FACILITY HIGHLIGHTS AND REACTOR LABS AVAILABLE AT THE UMASS-LOWELL RESEARCH REACTOR

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Abstract

The University of Massachusetts Lowell Research Reactor (UMLRR) is a 1 MW, low-enriched MTR flat-plate pool-type research reactor. The UMLRR has seen many significant improvements over the last 10-15 years, including the conversion from HEU to LEU fuel, the implementation of a modern digital control and data acquisition system, and the development of the UMLRR Online application that provides web-based accessibility to real-time and archived reactor data for over 50 sensors throughout the UMLRR. In addition, a new Reactor Experiments course has been developed recently with support that utilizes the remote accessibility of the UMLRR to take full advantage of all the resources that the facility can offer. In particular, ten separate lab modules, along with several additional supporting experiments and data analysis tools, have been developed to provide a strong link between theory and practice, with a focus on reactor theory, reactor safety, and reactor operations.

This report briefly summarizes the facilities and overall capabilities of the UMLRR, and then highlights the procedures and key educational objectives that can be met from several of the lab modules that have been generated for the Reactor Experiments course. The availability of a formal internet-based reactor laboratory course and/or selected reactor laboratory modules for educational use via remote access at other universities and organizations is also summarized.

1. 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. [1-2] 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 and online accessibility to real-time and archived reactor data for over 50 sensors throughout the UMLRR. [3-4]

A laboratory-based Reactor Experiments course that uses the UMLRR and its remote access capabilities to illustrate, validate, and expand upon a mix of topics from reactor core physics, reactor operations, and energy removal considerations in nuclear systems has also recently been developed. [5] Typical experiments include an approach-to-critical lab, reactivity measurements, generation of blade worth curves, analysis of various reactor kinetics and dynamics scenarios (including temperature and xenon effects), measurement of temperature coefficients and axial flux profiles, analysis of loss of flow and other pump transients, etc. MATLAB [6] is used extensively for data analysis and for reactor simulation. Although the topical coverage within the new course is rather traditional in scope, the format and delivery take full advantage of the modern data acquisition 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.

This paper first highlights the facility upgrades and overall capabilities of the UMLRR and then details the procedures and key educational objectives that can be met from several of the lab modules that have been generated for the Reactor Experiments course. In particular, concerning the reactor laboratory modules, this report briefly summarizing the following items: the development of several tools that supported the delivery, data acquisition, and analysis portions of the course, the basic course structure, the objectives and some summary results from the ten lab sequences that were developed, and finally, a brief overview of our future plans for the reactor labs developed as part of this project. The summary of the ten reactor labs makes up the bulk of this report but, to keep the size manageable, only a few key results for each of the labs are given -- the goal being to highlight the basic subject under study and the nature of the results, experiences, and insights that can be gained for each of the lab sequences. The formal reactor procedures, student handouts, and detailed analyses of the individual labs are not given here. However, sufficient detail is provided so that the reader can gain a good understanding of the goals and key take-aways expected for each of the labs.

2. FACILITY OVERVIEW, THE CDAS, DATA PROCESSING TOOLS, ETC.

2.1. UMLRR FACILITY DESCRIPTION

The University of Massachusetts Lowell Research Reactor (UMLRR) is a water moderated and cooled, graphite-reflected, open-pool, plate-type research reactor that has been in operation since January 1975. The reactor is primarily used for general nuclear engineering and health physics training and to generate neutron and gamma ray particle fluxes for a wide range of research projects and for the support of a range of irradiation services offered to a variety of industrial partners. The reactor may operate up to a licensed maximum thermal power level 1 MW in forced flow mode, and up 100 kW in natural convection mode.

As illustrated in the sequence of geometry/layout figures given below (see Figs. 1-3), the UMLRR core contains a 9x7 grid of fuel assemblies, graphite reflector elements, radiation baskets, lead-void boxes, and corner posts. Each fuel element has rough dimensions of 7.62 cm × 7.62 cm × 99 cm (3” × 3” × 39”). The LEU assemblies contain low enriched uranium silicide fuel in 16 plates, with two end plates containing pure aluminum. The meat within an LEU fuel plate is an U_3Si_2-Al alloy. The U_3Si_2 contribution is about 67 wt% and the uranium is enriched to less than 20 wt% U235. Each plate contains about 12.5 g of U235 giving 200 g of U235 per assembly (the partial elements have half the U235 loading). [7-8]

The reactor facility offers a variety of experimental services including in-core radiation baskets, three beam tubes at the axial centerline of the core, a large graphite thermal column, and a large excore fast neutron irradiation facility. [9] Figure 1, in particular, contains a top-view sketch of the current UMLRR facility, which highlights the core in the centre, the three beam ports at the bottom of the figure, the graphite reflector on the right, and the general location of the fast neutron irradiator (FNI) grid and sample canister at the top. The specific layout for the current M-2-5 LEU core arrangement, including the beam ports and thermal column, is also shown in Fig. 2. This explicit core configuration contains 19 full fuel assemblies and 2 partial assemblies arranged roughly in the centre of the 9x7 grid. Directly in the middle of the core is a central irradiation zone known as the flux trap. The flux trap design is similar to a radiation basket, except that the region between the inner irradiation tube and the outer aluminum can is filled with graphite. In addition to the flux trap, the three radiation baskets just to the left of the fuel are used as sample holders for material irradiations, and the remaining baskets simply act as water reflectors. Filling out most of the remaining positions is a series of 7.62 cm × 7.62 (3” × 3”) graphite reflector elements.

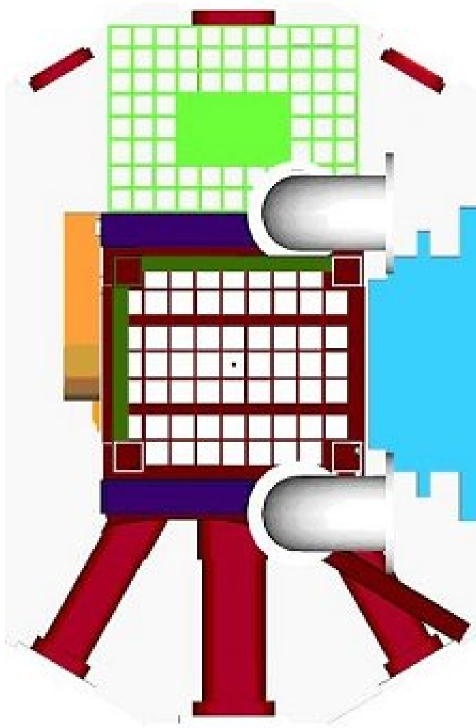


FIG. 1. Position of the core, beam tubes, thermal column, and FNI within the UMLRR. [9]

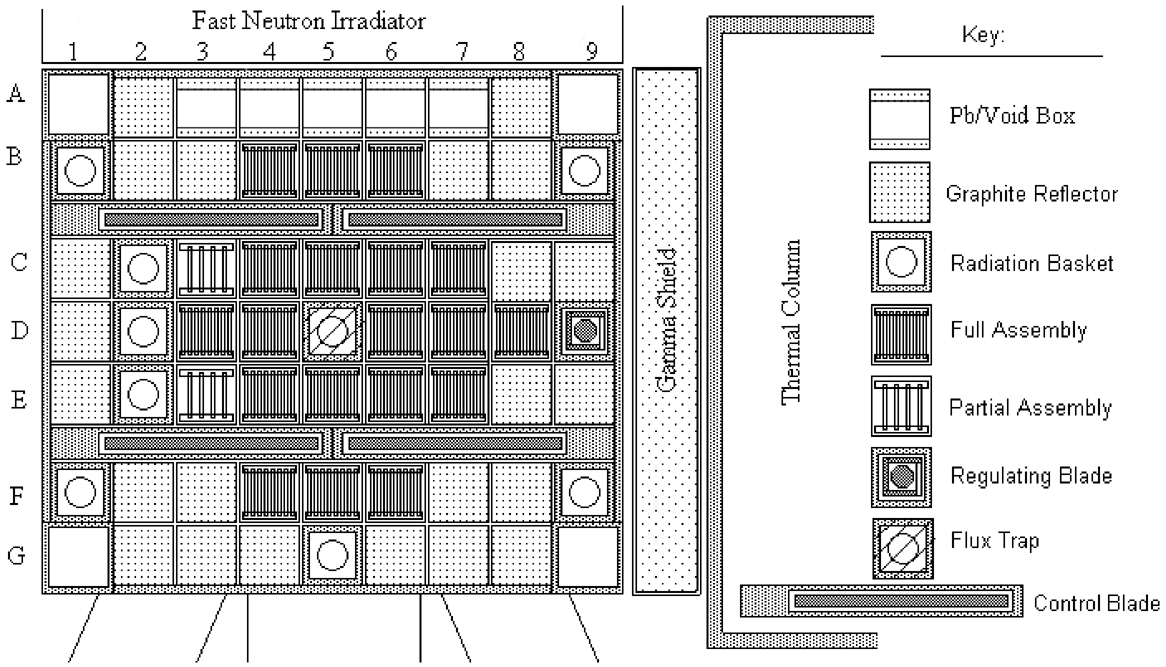


FIG. 2. Post-FNI core arrangement for the UMLRR (M-2-5 core). [9]

Note, however, that a new in-core element was designed as part of the complete FNI facility that contains about 1.27 cm (1/2 inch) of lead on either side of an air space. This in-core element is referred to as a lead-void box. It is about 74.7 cm (29 inches) long with a standard 7.62 cm × 7.62 cm (3” × 3”) square base so that it fits into any core grid position. Five of these elements were fabricated and inserted into the central five positions of row A within the core grid. This design feature provides about 2.5 cm of primary gamma shielding and it also tends to neutronically de-couple the core region from the remainder of the FNI facility. More importantly from the FNI perspective, however, is that these elements do not significantly decrease the fast neutron flux. [9]

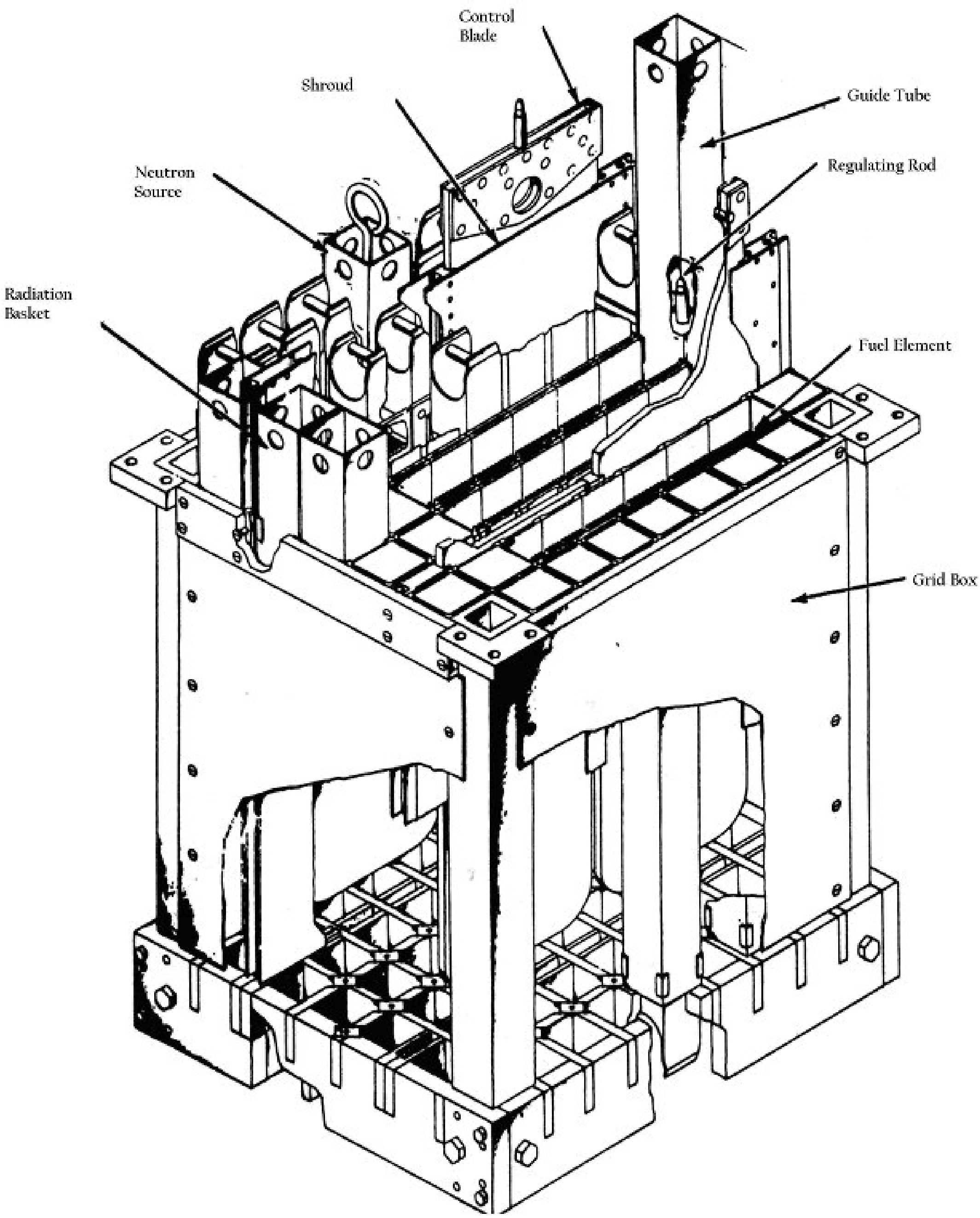


FIG. 3. General grid structure and individual core components for the UMLRR. [7]

The UMLRR core is suspended more than 7.62 m (25 feet) below the surface of a large pool. An aluminum grid plate and thin aluminum core box are part of the core support structure, as shown above in Fig. 3. As apparent, the individual core components can be arranged into many different configurations with this grid structure. The hollow corner posts at the four corners of the grid make up the physical supports that suspend the core from the reactor bridge, and they also house the four in-core neutron detectors within the facility that continuously monitor the neutron population in the core. The grid also has two locations reserved for an external neutron source for startup operations (location can vary), and a low-worth regulating blade (RegBlade) for fine reactivity control (located in grid position D9). Four large control blade assemblies are used for gross reactivity control and for flux shape adjustments. The reactor is surrounded by a large pool of demineralized water on the top and bottom and on three sides, with a lead shield and large graphite thermal column on the remaining side. A specific arrangement of fuel elements, graphite reflector blocks, radiation baskets, etc. make up a particular core configuration (see Fig. 2 for the current M-2-5 configuration).

During normal operation the reactor is located in the stall pool, adjacent to the thermal column and the beam ports, as shown in Fig. 4. When maintenance is required, the entire bridge and reactor can be moved to the bulk pool. If required, the bulk and stall pools can be physically separated by a gate and the stall pool can be drained to allow personnel access and maintenance as needed.

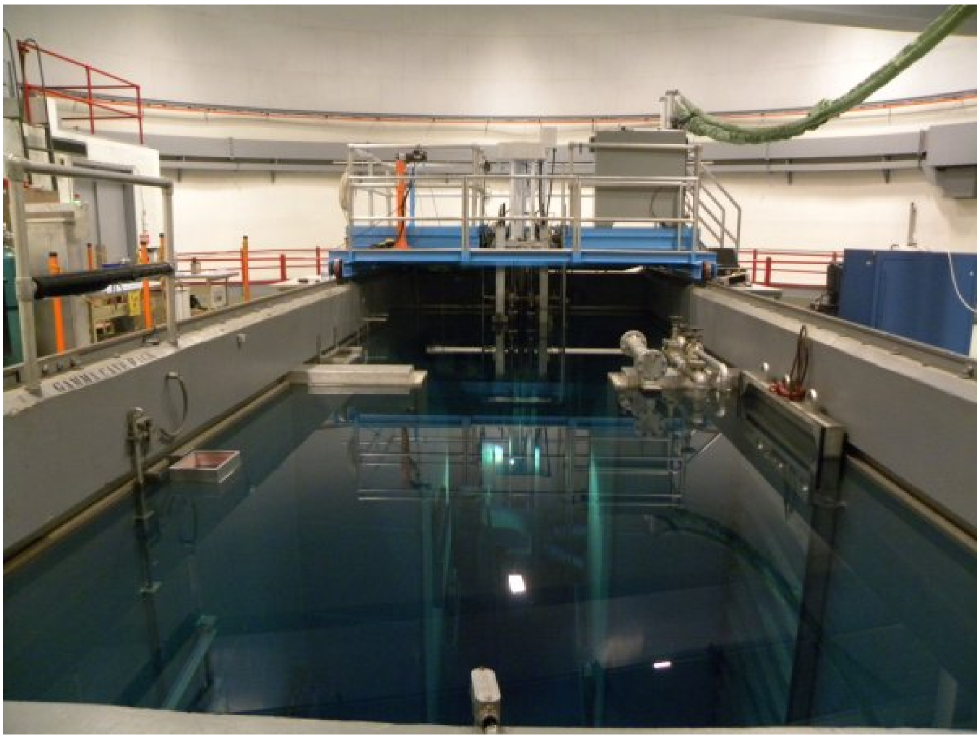


FIG. 4. View of pool surface, support bridge, and upper core support structure.

2.2. CONTROL AND DATA ACQUISITION SYSTEM

In the late 1990s, the U.S. Department of Energy initiated the University Reactor Instrumentation (URI) program. Funding from the program made it possible for U.S university research reactors to replace and upgrade reactor control and safety instrumentation, along with research instrumentation. In particular, in 2003, the UMLRR completed the third phase of three major control room digital upgrades that began in 1999. Phase-I included the installation of new radiation monitoring instrumentation and an upgrade of the area radiation monitoring system (ARMS) with a computer-based monitoring and control system. Phase-II involved the upgrade of the process controls system (controls for pumps, fans, etc.) to a computer-based system based on the same technology applied to the ARMS. For Phase III, the reactor control system was also upgraded with the same computer-based monitoring and controls technology used in the earlier upgrades. Since 2003, additional peripheral systems have also been upgraded with the same architecture, including the primary coolant water purification system and two research instrumentation stations. The digital systems implemented as part of these upgrades employ proven hardware and software developed for industrial automation, remote monitoring, and general data acquisition needs. The digital systems allow for distributed networking using Ethernet and the Internet Protocol (IP) communication and are very versatile and adaptable. All of the upgrades were done under the U.S. nuclear regulatory framework that allows for changes to be made which do not affect the original design bases or license technical specifications for the reactor.

The main elements of the UMLRR Control and Data Acquisition System (CDAS) now consists of four separate subsystems: the Process Control System (PCS), the Drive Control System (DCS), the Area Radiation Monitoring System (ARMS), and the Deionizer System (DIS). These systems use control and input/output hardware manufactured by OPTO 22, Inc. for process control, process monitoring, and data acquisition. [10] The software used to operate the system is an integrated suite of secure industrial control and automation software tools provided by OPTO 22. While designed primarily for manufacturing applications, the hardware and software are readily adapted to any function and are well suited to provide the status and control of UMLRR operations.

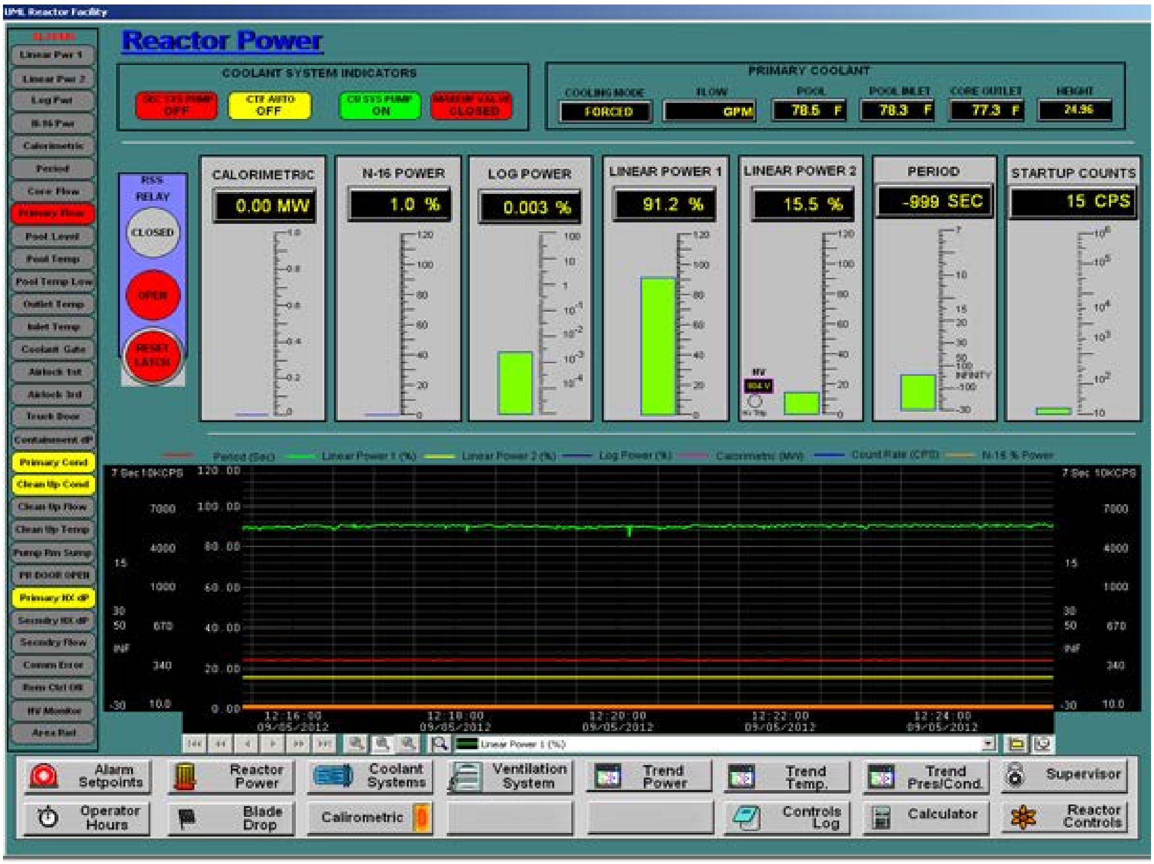


FIG. 5. PCS display showing various power measurements.

A series of personal computers with touch-screen displays connect to the CDAS controllers via an intranet Ethernet switch to provide human machine interfaces (HMI) in the UMLRR control room and at remote locations within the reactor building. The HMI display configurations are programmed using the OPTO 22 integrated software package to meet the individual needs of each application. With these interfaces the operator can view instrument readings, plot trends using real-time or historical data, and can view and acknowledge alarms. In particular, the PCS provides displays for power level indicators, various temperatures, flow rates, pressures, water purity, and on/off controls for various motors, valves, and fans, the ARMS provides displays for alarms and test functions for 25 radiation monitors, the DCS provides displays and controls for the reactor control blades, and the DIS provides display and control for the primary water conditioning system. Thus, with a single touch, a variety of essential operational information about the UMLRR is readily available. One example HMI display is shown above in Fig. 5 for the Process Control System (PCS).

2.3. REMOTE ACCESSIBILITY AND DATA PROCESSING TOOLS

In addition to the UMLRR's modern digital instrumentation and control system, 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. [3-4]

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 handled by InduSoft Web Studio (IWS), a supervisory control and data acquisition (SCADA) package donated to UMass-Lowell by InduSoft Ltd. [11] 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. 6 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 below in Fig. 7 -- 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 often of interest for the more specialized processing tasks that may be needed for a particular reactor laboratory exercise.

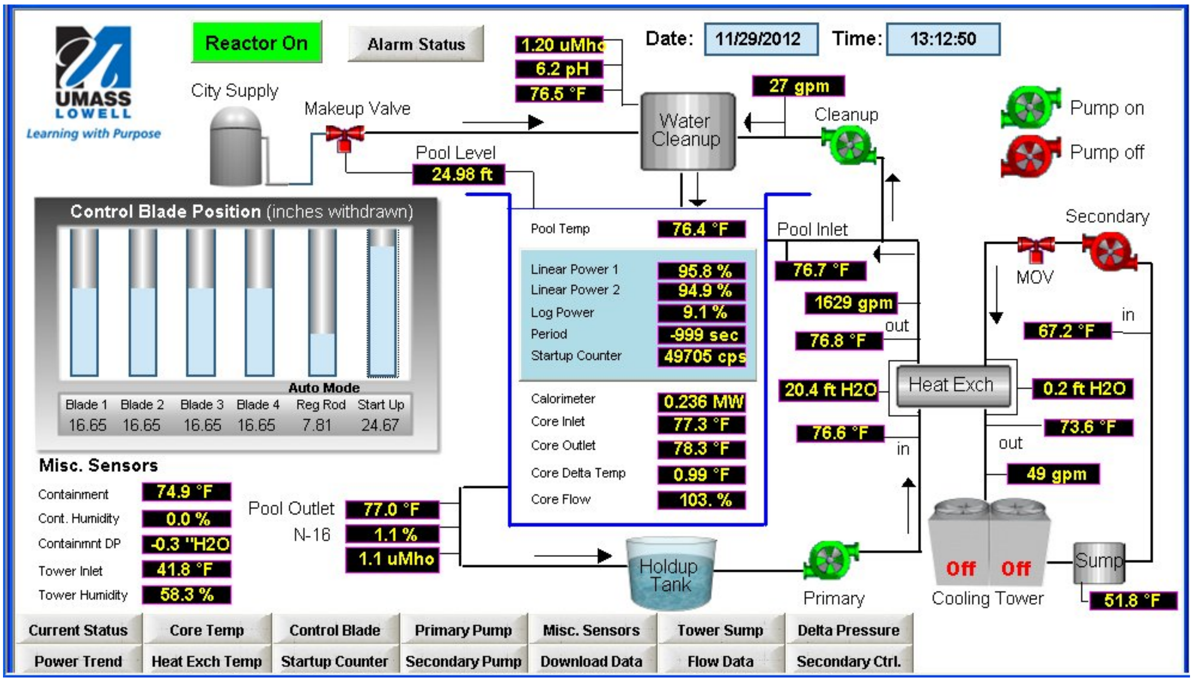


FIG. 6. Snapshot of the Current Status screen for the UMLRR Online application.

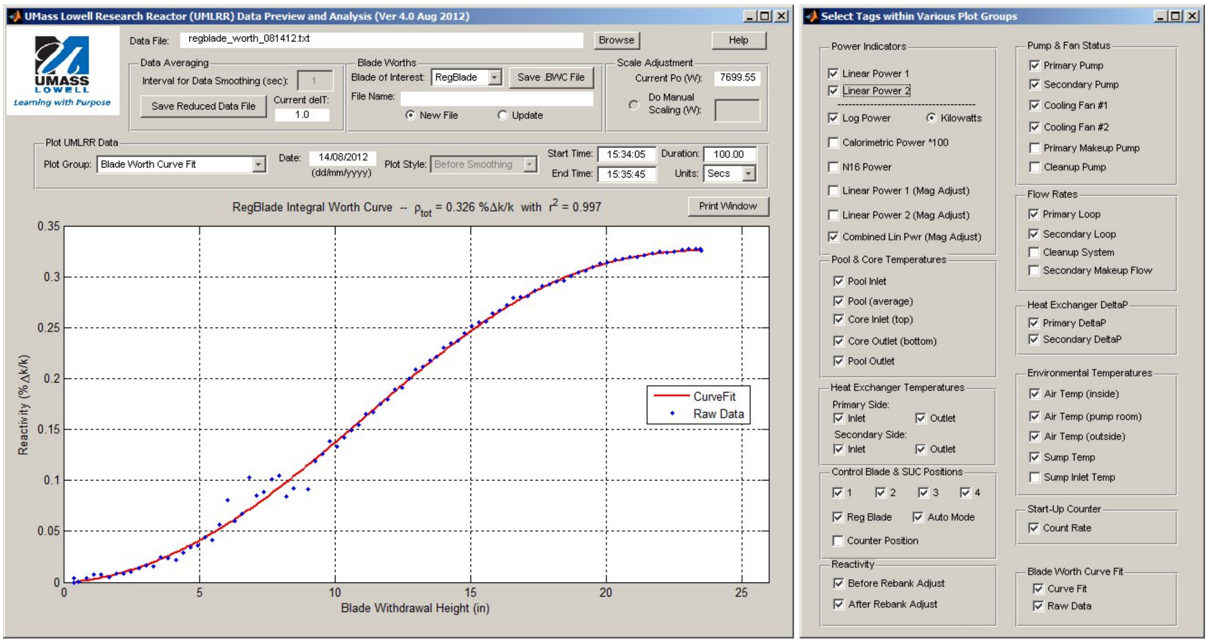


FIG. 7. Screen shots of the two user interface windows within the offline umlrr_data GUI.

As an illustration of some of this data analysis processing capability, Fig. 7 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 the reactor operators routinely 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 used to monitor the power level of the reactor during routine operation of the UMLRR. However, these 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 offline data processing GUI, as illustrated in the before and after power profiles displayed in Fig. 8. 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 (RegBlade) is ramped in at about the 2 minute mark then, after about 30 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. 7) -- and clearly, the "Mag Adjust" capability within the data processing GUI made this test much easier to interpret.

2.4. SIMPLE SIMULATION MODEL FOR THE UMLRR

In addition to the data processing and visualization tools noted above, a simple UMLRR core simulator was also developed to help support and explain several of the reactor labs that are performed at the facility. This relatively simple mathematical model of the UMLRR was constructed as part of the new Reactor Experiments course at UMass-Lowell (discussed in more detail below) to help the students (and instructor) plan several of the reactor runs and experiments and to help explain the various observations made as part of several of the labs. In particular, the reactor dynamics model consists of 11 coupled ordinary differential equations (ODEs) which are summarized in Fig. 9 (this figure was taken directly from a presentation given at the RRFM 2013 Conference [5]). As apparent, 7 equations are associated with the point kinetics equations, 2 equations are needed to model the average fuel and coolant temperatures within the system, and 2 equations are needed to simulate the I-Xe dynamics. A number of auxiliary coupling equations are also needed to interrelate the various reactivity effects, and several experiments were performed to determine the reactivity coefficients and the flux "correction factor, cf" that are needed for the simulation model.

Finally, we note that that a full thermal analysis model is also needed to estimate the overall heat transfer coefficients, U_{cc} and U_{fc}, for both forced and natural convection flow situations. The details of the UMLRR dynamics model are discussed as part of the theoretical background for several of the reactor experiments done as part of the Reactor Experiments course and the measured data from these labs are compared to the mathematical model as part of the post-lab activities. Overall this model proved to be a key part of the course as it was used extensively in the theoretical discussions, in the pre-lab planning phase, and in the post-lab comparisons -- and as a tool to help explain many of the observations made during the labs. In general, this MATLAB-based UMLRR core simulator has become an important educational resource within the Reactor Experiments course since it represents a bridge between theory and practice, and it integrates many of the key elements from reactor theory, reactor thermal hydraulics, and reactor operations to give a simple tool that can explain many of the observations made during operation of a real reactor.

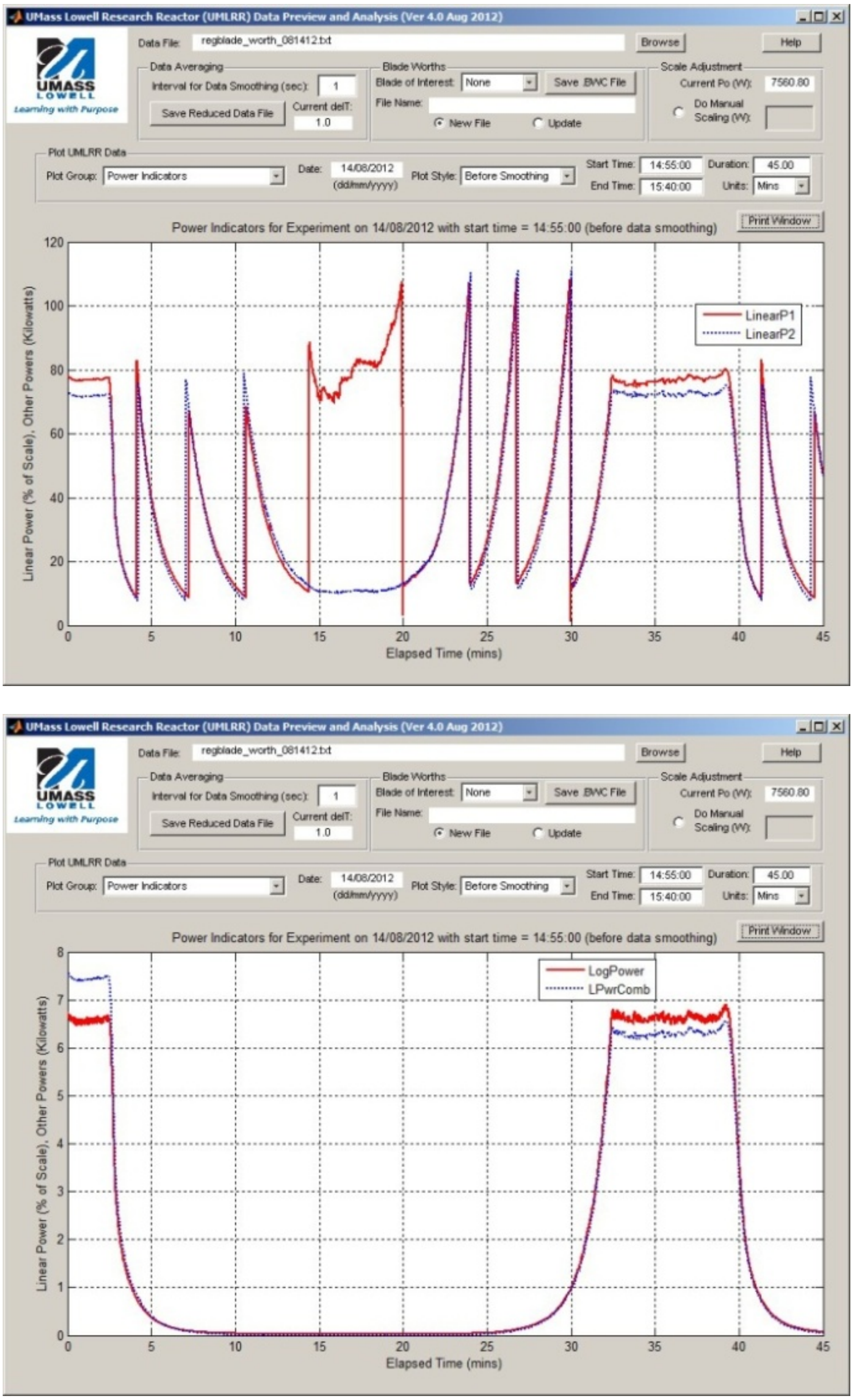


FIG. 8 Screen shots showing the transient power levels before (upper plot) and after (lower plot) application of the magnitude-adjustment algorithm.

(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)

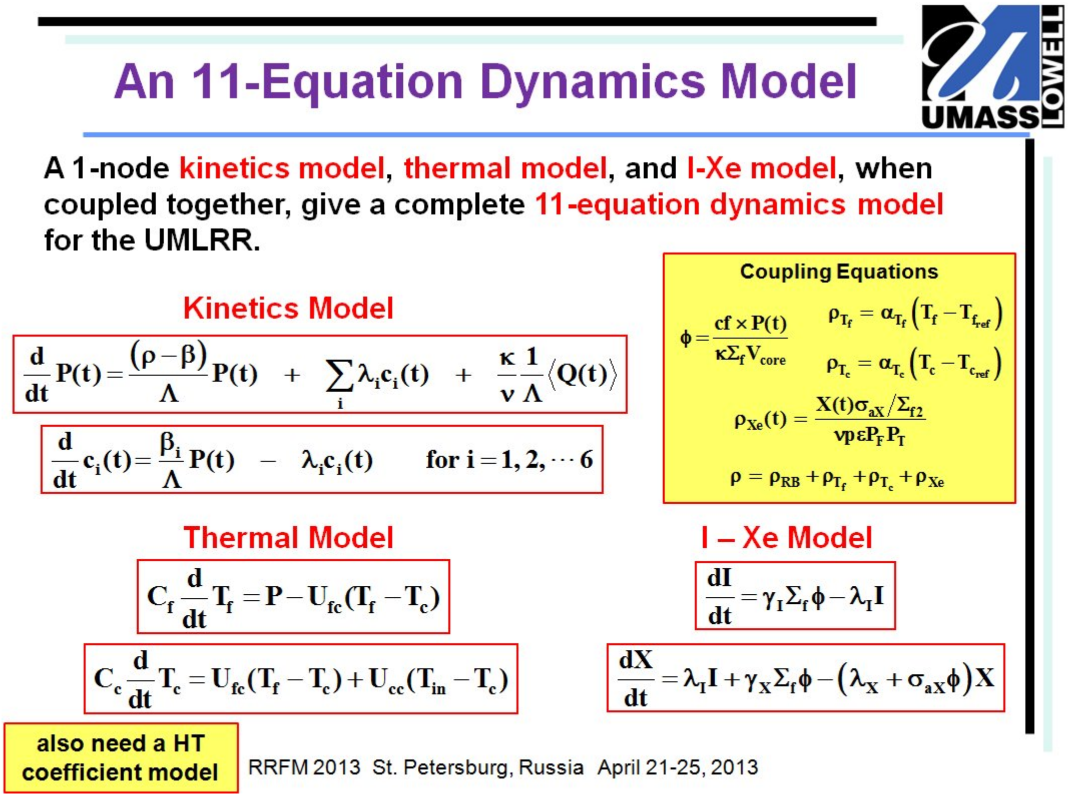


FIG. 9. Snapshot of the summary relationships for the UMLRR dynamics simulator. [5]

3. THE REACTOR EXPERIMENTS COURSE AT UMASS-LOWELL

3.1. 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 may be needed for a particular lab module. The experiments 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, the Reactor Experiments course is offered each year during the Spring semester (late January to early May), and each lab is an essentially autonomous educational module. Each lab module contains 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 current structure has six formal labs each semester. This assumes that 13 classes will be available 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 a conclusion 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.

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 is 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, is expected to give at least one live presentation at the scheduled class time. Thus, everyone is encouraged to actively participate, at some point, in these live sessions.

The web-based UMLRR Online application (see description above) and a live web-based conferencing tool (GoToMeeting [12]) 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 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.

Access to MATLAB [6] is also required since most of the post-processing and analysis of the collected data, and the UMLRR dynamics simulator, require the MATLAB software package, as well as a reasonable level of aptitude with using this tool (a whole series of sample simulations and data processing scripts are available, but the students usually will need to modify these illustrative examples to perform the required tasks for each lab). Thus, some prior familiarity within MATLAB is a prerequisite for this course.

3.2. THE TEN REACTOR LABS

Certainly the development and testing of the detailed procedures and the creation of course materials and exercises for ten different experiments for use within the UMLRR was the main focus of this work. This section of the report highlights a few key objectives and results from each of the labs, as listed below:

- Lab 1: Understanding Subcritical Multiplication via an Approach to Critical Experiment
- Lab 2: Reactivity Measurement Techniques
- Lab 3: Measuring Integral Blade Worth 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 within the UMLRR
- Lab 7: Quasi Steady State Energy Balance Lab
- Lab 8: Reactor Operations Demo
- Lab 9: Material Worth Measurements Lab
- Lab 10: Dynamic Modeling/Validation of the UMLRR Balance of Plant

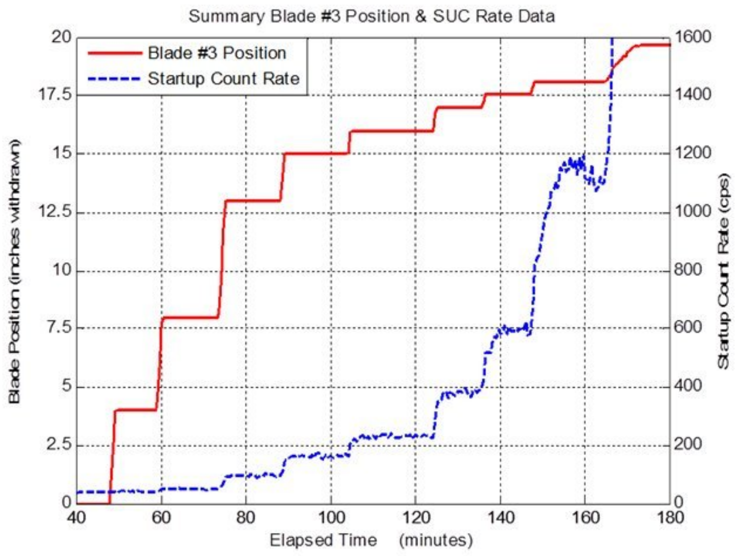
Since only six labs are given each semester, the extra labs allow some flexibility in changing up the course each year to keep it fresh and challenging for the students. To date, the course has been formally offered twice (Spring 2013 and Spring 2014), and many of the labs were also performed as part of the 2013 NEET program at UMass-Lowell [13]. Certainly as our experience grows, the details of the course materials, the reactor procedures, and the tasks requested of the students may change, based on both instructor and student feedback, but things are already starting to reach steady state for several of the labs that have been offered multiple times. The plan right now is to offer the first three labs and one of the feedback-effects labs as a base each time the course is taught, and then, for the last two labs in the course, to mix things up from year to year. For example, for the last two labs in Spring 2014 we focused on the use of 3-D computational models to predict various physics parameters for the UMLRR core (using the VENTURE code [14]) and we used Labs 6 and 9 to generate data to help understand and partially validate the model calculations. An alternate option, possibly for next year's class, would be to focus the last two labs on the study of the energy removal systems within the UMLRR with Labs 7 and 10, and this would take the last month of the semester down a completely different path. Thus, having ten labs available offers greater flexibility during the formal Reactor Experiments class, as well as more options for creating specialized short courses for focused audiences (such as was done for the NEET program in Summer 2013).

To better understand what is involved with the ten labs identified above, a brief synopsis for each of the labs follows:

Lab 1 -- Understanding Subcritical Multiplication via an Approach to Critical Experiment: The purpose of this experiment is 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, is used instead of the traditional critical loading of fuel assemblies [1-2, 15], since it is much easier to accomplish, yet it still nicely illustrates all the same concepts of interest.

As an example, a typical Approach to Critical lab using one of the control blades within the UMLRR 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 in the upper portion of Fig. 10, and the 1/M plot generated from the count rate vs. position data is shown in the lower portion of the figure. The predicted critical height during the experiment was about 18.6 inches withdrawn and the actual critical height was about 18.8 - 18.9 inches out -- not a bad estimate.

Student response to this lab has been quite good and, from their formal reports, it is clear that the lab is indeed successful in achieving its goals -- they actually have done a very nice job here!



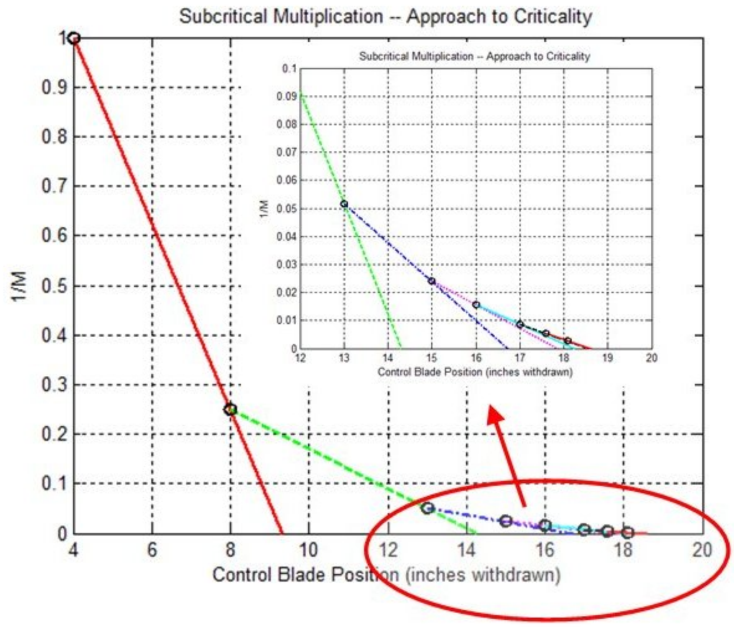


FIG. 10. Results from an Approach to Critical experiment performed in January 2013.

Lab 2 -- Reactivity Measurement Techniques: The goal of this lab is to become familiar with various techniques for measuring reactivity changes and reactivity levels within a variety of reactor configurations. This lab exercise addresses four different experimental techniques and shows 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 are 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 are used for application within subcritical systems. [16-17] Four separate reactor sequences or phases are 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 $P(t)/P_o = e^{t/\tau}$, 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, 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 from critical.

As an example, 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 profiles are displayed in Fig. 11. At about 5 minutes into the experiment, 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 5-6 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 RegBlade 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 nearly 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.

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 [18] in other transient low-power operations of the ULMRR, so the larger deviation obtained for this method was not a surprise.

Again, this lab is generally quite successful, with the measured data supporting the basic reactor theory discussed in the classroom, 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 is 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 are already addressed in the previous two labs, most of the focus is on the Inverse Kinetics Method (this is generally a new topic for most the students). In addition, some emphasis is placed on validating the simple point kinetics model (with no feedbacks) that is 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 [18]. This additional validation task is accomplished by comparing measured vs. actual $\rho(t)$ data for a specific operational sequence involving several movements of the RegBlade. Combined, the exercises performed here give the students a good understanding of feedback-free reactor kinetics and experience with several techniques used for measuring the integral worth curves for a real reactor.

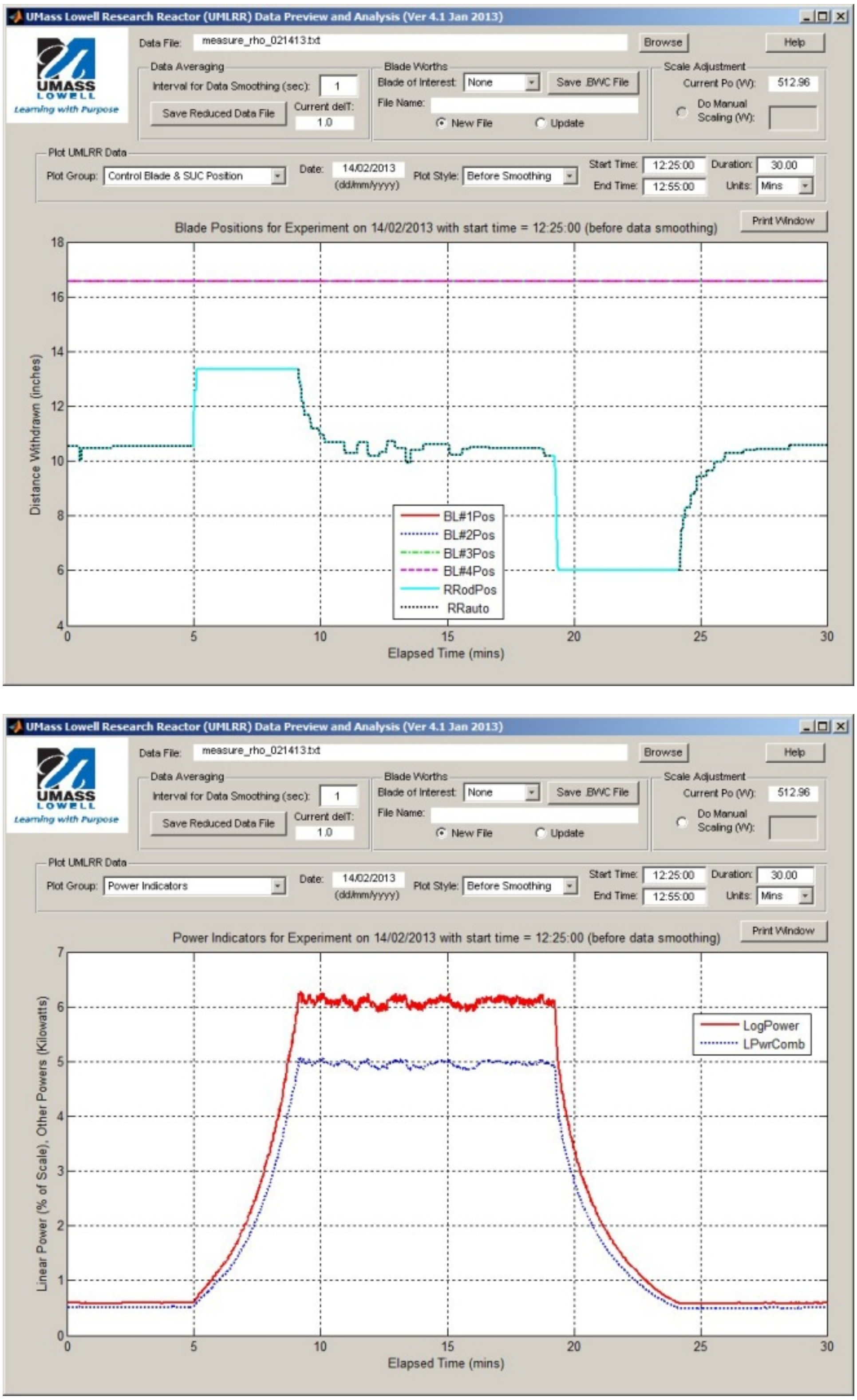


FIG. 11. Measured data used for illustrating the Stable Period Method for measuring $\Delta\rho$.

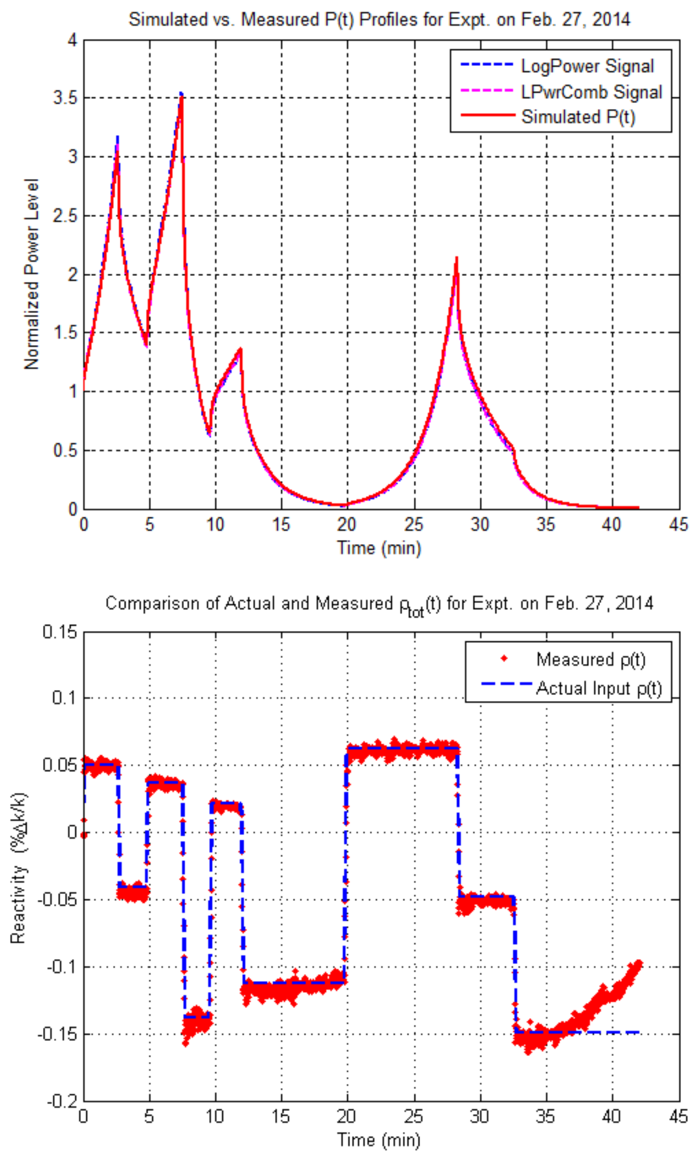


FIG. 12. Summary data from the validation tests performed as part of Lab 3 in Spring 2014.

Again, to be brief, we only show some summary results for the validation tests, as can be seen in Fig. 12 (note that a typical blade worth curve fit using Inverse Kinetics was already illustrated in Fig. 7). For this particular reactor sequence, several movements of the RegBlade were made over a 40-45 minute timeframe. Several P(t) signals and the blade position vs. time were recorded and, with the known blade worth curves, the actual ρ(t) profile is known. Using this known ρ(t), a simple point kinetics model generated the simulated P(t) result, which is compared to the measured profiles in the upper portion of Fig. 12. Also, using the measured P(t) data, inverse kinetics was used to obtain the measured ρ(t) result, which is compared to the actual reactivity that caused the P(t) transient in the lower part of the figure. In both cases, the comparisons are very good, showing that the point kinetics model is excellent 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 (i.e. no feedbacks). Finally, we note that the erroneous "drift" in the reactivity results after about 35 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, however, this situation is avoided since clearly the inverse kinetics result is unreliable under these conditions (rapidly decaying neutron levels from critical over extended periods).

Labs 4 and 5 -- Measuring and Interpreting Feedback Effects within the UMLRR: The goal of this set of labs is 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 are performed at low power (or during subcritical operation) with the intent of minimizing the effects of the inherent temperature and xenon feedback effects on the reactivity measurements and our overall observations of feedback-free reactor dynamics. Now, for this set of labs, the feedback effects are the primary focus area, so all the reactor sequences studied highlight one or more of the different feedback mechanisms that are inherent to all thermal reactor systems. Several reactor sequences are studied to help develop, rationalize, and quantify a proposed feedback model. Combined, the exercises performed here are designed to 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, 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 these experimental results are now routinely analyzed as part of the Feedback Effects Labs to help establish a working feedback model for the UMLRR. 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. [19] With these approximate relationships and the measured power vs. time data from the reactor, the goal for Lab 4 is to estimate the various feedback components associated with a particular reactor sequence, where the total reactivity is given by

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

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 suggested that the product of $\alpha_{Tf}\Delta T_f$ was 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 were discussed as part of the lab exercise -- and the best way to model this feedback is still a "work in progress". However, the option chosen for the current working UMLRR simulator model is simply to adjust the value of α_{Tf} based on the empirical results, and then use the "corrected" semi-empirical feedback model to predict the feedback components for a number of different scenarios. This semi-empirical model is what was built into the MATLAB-based UMLRR dynamics simulator.

Lab 5 takes the understanding and insight gained from the feedback model developed in Lab 4 one step further and uses the full 11-equation model (as discussed previously) to predict reactor behaviour under a variety of forced and natural convection flow situations. As an example, the summary results from two different reactor sequences that were run on March 13, 2014, one with the reactor operating in natural convection mode and the other for forced flow operation, are shown in Figs. 13 and 14, respectively. For both runs, the reactor was initially critical at low power (about 5 kW) with negligible xenon present in the system. At this point, 3 or 4 movements of the RegBlade are made, both outward and inward, to add small amounts of positive and negative reactivity as needed to generate a good test case. This test, in basic design, is similar to the one conducted as part of Lab 3 where we compared a feedback-free kinetics model to actual operation of the UMLRR. For Lab 5, however, the interval lengths between blade movements are usually longer than in the Lab 3 sequence, since now we need to give time for the feedbacks of interest to become significant.

For the natural convection case, both the fuel and coolant temperature feedbacks are important but, because the power levels are so low (< 100 kW), the xenon feedback is usually negligible for this mode of operation (at least for relatively short operational sequences). This is apparent in the measured and simulated reactivity profiles shown in the right half of Fig. 13. In this plot, the "green" measured reactivity and the "black" total simulated reactivity match fairly well, except for the first 15-20 minutes of operation after the initial RegBlade movement, where the simulated feedback reactivity generally under predicts the actual value (i.e. the green curve is below the black curve meaning that the simulated negative feedback is not subtracting enough from the positive insertion due to the RegBlade movement).

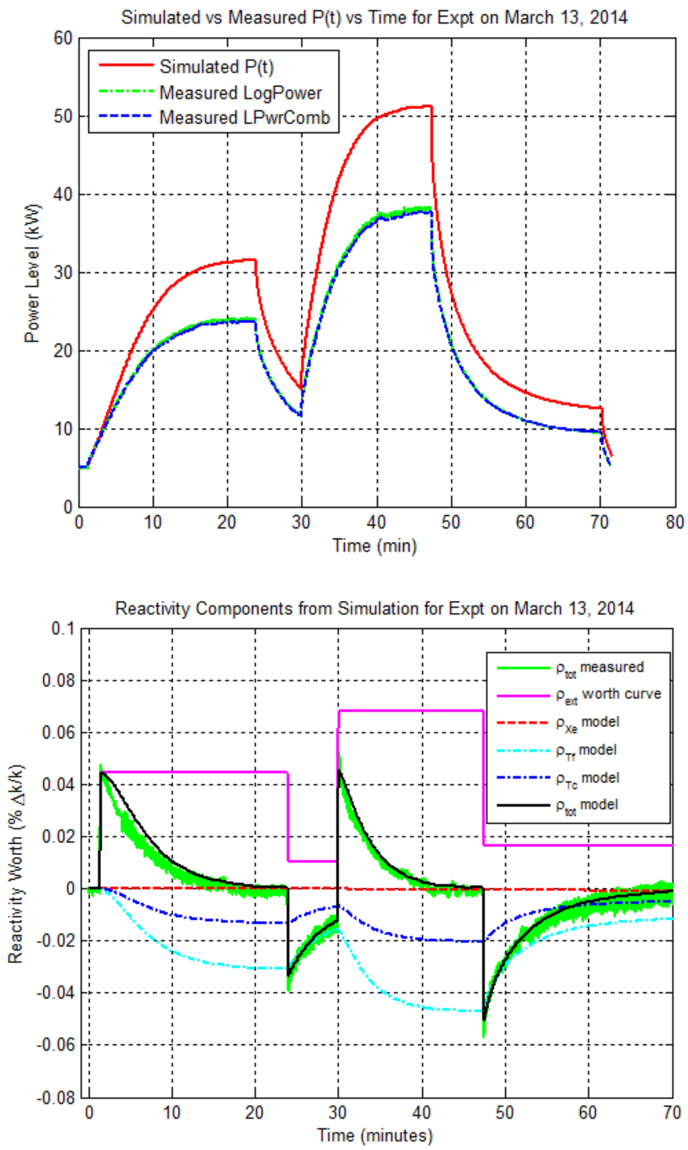


FIG. 13. Summary results from a natural convection test performed as part of Lab 5.

Unfortunately, this under prediction of the inherent feedbacks early in the transient has been observed for all the natural convection cases to date, and this is clearly the result of the steady state assumption associated with the flow model for this mode of operation. At present, the mathematical model [19] assumes that natural convection develops instantaneously for each new power level, which clearly is not the case. In particular, when increasing P(t), it can take several tens of seconds for steady state natural convection flow to develop in the physical system, so our assumption always over predicts the flow rate, under predicts the fuel temperature, and therefore, under estimates the corresponding negative reactivity feedback. This, in turn, causes the simulated powers to be over predicted as shown, for example, in the upper half of Fig. 13. This is a known limitation of the current UMLRR dynamics model when operated in natural convection mode, but it will take a bit of work to resolve this issue -- but this could indeed make a nice study for future offerings of this course!

For the forced flow case, the fuel temperature definitely dominates the reactivity feedback early in the reactor run but, after some operational time at higher power levels, xenon feedback starts to become important. This is apparent in the measured and simulated power profiles and reactivity profiles from the run made on March 13, 2014, as shown in Fig. 14. The observed P(t) behaviour clearly follows the expected trend, where the power initially increases due to the positive reactivity insertion associated with moving the RegBlade out a few inches. However, after about 20-25 minutes, the power peaks at about 700-800 kW because the negative fuel temperature feedback has caused the total reactivity to approach zero. At this point, a negative transient was initiated and, before a new equilibrium could be reached, another positive reactivity change was made (at about 28 minutes into the reactor sequence). After the RegBlade outward movement at about 28 minutes, all the blades were held fixed for a long period of time, yet the power, after peaking at about 700-780 kW for a second time, gradually decreases with time due primarily to the xenon feedback, which is now a significant fraction of the total feedback reactivity.

In addition to the P(t) profile, we also put a lot of emphasis on the $\rho(t)$ profile, and this is highlighted in the lower half of Fig. 14. The reactivity components, as obtained from the 11-equation dynamics model for the actual reactor run, are displayed and the overall comparison of calculated and measured total reactivity is quite good. Note that, as implied above, the coolant temperature feedback plays a relatively small role in this case, because the large flow rate through the core for all the forced flow cases results in a relatively small coolant temperature change.

Overall, except for a slightly faster drop off in P(t) after 45 minutes of operation, both the simulated power and reactivity curves compared quite favourably with the measured data (which has its own inherent uncertainty). Further study of this observed drop-off will also be something to consider in future Feedback Effects labs.

This set of labs has proved to be particularly instructive for the students where, in some cases, this was the first time they got a good appreciation for the safety associated with the negative temperature and xenon feedbacks that are an inherent part of all thermal reactor systems. With its emphasis on reactor safety, at least one of the Feedback Effects Labs will probably be run every time this course is taught -- since having a good understanding of reactivity feedbacks should be an essential outcome of every Nuclear Engineering Program in the world!

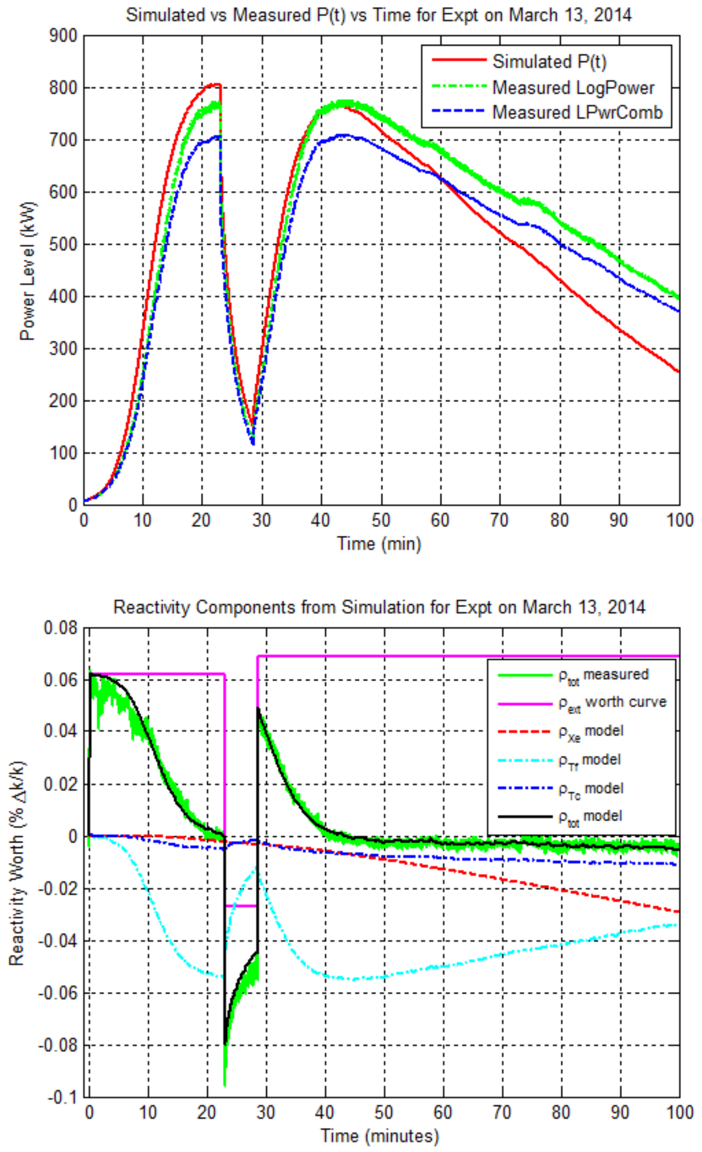


FIG. 14. Summary results from a forced flow test performed as part of Lab 5.

Lab 6 -- Comparing Calculated and Measured Axial Flux Profiles within the UMLRR: A new movable fission detector (MFD) was developed specifically for this lab. The device consists of a miniature fission detector at the end of a long cable placed in a dry aluminum tube which, in turn, can be placed in one of the radiation basket assemblies within the core. A vertical positioning drive assembly allows the detector to be moved axially within the dry tube so that the relative flux magnitude can be determined at several axial positions -- essentially allowing us to measure the axial flux shape in real time. The actual physical system was installed on the reactor bridge as shown in Fig. 15. The detector drive mechanism was integrated within the InduSoft Web Studio UMLRR Online application so that the detector movement can be controlled interactively by a remote user, which gives this lab a remote "hands-on" component -- which certainly makes the in-lab experience more enjoyable for the students (for most of the labs, the licensed reactor operators, who are in direct contact with the students via a web conferencing tool, do all the manipulations).

The goal of this experiment is to introduce some mathematical modeling into the new Reactor Experiments course and to emphasize the importance of validating the computer models with real experimental data. In particular, we currently have detailed 3-D models of the reactor using both deterministic and stochastic modeling tools (VENTURE [14] and MCNP [20], respectively), and these have been used extensively to support reactor operations and for training students in the use of these codes for several years now. [21] However, having real operational data to help further establish the credibility of these tools offers a new dimension that was not previously available. For example, as part of a typical lab exercise, the VENTURE code would be introduced in terms of its overall capabilities and limitations, and how it is used at UMass-Lowell within our local computational system. The students would first gain some fundamental experience with the code by putting together some relatively simple models and learn how to use some local pre- and post-processing tools for basic setup and analysis of the results of their calculations. The students are then introduced to the modeling philosophy and geometry details associated with the existing 3-D VENTURE model of the UMLRR, and asked to make some model changes to simulate different situations in the reactor, such as moving the control blades to simulate some specific reactor control configuration. And then, of course, they are asked to analyze and compare their VENTURE results to measured data from the reactor.

FIG. 15. Moveable flux detector vertical positioning system mounted on reactor bridge.

As a specific example, the relative axial flux profiles within the UMLRR core were measured with the MFD in position C2 for two different control blade configurations during a test on July 13, 2013 (see Fig. 2 for a view of the current core layout and the row-column notation used to specify the assembly position in the core). Since grid position C2 is close to Blade #2, this control element was used to cause a significant change in the axial flux profile in the vicinity of the control blade to clearly distinguish the two cases, where the goal of the experiment was to qualitatively compare the axial profiles for the two cases -- as well as to use the measured data to help further benchmark the existing computational models of the UMLRR. The actual blade positions recorded during the experiments with the movable fission detector (MFD) in C2 are given in Table 1 and, with MCNP, these location were modeled explicitly. However, since the VENTURE computational model only allows discrete axial positioning of the blades due to the fixed 19-layer model that is currently implemented, the closest position was selected for the VENTURE runs, and these are also given in the table (note that the blade position is given in "inches withdrawn" since this is the convention used by the UMLRR operators).

TABLE 1. CONTROL LOCATIONS FOR THE C2 AXIAL FLUX PROFILE EXPERIMENTS IN JULY 2013

Case #	Blade	Experiment/MCNP (inches out)	VENTURE (inches out)
1	Blades 1, 3, 4	16.5	16.0
	Blade 2	17.2	17.2
	RegBlade	10.5	11.3
2	Blades 1, 3, 4	19.4	18.4
	Blade 2	9.0	8.96
	RegBlade	10.5	11.3

Since the MFD current output has not been calibrated to correspond to a specific absolute flux level, the best we can do is to focus on the relative axial profiles, not the actual flux level. As such, the 3-D VENTURE model operating at 1 MW was selected as reference and the MCNP results and measured MFD currents at the peak location were made to agree with the VENTURE value, and the resultant normalization factor was then used to adjust the full thermal flux profiles accordingly. Thus, we are only comparing the axial profiles here, not the actual magnitude of the fluxes! Note that the actual test cases were run at a power level of about 80 kW, but everything given here is normalized to the licensed power of 1 MW.

Summary results from the C2 tests in July 2013 are given in Figs. 16 and 17. In both cases the computed vs. measured axial flux profiles are similar, and the MCNP vs. VENTURE comparisons also show good agreement (although there was some difference in the flux magnitudes). In addition, the effect of the control blade location on the local flux profile is abundantly clear where, for the C2 tests, it is obvious that the thermal flux in the vicinity of Blade #2 will be more bottom-peaked as the local control blade is inserted farther into the core. Also, the absolute value of the flux at the test site is noticeably lower for the case with the blade inserted farther into the core.

In general, these observations match well with expectations and they reinforce the basic theory discussed in class concerning the shape of the thermal flux profile in the vicinity of control material. As noted above, as an integral part of the lab, the students are asked to modify the existing in-house computer models to correspond to the given blade configurations, thereby getting a little experience with several aspects of computer modeling. The experience gained in this exercise in comparing the model results with measured data is critical, since it emphasizes the importance of model validation and benchmarking. Overall, this lab is quite straightforward to run and it is very informative -- both as a simple demonstration that discusses typical axial profiles within various configurations, and as a modeling and benchmarking activity for teaching the use of both deterministic and Monte Carlo simulation tools. In addition, the students seem to really enjoy the actual in-lab experience since they get to remotely control the vertical positioning of the MFD -- thus, this lab generally represents a positive experience from several perspectives.

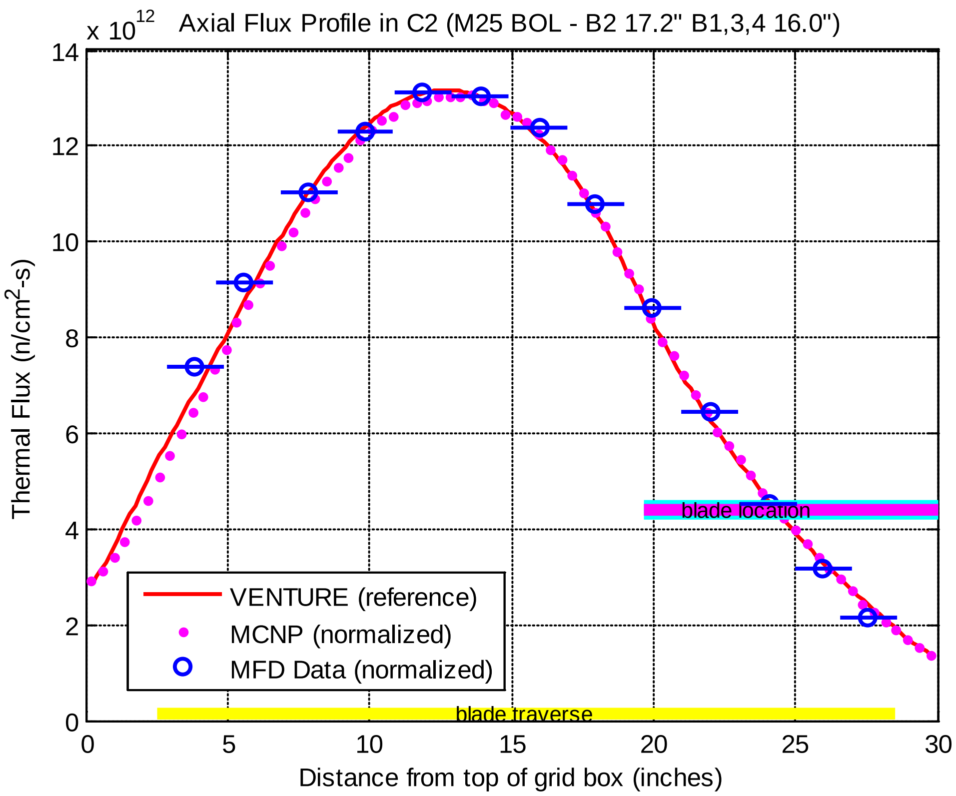


FIG. 16. Axial flux profiles in location C2 with Blade 2 at 17.2 inches out (July 2013).

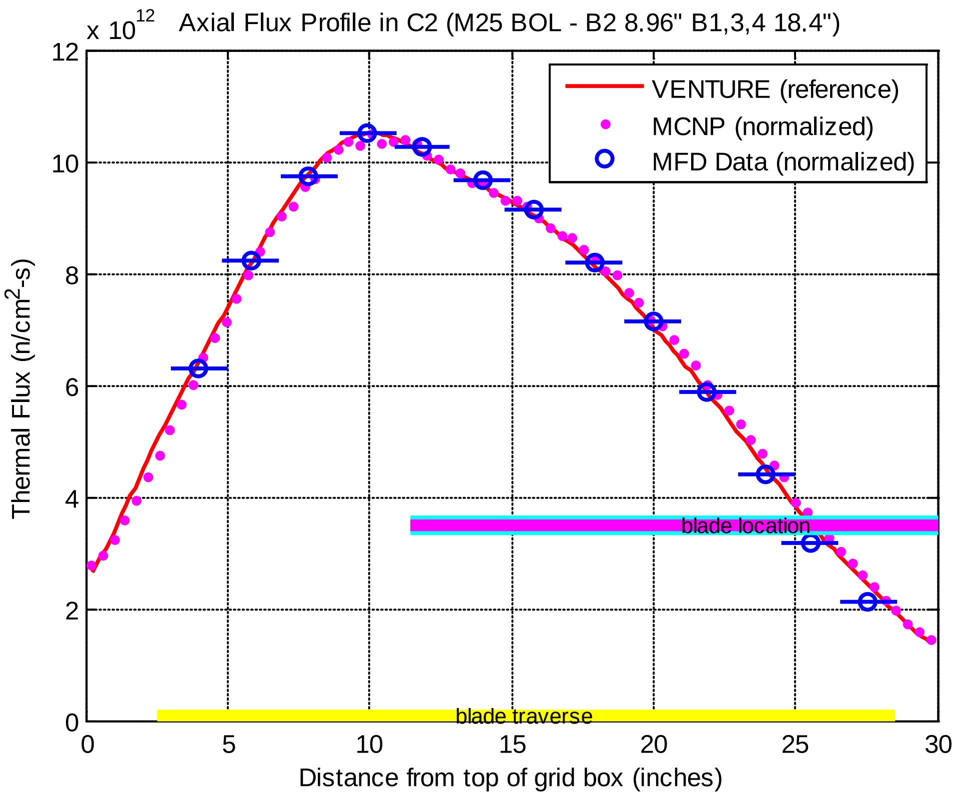


FIG. 17. Axial flux profiles in location C2 with Blade 2 at 9.0 inches out (July 2013).

Lab 7 -- Quasi Steady State Energy Balance Lab: In this lab the concept of steady-state energy balances is reinforced by running the reactor for several hours at constant power with different levels of cooling -- this is done simply by varying the on/off status of the secondary pumps and fans or by adjusting the motor-operated control valve (MOV) within the secondary loop. The students are asked to record temperature and flow data for the core, pool, and heat exchanger at various times and to verify the quasi steady-state energy balance relationships that are derived for these particular systems. This lab is appropriate for both undergraduate and graduate students, depending on the level of discussion associated with the various components within the UMLRR cooling system. For example, in a introductory class, one could simply focus on the steady state energy balances in typical power generation and energy conversion systems but, for a graduate class, one could expand the scope to include a detailed steady-state analysis of the shell and tube heat exchanger, the cooling tower, etc. In the past we have run this experiment as a simple demonstration lab for undergraduates [22] but, with more details and focus on the function and performance of individual components, we can also use this lab as part of the graduate Reactor Experiments course.

After a brief overview of the key energy removal components and specific plant layout for the UMLRR as illustrated in the sketch in Fig. 18, the students are given some basic information about the facility (power level, pool volume, coolant flow rates, etc.) and they are asked to do a set of pre-lab preliminary calculations that highlight some simple energy balance concepts (i.e. energy storage capacity, core ΔT, pool heat-up rate, etc.). During the live lab, the students again get to remotely turn on/off the secondary side cooling components and observe actual reactor operation using the web-based UMLRR Online application, they record various flow rates and temperature measurements for a variety of operating conditions, and then they use these to validate the series of quasi steady-state energy balance relationships developed and discussed in the pre-lab lecture. Worksheets are given for the pre-lab and in-lab calculations to help guide the analyses and to focus the post-lab discussions.

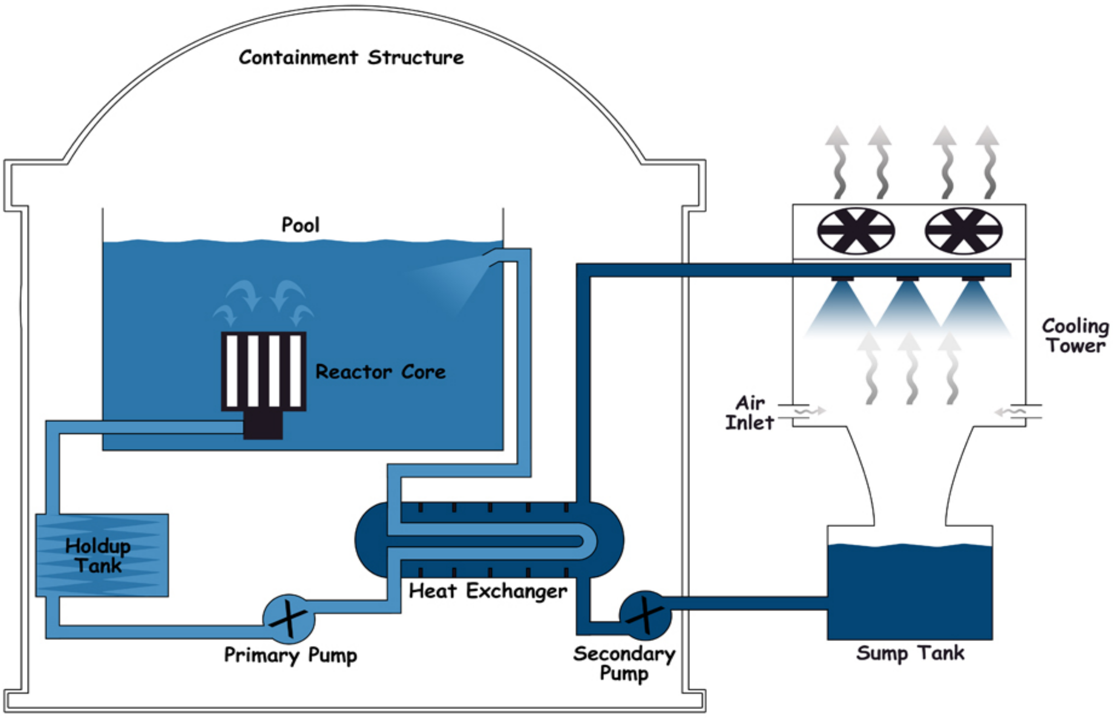


FIG. 18. UMLRR schematic highlighting the primary and secondary cooling mechanisms.

One problem with this experiment is that it cannot be performed during the summer months because of the hot outside environmental temperatures (where the "cool" outside air temperature is often greater than the inside core temperatures). Usually this is not an issue since the lab is often run in the early to late spring timeframe (February-April). However, as was done in Summer 2013 for the NEET program [13], we can easily use archived data to perform the desired energy balance calculations during a summer session -- and the discussion associated with why the experiment is not performed live during the summer is also quite instructive in itself.

As an example, an overview slide used during the pre-lab discussions, and the actual pool, core, and heat exchanger temperature data used in the lab exercise performed in Summer 2013 for the NEET students are shown in Figs. 19-21. The data here clearly show the four different cooling regimes that were established, and the quasi steady state quantitative data obtained from the recorded temperatures do indeed approximately validate the expected energy balance relationships. Note here that the "quasi steady state" regions are when all the temperatures are changing approximately linearly at the same rate. Also, we note that the energy balances are only "approximately" validated because of the uncertainty that is associated with the thermocouple readings and the relatively small ΔT values that are observed within the UMLRR. Overall, however, this lab is quite instructive, with the students leaving with a much better understanding of the basic energy balance concepts that were the focus of this lab.

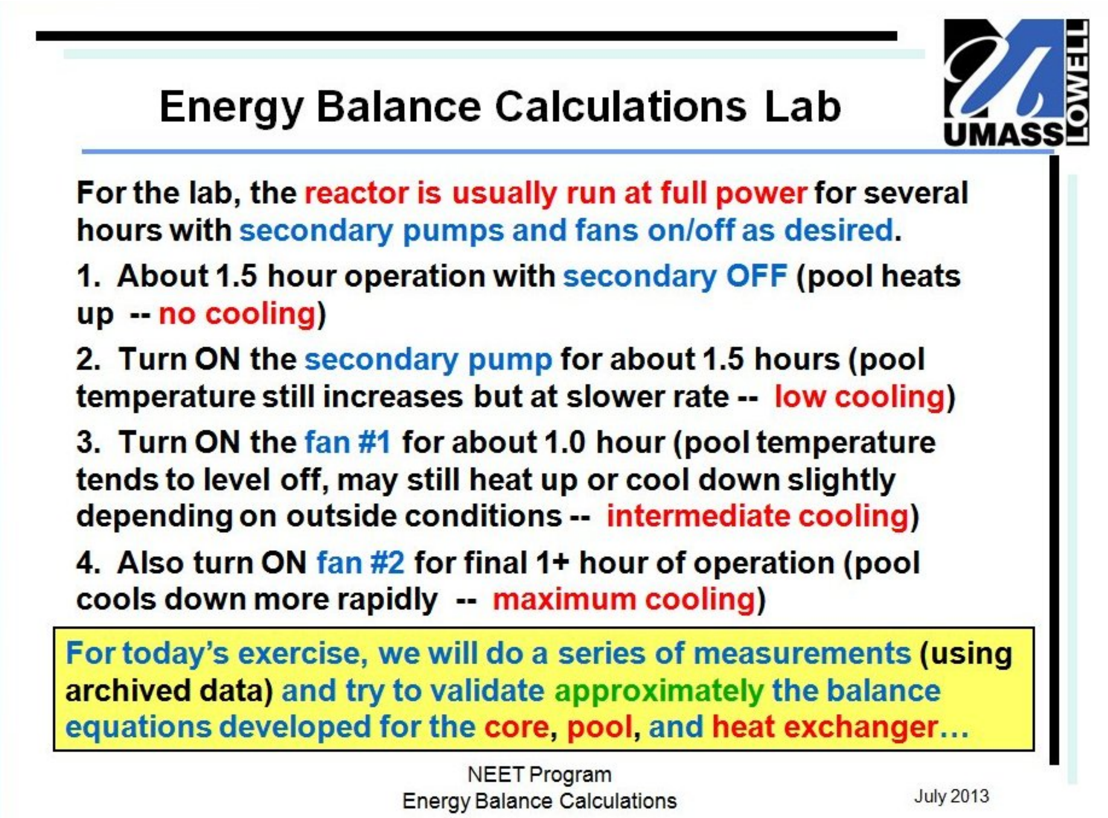


FIG. 19. Typical sequence of operations for the Energy Balance Lab.

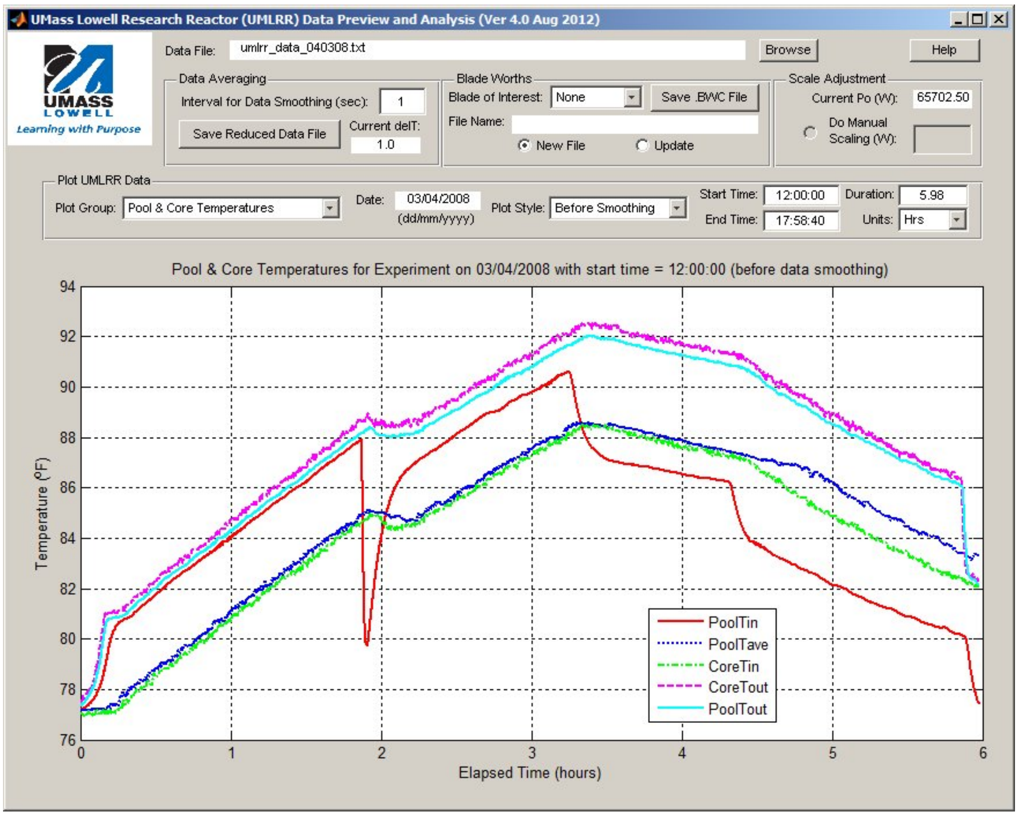


FIG. 20. Selected pool and core temperatures during the experiment of April 3, 2008.

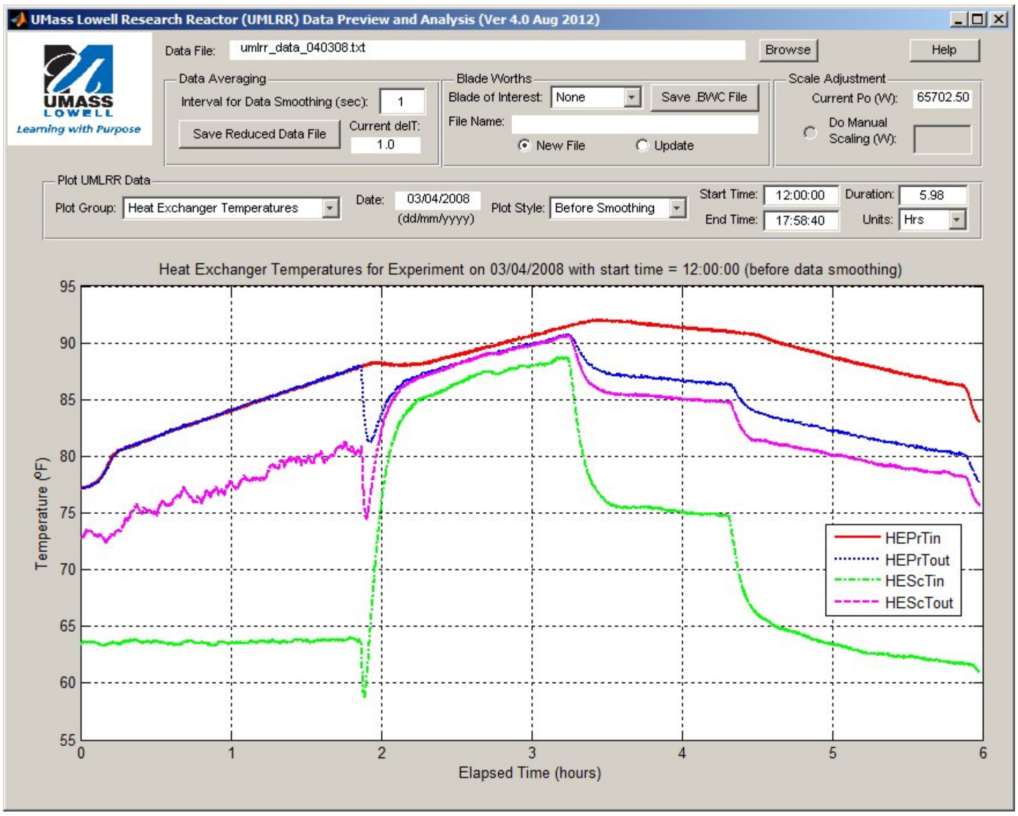


FIG. 21. Heat exchanger temperatures during the lab of April 3, 2008.

Lab 8 -- Reactor Operations Demo: This lab was designed to reinforce several reactor kinetics concepts that are usually discussed in some detail in a normal lecture class. Although this subject is usually discussed quite thoroughly in our basic reactor theory course, experience has shown that the students really don't fully appreciate many of the key concepts until they have had an opportunity to experience them first hand. Thus, the Reactor Operations Demo was designed to give this direct experience within a real operating reactor. As currently configured, it involves a sequence of several reactor transients that illustrate both positive and negative reactivity changes, a discussion/demonstration of "auto mode" vs. "manual mode" operations of the UMLRR regulating blade, a loss of flow transient in both auto and manual mode, and the initiation of a cold water insertion transient (i.e. a pump-on transient). These operational transients demonstrate many important reactor kinetics concepts, including the importance of negative temperature feedback and the inherent stability associated with the UMLRR design.

As an example, this lab was performed in July 2013 using the NEET students as the audience/participants (23 undergraduate students from Saudi Arabia) and it worked great! Selected data from the actual reactor run are presented in Figs. 22-24 to illustrate the observations made during the lab. There were seven individual demonstrations that made up the complete lab experience, and these are listed below. In addition, the timing for each portion of the full lab is indicated on the plots of power vs. time, blade position vs. time, and core "inlet" and "outlet" temperature vs. time:

Demo #1: Negative Reactivity Insertion
Demo #2: Positive Reactivity Insertion
Demo #3: Negative Reactivity Insertion again
Demo #4: Illustration of Auto Control
Demo #5: Pump-Off Transient (transition from forced to natural convection flow)
Demo #6: Pump-On Transient (cold water insertion)
Demo #7: Pump-Off Transient when in Manual Mode

A detailed explanation of each demo is not given here -- but it should be emphasized that each demo worked exactly as expected and, combined, this set of seven demos represent a pretty powerful illustration of several key concepts from the fields of reactor kinetics and reactor operations and control. And the last three tests also nicely emphasize the inherent safety associated with the negative temperature feedbacks within the UMLRR! These demos certainly made for some interesting and educational discussions with the NEET students, and a similar sequence of operational scenarios is often performed after discussing reactor kinetics within our regular UMass-Lowell reactor theory classes (to reinforce the theoretical concepts discussed in the lecture).

Finally, it should be noted that this basic lab sequence is appropriate for both undergraduate and graduate student audiences. As executed for the undergraduate NEET students in Summer 2013, it is simply a powerful demonstration of the basic theory discussed in the lectures on reactor kinetics. However, if the students were asked to do quantitative simulations for some of the measured transients, then it could easily become a challenging modeling exercise that fits in nicely with the theme of the other modules within the Reactor Experiments course (note that pieces of this lab are already included within Labs 2, 4, and 5, but within a somewhat different context). Thus, depending on the particular emphasis, this basic lab sequence can be easily incorporated into several instructional modules with the Nuclear Engineering (NE) curriculum at UMass-Lowell at both the undergraduate and graduate levels.

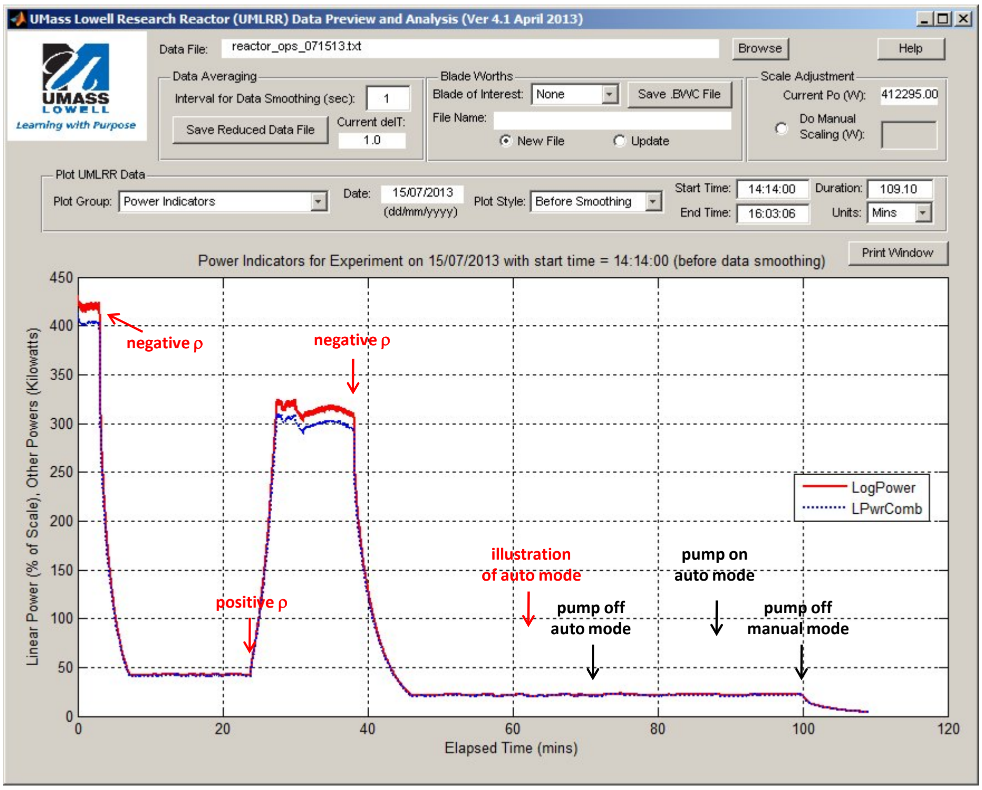


FIG. 22. Power vs. time during the reactor operations demo of July 15, 2013.

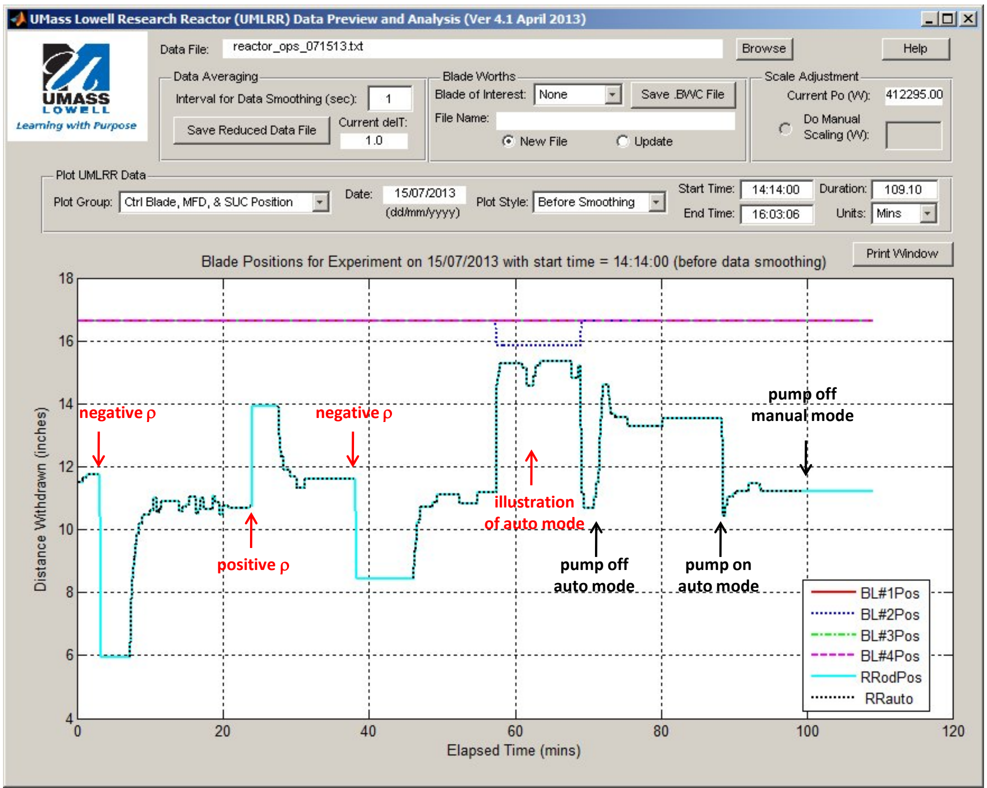


FIG. 23. Blade position vs. time during the reactor operations demo of July 15, 2013.

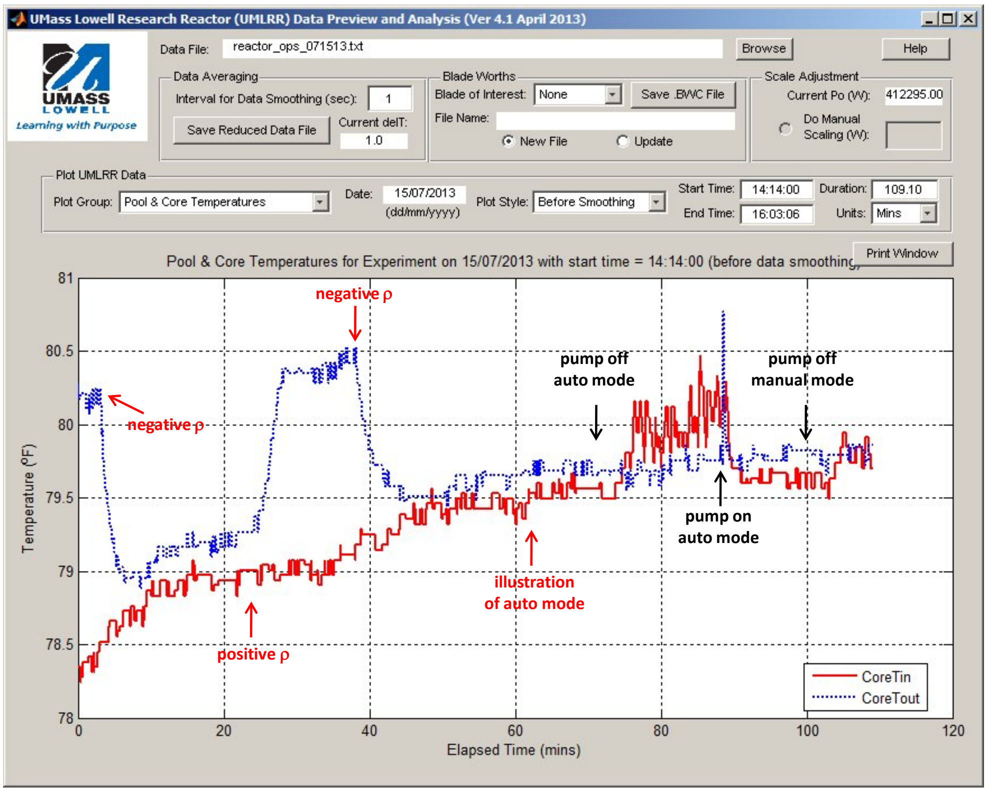


FIG. 24. Core inlet and outlet temperatures vs. time during the demo of July 15, 2013
(note that the interpretation of "inlet" and "outlet" changes for natural convection flow since the flow direction during the usual forced flow case is down through the core).

Lab 9 -- Material Worth Measurements Lab: The original relatively-focused goal for this lab was to measure the worth associated with a void volume that is created at different locations within the UMLRR core. In particular, the lab was to involve real-time measurement of the reactivity effect associated with moving polyethylene (i.e. moderation) into or out of one of the dry radiation basket locations within the UMass-Lowell research reactor (UMLRR). Several MCNP calculations were made to help design and analyze such a system. The major challenge here was to design a device that has sufficient worth so that it is easily measureable (> 0.02% Δk/k) and, at the same time, has a worth less than the current limit for moveable experiments (< 0.10% Δk/k). In addition, if possible, the goal was to design a single device that will satisfy these reactivity criteria, 0.02% Δk/k < ρ < 0.10% Δk/k, in multiple locations within the core -- in particular, in the radiation baskets on the core periphery as well as in the D5 central flux trap location. A 1" diameter polyethylene cylinder with a length of between 6" and 8" should satisfy the upper limit in the D5 location, but this gives a very low worth on the core edge with the current M-2-5 core configuration. In fact, a full length 24-inch polyethylene sample in D2 barely meets the lower limit of the desired reactivity range. Thus, we were not able to meet our original design criteria with a single experimental device.

In evaluating the various options available to address this issue, we decided to go down a slightly different path for now. In particular, it was decided to broadened the original scope of the lab to include a variety of non-moveable material worth measurements. This broader classification allows experimental samples with reactivity worths up to 0.50% Δk/k, and it also includes the possibility of looking at the reactivity effect associated with the movement of fuel assemblies, radiation baskets, and graphite reflector elements within the core. The negative side, of course, is that the reactor needs to be shutdown while the core assemblies are moved or a secured sample material is inserted into one of the experimental facilities -- so this experiment cannot be performed effectively as an online lab. This experimental option, however, does fit nicely with the computational modeling and model validation focus of the new graduate Reactor Experiments course. Within this lab exercise, we can focus on modeling a variety of different core configurations within either the VENTURE and/or MCNP codes to determine the reactivity gain or loss, and then actually measure the reactivity change by having the reactor staff configure the core appropriately. Low-power steady state operation with the new core configuration is used to determine the critical blade heights for the new arrangement. This procedure should give a lot of information about the validity of the existing computational models and again emphasize the importance of model validation when using numerical models to simulate reactor performance.

This option for the Material Worth Measurements Lab (Lab 9) was selected for actual implementation in Spring 2014. As part of this lab, the existing BOL 3-D VENTURE model of the UMLRR was used to predict the reactivity change associated with several different core layouts and then the goal was to actually measure and compare the critical blade heights for some of these configurations. The set of five configurations described in Table 2 were suggested, where the core grid positions mentioned here can be visualized via reference to Fig. 2. Cases 1 and 3 were chosen for implementation and testing in Spring 2014, and the students were broken into two groups to physically go into the control room and observe the actual configuration change and core startup first hand.

TABLE 2. POSSIBLE CORE CONFIGURATIONS TO BE TESTED AS PART OF THE MATERIAL WORTH MEASUREMENTS LAB FOR SPRING 2014

Case #	Description (change from reference)	VENTURE $\Delta\rho$ (% $\Delta k/k$)
1	Interchange the radiation baskets in C2, D2, and E2 with the graphite reflectors in C1, D1, and E1	0.60
2	Interchange the partial fuel assembly in C3 with the full fuel element in C4	-0.28
3	Interchange the radiation basket in D2 with the full fuel element in D3	-0.85
4	Interchange the partial fuel elements in C3 and E3 with the full fuel assemblies in C7 and E7	-0.28
5	Interchange the water baskets in B1, B9 and F1, F9 with the graphite reflector elements in B3, B7 and F3, F7	-1.03

The results of this exercise for Cases 1 and 3 were near perfect as summarized below in Table 3. The range of the predicted critical heights were determined by using the estimates of $\Delta k/k$ from both MCNP and VENTURE with the measured blades worth curves for the UMLRR, along with a small correction associated with the xenon worth in the system due to operation in the days prior to the experiment (note that the 3-D steady state model assumes no xenon and that the students only used the VENTURE code for their calculations -- but the instructor used both code models as formal verification before the tests were run). Both estimates were quite good, showing that the predicted worths for these two particular material perturbations (assembly interchanges) were quite accurate. And, in addition to the modeling and validation experience gained here, the students also got to participate in the execution of the experiment within the UMLRR control room -- and the students loved this!

TABLE 3. RESULTS FROM THE MATERIAL WORTH MEASUREMENTS LAB FOR SPRING 2014

Case #	**Predicted** Critical Blade Heights	**Measured** Critical Blade Heights
1	Blades 1-4 at 15.7-15.8 inches out with the RegBlade at 9 inches withdrawn.	Blades 1-4 at 15.95 inches withdrawn with the RegBlade at 8.0 inches out.
3	Blades 1-4 at 18.3-18.5 inches out with the RegBlade at 9 inches withdrawn.	Blades 1-4 at 18.40 inches withdrawn with the RegBlade at 10.8 inches out.
Notes: In April 2014, the reference critical height for the M-2-5 xenon-free configuration was 16.7 inches out with the RegBlade at about 10 inches withdrawn. Also, for operation near the mid-core region, a Δz = 2.5 inches for the RegBlade corresponds to about a 0.1 inch change in the banked height of the four large control blades.		

Finally, we note that, since the measurement of the void worth (or void coefficient) in the UMLRR is still of real interest, we have not given up on the original goal of this lab. Within this context, the current plan is to modify our original design criteria for the Void Worth Lab (now considered a subset of the Material Worth Measurements Lab) to include two separate devices to insert polyethylene into different locations in the core. As indicated above, we were not successful in our attempt to design a single device that would work in both the central and peripheral core locations. However, if we have two dry Al tubes with moveable polyethylene cylinders of different lengths (one long and one short), then we may be able to achieve our original goal. In particular, the local void worth in the center of the UMLRR core is positive and the local void worth on the outer edge is negative, and the original premise of this proposed experiment was to demonstrate this behaviour and to explain, in some detail, why this happens. Thus, only having one location available for testing, although still of some interest, certainly did not have the same flavour or impact as having worth measurements in two different locations (i.e. in the D2 and D5 locations, for example).

We now have acquired two dry Al tubes for use in a Void Worth Lab. Due to physical space limitations above the core support structure, the challenge now is how to easily connect/disconnect the vertical drive mechanism to/from the tube and cable combination so that only one drive motor and data acquisition unit will be required. In addition, we need to address how to design the devices so that only the low-worth element can be placed in the high-worth D5 location so that there is no possibility of violating the technical specifications for the worth of moveable experiments in the UMLRR. These issues are currently being addressed and the plan is to have the Void Worth Lab ready for testing later this year. Thus, an actual Void Worth Experiment may be available in the near future as an option to the current Material Worth Lab procedure.

Lab 10 -- Dynamic Modeling/Validation of the UMLRR Balance of Plant: The ultimate goal of this lab is to build upon our experience with the Quasi Steady State Energy Balance Lab (Lab 7) to eventually include full dynamic modeling of both the primary and the secondary side cooling systems and to integrate these within our existing 11-equation model of the core dynamics -- that is, to generate and utilize a full-model dynamic simulator for the complete UMLRR facility. As a first step towards this goal, we have identified the UMLRR heat exchanger as one of the most important components within the balance of plant systems, and we have decided to focus our current attention on developing and validating a simple dynamic model for this device. Although of real interest, the modeling of the remaining components and processes (such as the primary and secondary pumps, the holdup tank, the cooling tower, and the time lag associated with the flow and partial mixing of the primary fluid within a 76,000 gal pool before it enters the core) will all have to be considered as future work for another day.

Thus, within the context of the overall modeling, simulation, and validation theme shared by many of the labs developed for the graduate Reactor Experiments course, we have decided to use the TRACE code [23] as the primary tool for modeling the UMLRR heat exchanger, and to verify the model with actual experimental data from the UMLRR.

In particular, the UMLRR uses a traditional U-tube shell and tube heat exchanger with two tube passes. The tube length per pass is about 4.06 m (160 inches), giving the total length traversed by the primary fluid as 8.13 m (320 inches). The tubes are SS304 with an ID = 1.34 cm (0.527) inches and OD = 1.59 cm (0.625 inches). The shell side of the heat exchanger is also made from SS304 and it has an ID of 61 cm (24 inches). The heat exchanger has 14 double segmented baffles, which are used to increase heat transfer by introducing turbulence in the fluid stream on the shell side and, of course, to provide support for the 320 tubes that make up the interior of the heat exchanger. Note, however, that the baffles are not modeled explicitly within current TRACE model -- instead, their effect is treated implicitly by artificially increasing the heat transfer surface area between the tube side and shell side fluids (see discussion below).

Figure 25 shows a diagram of the heat exchanger modeled in TRACE. The model consists of three major components; the shell, heat structure, and tubes. The shell and tube sections of the heat exchanger are modeled in TRACE by utilizing the PIPE component and the boundary conditions are set by the FILL, BREAK, or another PIPE component. The FILL command is used in this simulation to input a set of time-dependent measured inlet temperatures and velocities for the shell and tube side fluids, and our goal is to try to compute a set of outlet temperatures that match the experimental data.

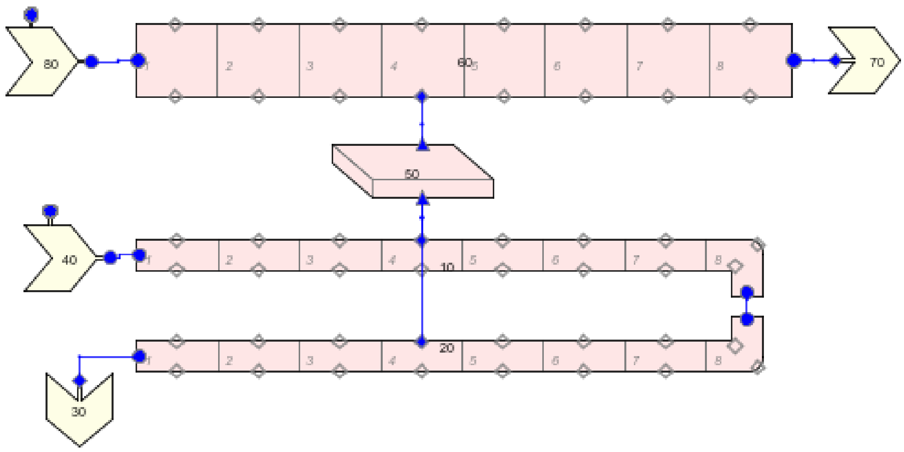
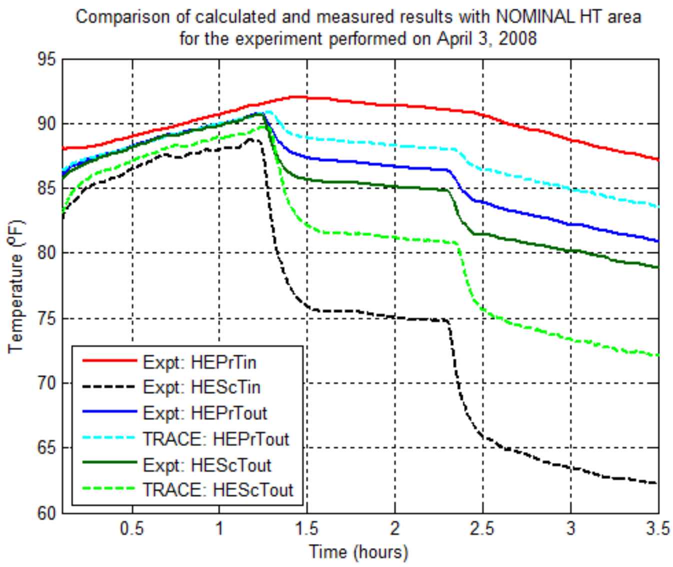


FIG. 25. TRACE representation of the UMLRR heat exchanger.

The HTSTR component in TRACE is utilized to transfer energy from the primary to secondary side fluids. The key element here is to get the heat transfer (HT) area correct and also to maintain the proper fluid and metal masses to correctly model the energy storage (capacitance) in the system. However, since the baffles were not modeled explicitly, we anticipated that the energy transfer rate via convection heat transfer would be seriously under predicted in the base model, primarily due to the simple assumptions made for modeling the shell side fluid. Thus, the initial plan was to compare the predicted outlet temperatures using the nominal HT area and flow area as defined by the physical geometry (with no baffles), and then to simply increase the HT surface area until the outlet temperatures matched reasonably well to the measured heat exchanger data.

The result of this process can be seen in Fig. 26 for the same data set used for the discussion of Lab 7 -- namely the data from a reactor energy balance experiment performed in April 2008. As apparent, simply increasing the effective HT area (by about a factor of 2.5) seems to have adequately accounted for most of the modeling simplifications. After the area adjustment, as shown in the lower portion of the figure, the predicted outlet temperatures match pretty well with the measured profiles. In addition, as an independent evaluation of this new semi-empirical TRACE model for the UMLRR heat exchanger, two other comparisons were also performed as shown in Fig. 27, where near perfect agreement was also obtained. Thus, it appears that we now have a reasonable qualitative and quantitative representation of the UMLRR heat exchanger within the TRACE package.



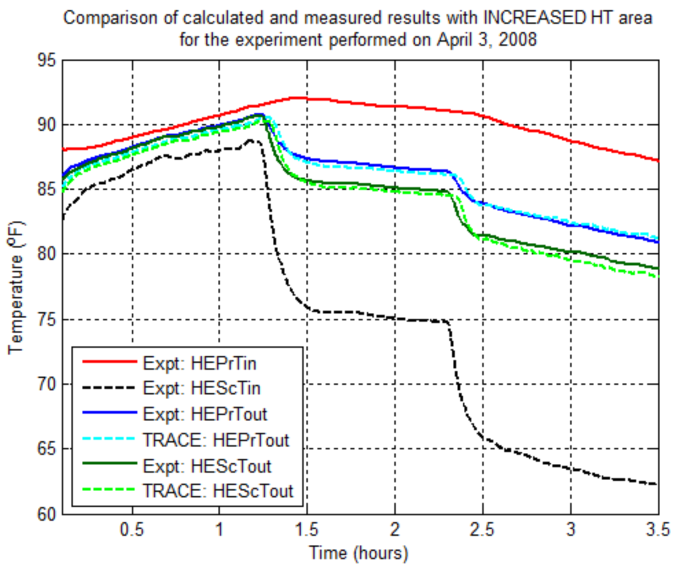


FIG. 26. TRACE simulation results before (upper) and after (lower) adjusting the HT area.

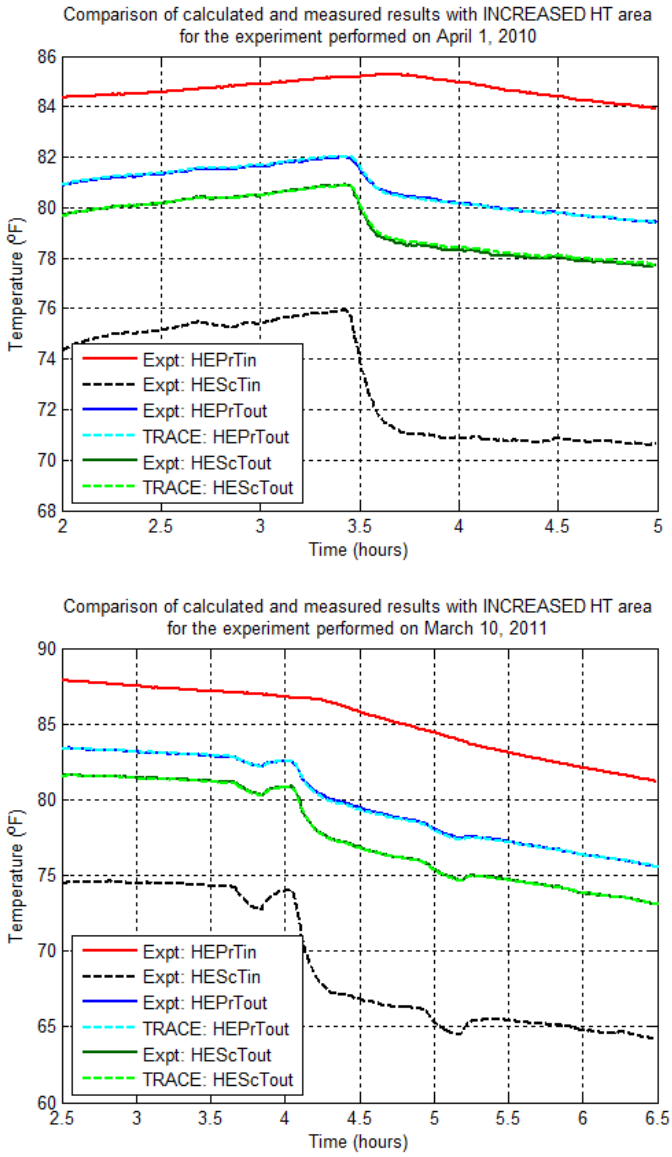


FIG. 27. Two additional TRACE simulation tests that use the increased HT area.

Although the final TRACE model for the UMLRR heat exchanger is very simple, it allows for a good discussion of the general behaviour of U-tube heat exchangers and it allows us to use this experiment to introduce SNAP [24] and TRACE [23] and some of their many capabilities into the Reactor Experiments class -- with a focus on providing experimental evidence that the models can indeed predict the behaviour of real systems. Although this lab has not been formally tested in a classroom environment as yet, it is expected that the introductory modeling to be done in SNAP/TRACE will be well received by the students. This introduction to TRACE, along with a successful validation test via comparison to real experiments, should make for quite a rewarding educational experience. This lab will be formally tested in a future class and, if it is indeed successful in its stated goals and it gets good reviews from the students, then we will definitely invest the time to incorporate additional component models and eventually integrate these into the full-model dynamic simulator for the UMLRR that was originally envisioned.

4. SUMMARY AND FUTURE WORK

The above overview of the UMass-Lowell research reactor (UMLRR) and the brief description of the ten lab sequences that are currently available should give the reader a good perspective of the educational opportunities that exist at UMass-Lowell, as well as a good summary of the topics and the depth of coverage that can be delivered. The new Reactor Experiments course is certainly one mechanism where interested universities or organizations without access to a research reactor can participate and benefit from some of the unique capabilities of the UMLRR. Note also, however, that there is a lot of flexibility here, where a focused 3 to 5-day short course, or even an intensive 2-week combined theoretical, experimental, and computational program, that includes all or only a subset of these experiments is also possible -- and the theoretical details, computational rigor, and expectations of the participants can easily be adjusted to accommodate the needs of the client audience. Each lab module discussed above uses real data from the 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 couple of offering of the course is quite positive so far.

As noted above, an immediate positive outcome from the Reactor Experiments course is the availability of several educational reactor labs that can be used in a variety of settings. As a concrete example, this asset became one of the focal points in our Nuclear Energy Education and Training (NEET) program in summer 2013 [13]. As part of the 8-week 2013 NEET program, UMass-Lowell hosted 23 Nuclear Engineering sophomores and juniors from King Abdulaziz University (KAU) in Jeddah, Saudi Arabia. The full program consisted of classroom lectures by UMass-Lowell professors and industry experts on the fundamentals of nuclear science and engineering, radiation protection, reactor kinetics and dynamics, reactor operations, and reactor systems and safety. It also included seminars on nuclear plant site selection, economics, and construction management -- and all these were supplemented by tours of commercial nuclear power plants and other industrial facilities, and by actual experiments within the UMLRR.

Relative to the reactor laboratory portion of the program, the NEET students got a good preview discussion of the UMLRR, actually toured the facility, and then performed several experiments and demonstrations within the facility -- including, in order: an Energy Balance Lab (Lab 7), the Axial Flux Profile Experiment (Lab 6), a Reactor Operations Demo (Lab 8), the Measurement of the Blade Worth Curve for the Regulating Blade (using inverse kinetics as part of Lab 3), and a Reactivity Feedbacks Demonstration (part of Lab 4) that emphasized the inherent stability of the system under both forced and natural convection operations. All this was done within a 2-week unit as part of the full 8-week program. Certainly the level of detail and the amount of work requested of the students were far less than expected from the graduate class, but the dual use of the same basic labs demonstrates that these experiments can really serve several different audiences with a somewhat different focus. This series of experiments and demonstrations was well received by the students and it allowed them to experience first-hand many important reactor operations and reactor safety concepts. All this would not have been possible without the availability of the reactor labs and the data analysis and visualization tools that were developed as part of the Reactor Experiments course at UMass-Lowell.

Also, with remote accessibility to the real-time and archived reactor data via the UMLRR Online application, and with the relative ease and low overhead associated with current web-based communications, most of the labs were envisioned, from the start, with the remote user in mind. The plan from initial conception of the course was to work out the course details with in-house participants during the first couple of offerings of the course 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 via an online education portal. Thus, the infrastructure needed to offer this course to both the on-campus and online student has already been developed and tested, and we hope to have a good mix of both on and off-campus students engaged in this course in future years.

Concerning future enhancements and the development of additional labs, we certainly are not at a loss for ideas here. There are still lots of fine details to improve upon in some of the available resource materials for a few of the existing labs, and clearly many of the current labs can be modified to highlight different aspects of the main topic -- so we will be modifying and improving things for many years to come. Also, as highlighted in the above discussions, there are plenty of enhancements that can be made to improve the capabilities and learning experiences that Labs 9 and 10 have to offer, and plans are already underway to bring the planned Void Worth Experiment to completion. And, of course, there are also many new ideas for interesting and educational experiments/demonstrations that are still just waiting for some creative students to give them a test run. However, the future is clearly dependent on the interest level and number of formal collaborations that can be developed with other universities and organizations involved in the training of the next generation of nuclear engineers. Thus, significant involvement with several on-campus and off-campus groups will indeed be necessary to justify, maintain, and enhance the current reactor laboratory capabilities at UMass-Lowell.

As a final note, there seems to be a lot of general interest in internet-based reactor laboratories (IRLs) for students who do not have access to a physical reactor facility. For example, there were four related papers that touched on this subject at the recent RRFM 2013 Conference in St. Petersburg, Russia. In addition to the UMass-Lowell contribution [5], there was one paper from the Jordan University of Science and Technology, one from the National Institute for Science and Technology within the CEA Saclay Research Center in France, and one from the Jozef Stefan Institute in Slovenia. [25-27] The paper from Jordan discussed the relationship they have with North Carolina State University and concluded with some survey data that showed that the IRLs were indeed an effective tool in training students without access to a physical facility. The other two papers focused on the type of experiments performed, on recent upgrades to their respective facilities to support additional reactor labs, and on their (somewhat reluctant) movement towards an internet-based distance education approach to deliver at least some portion of the reactor-based education and training that they do each year. These latter two projects were supported in part by educational programs funded by the International Atomic Energy Agency (IAEA).

The take-away from the meeting regarding IRLs was that they could indeed become an important mechanism for educating the future nuclear workforce. The IRLs will probably never replace the hands-on face-to-face training that is possible within a physical reactor facility, but it is simply not possible to have a research reactor at each University and the cost associated with students travelling to such a facility can be prohibitive. Thus, a set of well-constructed internet-based reactor laboratories may be the best option for many students -- and the UMLRR certainly would like to be one of the key IRLs of the future.

REFERENCES

[1] Report on the HEU to LEU Conversion of the University of Massachusetts Lowell Research Reactor, submitted to the US Nuclear Regulatory Commission in fulfillment of Amendment No. 12 to License No. R-125 (April 2001).

[2] WHITE, J. R. and L. BOBEK, L. M., Startup Test Results and Model Evaluation for the HEU to LEU Conversion of the UMass-Lowell Research, 24th International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR 2002), San Carlos de Bariloche, Argentina (Nov. 2002).

[3] WHITE, J. R., BOBEK, L. M., and JIRAPONGMED, A., A Web-Based System for Access to Real-Time and Archival Research Reactor Data, Trans. Am. Nuc. Soc., 90, p. 322 (June 2004).

[4] JAIN, P., MARKIDIS, S., JONES, B. G., RIZWAN-UDDIN, WHITE, J. R., and BOBEK, L. M., Web-casting of Nuclear Reactor Experiments, Trans. Am. Nuc. Soc. (Nov. 2006).

[5] WHITE, J. R., New Reactor Experiments Course at the University of Massachusetts Lowell, Research Reactor Fuel Management Conference (RRFM 2013), St. Petersburg, Russia (April 2013).

[6] MATLAB, http://www.mathworks.com.

[7] PHELPS, J. P., et. al., Final Safety Analysis Report for the Lowell Technology Institute Reactor, University of Lowell (Sept. 1973).

[8] FSAR Supplement for Conversion to Low Enrichment Uranium (LEU) Fuel, submitted for review by the NRC for conversion of the UMass-Lowell Research Reactor (May 1993).

[9] WHITE, J. R., JIRAPONGMED, A., BOBEK, L. M., and REGAN, T. M, Design and Initial Testing of an Ex-Core Fast Neutron Irradiator for the UMass-Lowell Research Reactor, 2002 ANS Radiation Protection and Shielding Topical Conference, Santa Fe, New Mexico (April 2002).

[10] OPTO 22, http://www.opto22.com.

[11] InduSoft Web Studio, http://www.indusoft.com.

[12] GoToMeeting, http://www.gotomeeting.com/.

[13] NEET: UMass-Lowell hosts Saudi Students, article in Nov. 2013 issue of Nuclear News, American Nuclear Society.

[14] VENTURE-PC - A Reactor Analysis Code System, Radiation Safety Information Computational Center, CCC-654 (1997).

[15] WHITE, J. R., BYARD, J., and JIRAPONGMED, A., Calculational Support for the Startup of the LEU-Fueled UMass-Lowell Research Reactor, Topical Meeting on Advances in Reactor Physics and Mathematics and Computation, Pittsburgh, Pennsylvania (May 2000).

[16] HENRY, A. F., Nuclear-Reactor Analysis, MIT Press, Cambridge, Massachusetts (1975).

[17] SKODA, R., AGN-201M Exercises - Part 1 (Draft), Texas A&M University (Dec. 2010).

[18] MICHAUD, T. P., Implementation of the Inverse Kinetics Method for Reactivity Calculations at the UMLRR, M.S. Thesis in Energy Engineering (Nuclear Option), UMass-Lowell, (Dec. 2011).

[19] WHITE, J. R., Steady-State temperature Profiles in a UMLRR Fuel Channel, part of a series of Lecture Notes for the Nuclear Engineering Program at UMass-Lowell (Feb. 2013).

[20] MCNP5 (ver. 1.6) - Monte Carlo N-Particle Transport Code System, Radiation Safety Information Computational Center, CCC-740 (2011).

[21] WHITE, J. R., GOCHT, R., PIKE, M. and MARCYONIAK, J., Validation of the 3-D VENTURE and MCNP UMLRR Core Models used in Support of the WPI Fuel Transfer Project, Research Reactor Fuel Management Conference (RRFM2012), Prague, Czech Republic (March 2012)
[22] WHITE, J. R. and L. BOBEK, L. M., Innovative Use of a Research Reactor for Interdisciplinary Engineering Education, 2007 ASEE Conference, Honolulu, Hawaii (June 2007).
[23] TRACE V5.0p3 User's Manual, Nuclear Regulatory Commission (NRC) (2011).
[24] SNAP V2.2.1 User's Manual, Applied Programming Technology, Inc (2012).
[25] MALKAWI, S. R. and AL-ARAIDAH, O., Evaluation of Nuclear Reactor Physics Laboratory Education Through Remote Utilization of Research Reactors, Research Reactor Fuel Management Conference (RRFM 2013), St. Petersburg, Russia (April 2013).
[26] FOULON, F., LESCOP, B., and WOHLEBER, X., Focus on Safety in Training Courses on ISIS Reactor, Research Reactor Fuel Management Conference (RRFM 2013), St. Petersburg, Russia (April 2013).
[27] SMODIS, B. and SNOJ, L., Recent Utilization of the Solvenian TRIGA Reactor Reactor, Research Reactor Fuel Management Conference (RRFM 2013), St. Petersburg, Russia (April 2013).

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