somewhat contaminated signal since the gamma background is decaying less rapidly than the neutron level. This issue with a corrupted power monitor signal due to gamma background had been observed previously [6], so the larger deviation obtained for this method was not a surprise.

Again, this lab was generally quite successful, with the measured data supporting the basic reactor theory, and the students coming away with a good appreciation for various reactivity measurement techniques and the tools and processes needed to analyze the results of the experiments.

Lab #3: Measuring Integral Blade Worths Curves within the UMLRR: The primary purpose of this experiment was to address three different methods for measuring blade worths curves within the UMass-Lowell research reactor, including the Stable Period Method, the Inverse Count Rate Method, and the Inverse Kinetics Method. However, since much of the theory and application of the first two methods were already addressed in the previous two labs, most of the focus was on the Inverse Kinetics Method (this was a new topic for all the students). In addition, some emphasis was placed on validating the simple point kinetics model (with no feedbacks) that had been used to illustrate the various reactor operations scenarios addressed thus far in the semester, and also to formally benchmark the recently-implemented Inverse Kinetics capability at UMass-Lowell [6]. This additional validation task was accomplished by comparing measured vs. actual $\rho(t)$ data for a specific operational transient sequence involving several movements of the regulating blade. Combined, the exercises performed here gave the students a good understanding of basic reactor kinetics (with no feedbacks) and the various techniques used for measuring the integral worth curves for a real reactor.

Again, because of limited space, no real details will be given here other than to show some summary results for the validation test, as can be seen in Fig. 6. For this reactor sequence, several movements of the regulating blade were made over a 30 minute timeframe. Several $P(t)$ signals and the blade position vs. time were recorded and, with the known blade worth curves, the actual $\rho(t)$ profile is known. Using this known $\rho(t)$, a simple point kinetics model generated the simulated $P(t)$ result, which is compared to the measured profiles on the left side of Fig. 6. Also, using the measured $P(t)$ data, inverse kinetics was used to obtain the measured $\rho(t)$ result, which is compared to the actual reactivity that caused the $P(t)$ transient on the right side of the figure. In both cases, the comparisons are quite good, showing that the point kinetics model is quite reasonable for simulating the $P(t)$ profile, and that the inverse kinetics method also does a good job at obtaining the reactivity in the system for low power operations (no feedbacks). Finally, we note that the erroneous "drift" in the reactivity results after about 30 minutes is due to the same gamma background issue with the power detectors as noted above. The conditions that caused this behaviour were planned as part of the overall test so that we could clearly demonstrate this gamma contamination issue. For general application, this situation is avoided since clearly the inverse kinetics result is unreliable under these conditions (rapidly decaying neutron levels from critical over extended periods).

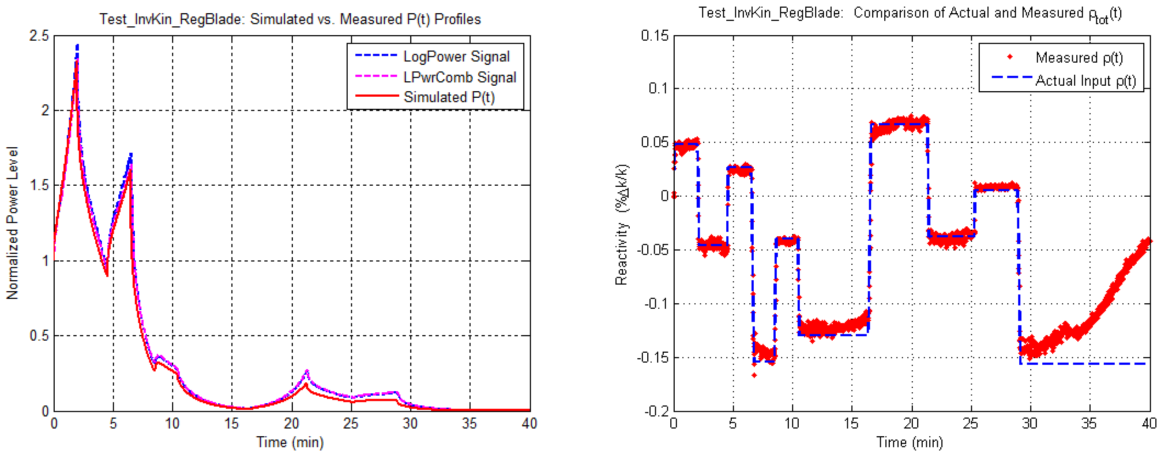


Fig. 6 Summary results from the validation tests performed as part of Lab #3.

Lab #4: Measuring and Interpreting Feedback Effects within the UMLRR -- Part I: The goal of this lab was to develop and validate a model to represent the inherent feedback effects within the UMLRR. In particular, all the lab exercises up to this point were performed at low power (or during subcritical operation) with the intent of minimizing the effects of the inherent temperature and xenon feedback effects on our reactivity measurements and our overall observations of feedback-free reactor dynamics. Now, for this lab, the feedback effects were the primary focus area, so all the reactor sequences studied highlighted one or more of the different feedback mechanisms that are inherent to all thermal reactor systems. Several reactor sequences were studied to help develop, rationalize, and quantify a proposed feedback model. Combined, the exercises performed here were designed give the student a good understanding of how to measure and model the various inherent feedback mechanisms and how they affect real reactor operations.

In January 2013 (before the start of the semester), two reactor runs were made to determine the total temperature coefficient within the UMLRR (fuel + coolant) and to validate a simple xenon reactivity model for the system. The data from these experiments were archived and analyzed as part of Lab #4 to help establish a working feedback model. In addition, since the UMLRR has no direct measurement of the fuel or in-core coolant temperatures, a simple quasi-steady state mathematical model was developed to estimate these temperatures versus power level under both forced and natural convection conditions. With these approximate relationships and the measured power vs. time data from the reactor, our goal was to estimate the various feedback components associated with a particular reactor sequence, where the total reactivity is given by

$$\rho_{tot}(t) = \rho_{ext}(t) - \alpha_{T_c}\left\{T_c(t) - T_c^{ref}\right\} - \alpha_{T_f}\left\{T_f(t) - T_f^{ref}\right\} + \rho_{Xe}(t) \tag{1}$$

Our first attempt at estimating the individual components and comparing the sum to the total measured reactivity (determined via inverse kinetics) showed that the fuel component was under predicted by a relatively large amount. The error noted here suggests that the product of $\alpha_{Tf}\Delta T_f$ is too low, which could be because of the estimated reactivity coefficient, or the estimated ΔT_f, or that both quantities are under predicted. Various possible "fixes" for this situation are currently being studied by the students -- so the best way to model this feedback is still a "work in progress". In one option, for example, the value of α_{Tf} was simply adjusted based on the empirical results, and then the "corrected" semi-empirical feedback model was used to predict the feedback components for a number of different scenarios.

The summary results from one reactor sequence with the reactor operating in forced flow mode are shown in Fig. 7. For this run, the reactor was initially critical at low power (about 5 kW). To start the transient, a positive reactivity perturbation was made by moving the regulating blade outward about 1.5 inches. At this point, no additional operator control was made, since the goal was to show that the inherent negative feedbacks in the system would automatically stabilize the reactor without operator intervention. As expected, after the initial reactivity perturbation, the increasing power level caused the core temperatures to increase and xenon started to build up. These two effects induced a negative feedback reactivity, which eventually compensated for the initial positive reactivity addition and even began to shutdown the reactor due to xenon poisoning.

The measured power profile from this run is shown on the left side of Fig. 7. The observed behaviour clearly followed the expected trend, where the power initially increased, peaked at about 400 kW, and then steadily declined due to the negative xenon reactivity that is building up with continued power operation. Much of the initial rise and leveling out at near 400 kW is due to the temperature feedback compensating for the initial positive reactivity insertion, and the decreasing power after about 50 minutes is primarily due to the xenon effect. Thus, this transient contains both feedback elements, with the temperature feedback being dominate in the early part of the transient and the xenon feedback controlling the response after the peak power has been reached.

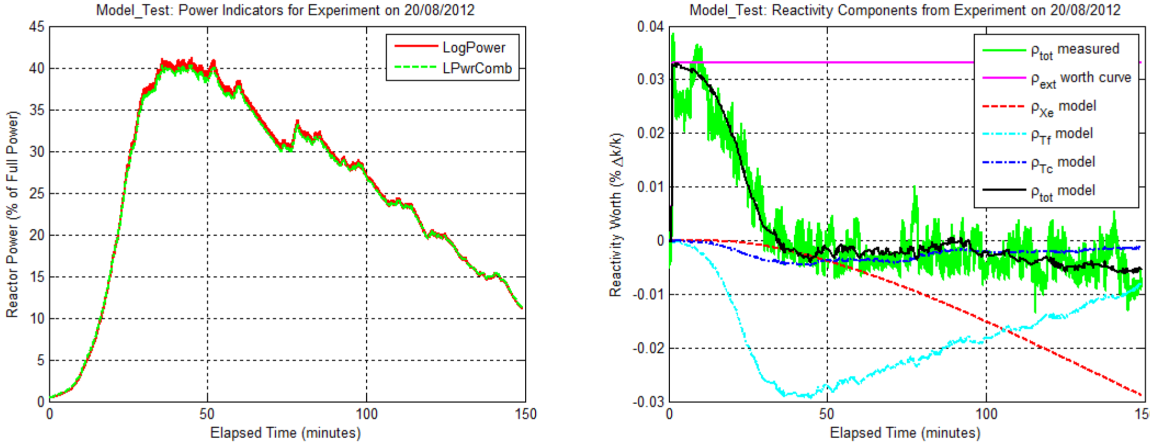


Fig. 7 Summary results from one test of the feedback model generated as part of Lab #4.

Now, the goal of the feedback model was to quantify the individual effects and to compare their sum to the total measured reactivity feedback. The measured result was obtained by passing the measured P(t) profile though the inverse kinetics routine. In contrast, the individual components, which are also based on the measured P(t), come from the semi-empirical feedback model developed as part of this lab exercise -- and the composite results for this case with an "adjusted" α_{Tf} value are shown on the right side of Fig. 7. Here we see that, as expected, the fuel temperature feedback dominates the early part of the transient to essentially cancel the initial positive external reactivity, ρ_{ext}, and, after 40-45 minutes into the experiment, the xenon feedback increases and the fuel temperature effect decreases to give a slowly varying negative total reactivity. Note that the coolant temperature feedback plays a relatively small role in this case because the large flow rate through the core for this forced flow case results in a relatively small coolant temperature change. Finally, comparing the predicted total feedback reactivity with the measured result shows good agreement throughout the transient for this case. Thus, it appears that the feedback model developed here can indeed be used to predict and interpret the feedback effects within the UMLRR. However, it should be emphasized that not all of the results obtained to date are as good as those shown in Fig. 7, so the "jury is still out" on how best to model the reactivity feedbacks within the UMLRR.

The Future...

Well, the above brief summary of the first four labs should give a good overview of the topics and the depth of coverage that are envisioned for the new Reactor Experiments course. As noted above, we plan to develop about ten experiments similar to those described above, but only six labs will be offered in any one semester. Note also that, once all the modules have been developed and tested, a focused 4 or 5-day short course that includes a subset of these experiments is also possible. The course uses real data from the UMass-Lowell research reactor (UMLRR) to solidify and expand upon many reactor theory, reactor operations, and reactor heat removal concepts and, through the comparison of simulation and experiment, many important and interesting phenomena can be highlighted. It is expected that the experience and insight gained from observing, analyzing, and explaining real data from an operating reactor in a variety of situations will make a more lasting impression on the student participants -- and the early feedback from the first offering of the course is quite positive so far.

With remote accessibility to the real-time and archived reactor data, and with the relative ease and low overhead associated with current web-based communications, the course is also being developed from the start with the remote user in mind. The original plan was to work out the course details during the first offering and then, in subsequent years, to provide the opportunity for students at other universities without access to a reactor facility to actively participate within the Reactor Experiments course at UMass-Lowell -- and this plan is progressing on schedule. Thus, the infrastructure needed to offer this course to both the on-campus and online student is already being testing, and we hope to have a good mix of both on and off-campus students engaged in this course the next time the course is given.

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