Analysis of the Blade #4 Approach to Critical Experiment #1
Performed on July 13, 2005

Introduction

An approach to critical experiment using Blade #4 was performed in the UMass-Lowell research reactor (UMLRR) on July 13, 2005. The purpose of the experiment was to demonstrate the concept of subcritical multiplication and the utility of a 1/M plot for predicting the critical position of a control blade within the UMLRR. The experiment followed the general guidelines and overall procedure given in Ref. 1.

The actual reactor run for this experiment was pretty straightforward. With all the other control blades at fixed positions, the reactor operators were asked to pull Blade #4 out by some amount and wait for the count rate on the startup counter to stabilize. From an estimate of the count rate for the current configuration, one can determine the relative subcritical multiplication factor and make a rough estimate, using a 1/M plot, of the critical height of the blade. With a new estimated critical height, a new blade position is requested (about 1/2 of the predicted change needed for criticality), and the process is repeated. After several steps, one should have a very good estimate of the real critical location.

The experiment occurred over a period of about 2 hours on the morning of July 13, 2005. The operations data during the run have been archived for future use within a single text data file, **050713a.dat**. The goal of the current document is simply to explain the contents of this file, to display graphically the operations data for a few key plant parameters, and to show the resultant 1/M plot for this particular approach to critical experiment. This is provided as an example for experiments of this type -- that is, those involving the use of a 1/M plot to predict where criticality will occur for a given system. Hopefully this example will be useful as an illustration of future approach to critical demonstrations and experiments.

UMLRR Operational Data for July 13, 2005

As for all experiments, the UMLRR control and data acquisition system (CDAS) continuously records measured signals from a variety of power, temperature, flow, pressure, position, and on/off status indicators throughout the facility. The recorded history files for July 13, 2005 were processed to extract the pertinent data from the **Blade #4 Approach to Critical Experiment #1**. In particular, a series of 27 indicators were saved at 30-second intervals for about 2 hours, with a start time of 11:05:00. The raw data are stored within data file **050713a.dat**.

The key results from the reactor run, focusing on power versus time, on blade position versus time and, in particular, on a single plot that shows the Blade #4 location and the startup count rate during the 2-hour run, are given in Figs. 1-3. A Matlab script file, **b4_critpos1_post.m**, was written (see listing in Table 1) to read the **050713a.dat** file and produce this series of resultant plots.

Since this was an approach to critical experiment, the reactor was subcritical until the last part of the demonstration when the operations staff actually took the system to slightly supercritical. This can be seen clearly in Fig. 1, which shows several power indicators versus time. The auto-ranging linear power 1 and 2 channels, which display power in % of full scale, and the log power channel, which gives % of full power, all show essentially zero power, except for the last 10 minutes or so. In the last several minutes there is a slow rise in the power indicators, showing that the system is slightly supercritical with a small positive period.

The blade position information, shown in Fig. 2, also tells a similar story. During the first 20-25 minutes, all the control blades, excluding the blade of interest, were brought to their desired positions for this particular experiment -- 14.8 inches withdrawn for Blades 1-3 and about 10 inches out for the regulating blade. Blade #4 was then moved out to 6 inches, and this is when we started recording the count rate data for the subsequent 1/M plots. As apparent, Blade #4 was moved out in a stepwise fashion to the 17.6 inches withdrawn position, with quiet intervals of about 10-15 minutes between movements to allow for the transients to stabilize and to allow for enough time at steady state to get a good average count rate reading. Even at 17.6 inches withdrawn, the system is still subcritical as apparent from the nearly constant power vs. time curves in Fig. 1. After the experiment was essentially complete (with a predicted critical height of about 18.1 inches -- see below), the reactor staff actually took the system slightly above critical by moving Blade #4 to about 18.2 inches out. This is the period of time towards the end of the measurement period where the power curves start to show the expected exponential increase. The system was only supercritical with a small positive period for a few minutes when Blade #4 was moved back to the 17.6 inch position -- which made the system subcritical again.

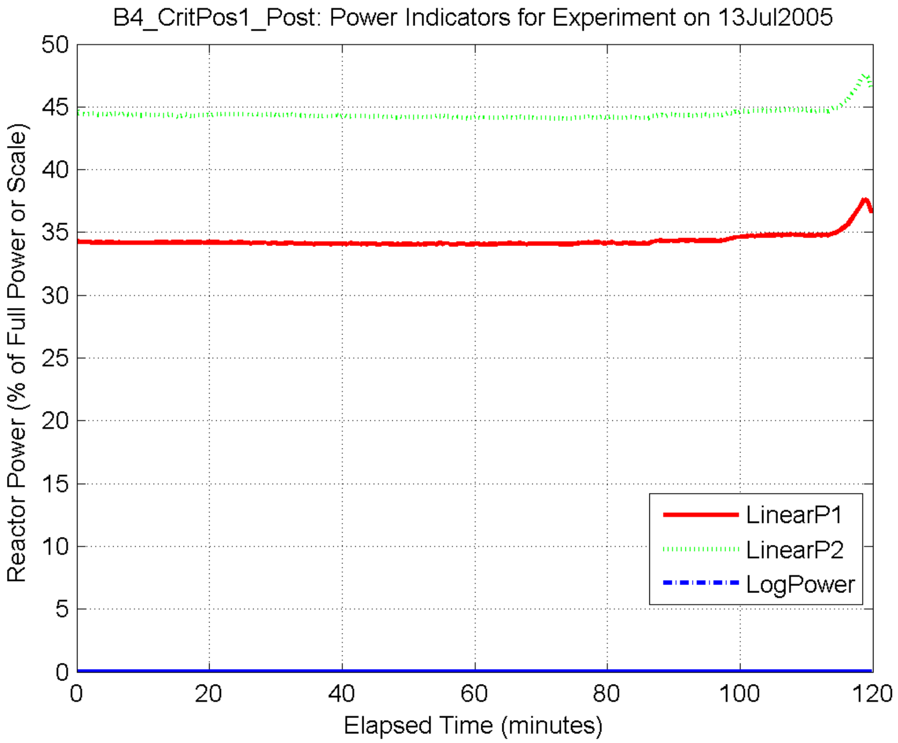

Fig. 1 Power profiles for the approach to critical experiment (July 13, 2005).

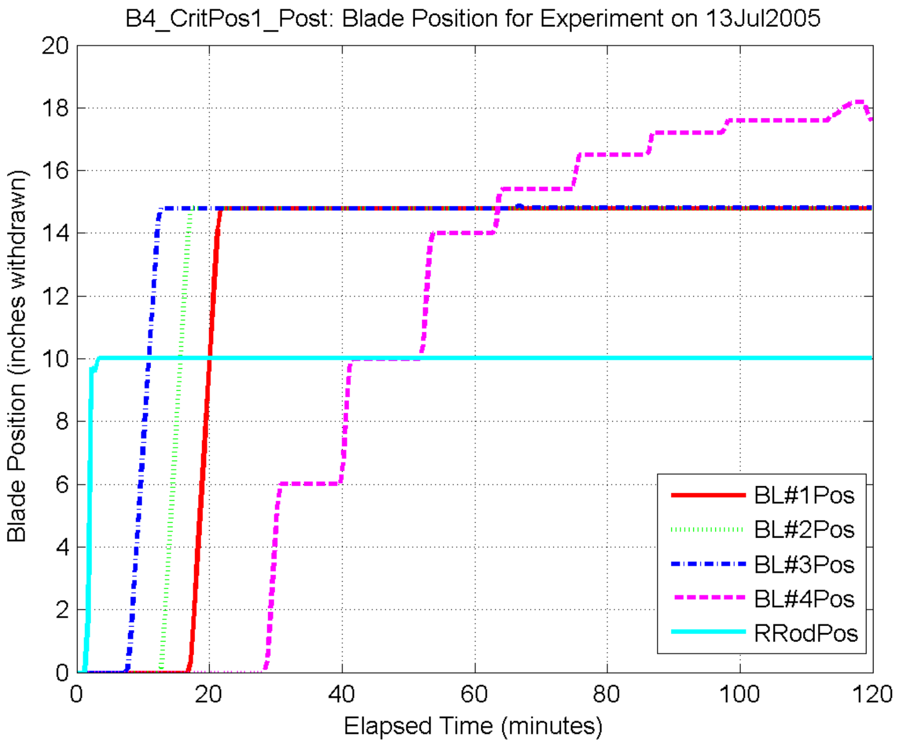

Fig. 2 Blade position indicators for the approach to critical experiment (July 13, 2005).

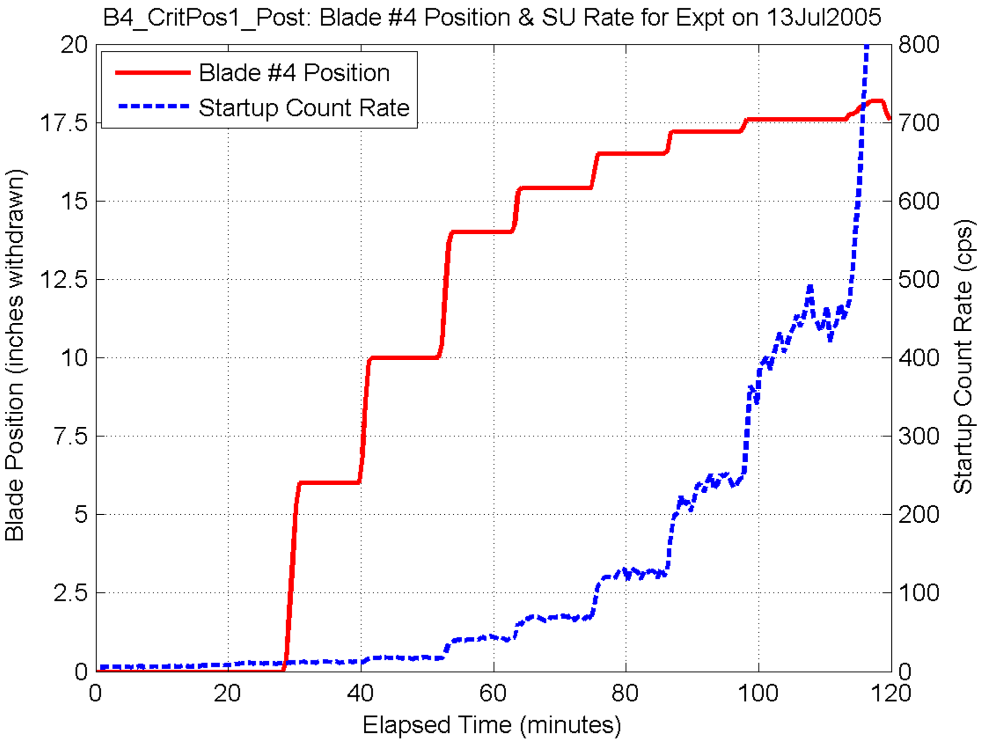

Fig. 3 Summary Blade #4 position and detector count rate data (July 13, 2005).

Table 1 Listing of the b4_critpos1_post.m script file.

```
%
%
%   B4_CRITPOS1_POST.M   Operational Data Plotting for Blade #4
%               Approach to Critical Experiment #1 performed July 13, 2005
%
%   An experiment was performed in the UMLRR on July 13, 2005.  The goal was to use
%   the concept of subcritical multiplication to predict the critical position of
%   Blade #4 (with all the other control blades at some fixed position).
%
%   The reactor run was pretty simple: that is, the reactor operators were asked
%   to pull Blade #4 out by some amount and wait for the count rate on the startup
%   counter to stabilize.  From an estimate of the count rate for the current
%   configuration, one can determine the relative subcritical multiplication factor
%   and make a rough estimate -- using a 1/M plot -- of the critical height of the
%   blade.  With a new estimated critical height, a new blade position is requested
%   (about 1/2 of the predicted change needed for criticality), and the process is
%   repeated.  After several steps, one should have a very good estimate of the real
%   critical location.
%
%   This file generates several plots that summarize the operational conditions
%   associated with this experiment.  The reactor data for the run have been
%   processed and stored in file 050713a.dat. This dataset contains information
%   for 27 different reactor measurements.  The measurements were taken at 1 second
%   intervals, but this info has been averaged over 30 sec periods.  Thus, an
%   average value for each of the 27 measured points is given at 30 second intervals
%   within file 050713a.dat.
%
%   Note: At about 110 minutes into the experiment there was a blip in the core
%   inlet temperature -- this is clearly a bad data point, so it is simply ignored
%   in any post analysis (this data was not used directly anyway)...
%
%   File prepared by J. R. White, UMass-Lowell (July 2005)
%


%
%   getting started
      clear all, close all, nfig = 0;
%
%   set color and marker code for creating plots
      Ncm = 6;  scm = ['r- ';'g: ';'b-.';'m--';'c- ';'k: '];
%
%   read experimental data
      fname = '050713a.dat';  fid = fopen(fname,'rt');
      exptdate = fscanf(fid,'%s',1);  starttime = fscanf(fid,'%s',1);
      Nrow = fscanf(fid,'%i',1);                   % # of rows in data set (time pts)
      Ncol = fscanf(fid,'%i',1);                   % # of cols in data set (#tags+1)
      tags = cell(Ncol,1);                         % initalize array for tag names
      for i = 1:Ncol,  tags{i} = fscanf(fid,'%s',1);  end
      tags = char(tags);                           % convert to character array
      data = fscanf(fid,'%e');                     % read rest of data
      data = reshape(data,Ncol,Nrow)';             % put into matrix (Nrow x Ncol)
      fclose(fid);
%
%   now lets plot some data to view reactor operation during the run
      te = data(:,1)/60;                        % time vector for expt (mins)
%   power indicators
      nfig = nfig+1;  figure(nfig);
      itag = [2 3 4]; ntag = length(itag);      % tags of interest for this plot
      st = char(zeros(ntag,8));                 % storage for labels in legend command
      jj = 0;                                   % counters for marker type
      for j = 1:ntag
        it = itag(j);   jj = jj+1;  if jj > 6, jj = 1; end
        plot(te,data(:,it),scm(jj,:),'LineWidth',2); hold on
        st(j,:) = tags(it,:);
      end
      grid on, hold off
      rr = axis;  rr(3) = 0;  axis(rr);
      title(['B4\_CritPos1\_Post: Power Indicators for Experiment on ',exptdate]);
      xlabel('Elapsed Time (minutes)'),ylabel('Reactor Power (% of Full Power or Scale)')
      legend(st)
%   core temperature indicators
      nfig = nfig+1;  figure(nfig);
```

```
      itag = [8 7 15 14 9]; ntag = length(itag); % tags of interest for this plot
      st = char(zeros(ntag,8));                  % storage for labels in legend
      jj = 0;                                    % counters for marker type
      for j = 1:ntag
        it = itag(j);   jj = jj+1;  if jj > 6, jj = 1; end
        plot(te,data(:,it),scm(jj,:),'LineWidth',2); hold on
        st(j,:) = tags(it,:);
      end
      grid on, hold off
      title(['B4\_CritPos1\_Post: Core Temperature Indicators for Expt on ',exptdate]);
      xlabel('Elapsed Time (minutes)'),ylabel('Various Temperatures (^oF)')
      legend(st)
%   blade position indicators
      nfig = nfig+1;  figure(nfig);
      itag = [23 24 25 26 27]; ntag = length(itag); % tags of interest for this plot
      st = char(zeros(ntag,8));                % storage for labels in legend command
      jj = 0;                                  % counters for marker type
      for j = 1:ntag
        it = itag(j);   jj = jj+1;  if jj > 6, jj = 1; end
        plot(te,data(:,it),scm(jj,:),'LineWidth',2); hold on
        st(j,:) = tags(it,:);
      end
      grid on, hold off
      title(['B4\_CritPos1\_Post: Blade Position for Experiment on ',exptdate]);
      xlabel('Elapsed Time (minutes)'),ylabel('Blade Position (inches withdrawn)')
      legend(st)
%   Blade #4 position & startup count rate (two y-axes for different scales)
      nfig = nfig+1;  figure(nfig);
      [ax,h1,h2] = plotyy(te,data(:,26),te,data(:,22)); grid
      xlabel('Elapsed Time (minutes)'),
      title(['B4\_CritPos1\_Post: Blade #4 Position & SU Rate for Expt on ',exptdate]);
      axes(ax(1)),ylabel('Blade Position (inches withdrawn)')
      set(ax(1),'YColor',[0 0 0])
      set(ax(1),'XLim',[0 120],'YLim',[0 20], ...
                'YTick',[0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 ], ...
                'YTickLabel',[0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0]');
      axes(ax(2)),ylabel('Startup Count Rate (cps)')
      set(ax(2),'YColor',[0 0 0])
      set(ax(2),'XLim',[0 120],'YLim',[0 800], ...
                'YTick',[0 100 200 300 400 500 600 700 800 ], ...
                'YTickLabel',[0 100 200 300 400 500 600 700 800]');
      set(h1,'LineStyle','-','Color','r','LineWidth',2);
      set(h2,'LineStyle','--','Color','b','LineWidth',2);
      legend([h1 h2],'Blade #4 Position','Startup Count Rate')
%   just plot the startup count rate (use Matlab's zoom command to extract cps data)
      nfig = nfig+1;  figure(nfig);
      plot(te,data(:,22),'r-','lineWidth',2); grid
      xlabel('Elapsed Time (minutes)'),ylabel('Startup Count Rate (cps)')
      title(['B4\_CritPos1\_Post: SU Rate for Experiment on ',exptdate]);
%
%   end of program
%
```

When the system is subcritical, the most important detector measurement is from the startup counter. This detector is not scaled to indicate reactor power. Instead, it gives a direct measure of the neutron interaction rate within the detector in counts per second (cps). As discussed in some detail in Ref. 2, the observed relative count rate in two different configurations is related to the subcritical multiplication factor, M, for the particular configuration -- the higher the relative count rate, the larger the value of M (and vice versa). By observing the count rate in different configurations (at different Blade #4 positions, for example), one can infer the degree of subcriticality in the system. And, as criticality is approached, 1/M goes to zero, which leads to a nice visual indication of the approach to critical as the particular variable of interest is altered.

The startup count rate data for this experiment are summarized in Fig.3, along with the blade position data for Blade #4. Two y-axes are used here, since the scales of interest for blade position and counts per second are quite different. However, having the blade position and count rate information on the same plot makes it much easier to correlate the observed behavior. As apparent, each time the blade is withdrawn, there is a subsequent increase in the detector count rate. In the early stages, when the system is far subcritical, the count rate appears to reach steady state fairly quickly. However, in the last two steps, a longer and longer time interval is needed for the delayed neutrons, which are more important as one nears criticality, to stabilize. Finally, once the system is brought to critical (or just beyond), the count rate increases very rapidly.

Prediction of Critical Height -- the 1/M Plot

The data for blade position and count rate from Fig. 3 can be used to generate a 1/M plot and to predict the critical position of Blade #4 for this experiment using the theory and techniques described in Refs. 1 and 2. This capability has been implemented in a relatively simple Matlab function file called **critical_height.m** (see note under Ref. 3). This function file requires a vector of heights and a vector of count rates and it automatically creates a 1/M plot for predicting the critical height of a control blade or regulating blade for the UMLRR. A straight line of the form y = mx+b is drawn between each set of data points and extended until it intercepts the x-axis (this is the estimate of the critical height). The coefficients for the linear fit are found by using Matlab's ***polyfit.m*** routine. The **critical_height** function also prints a short summary table of numerical results for the experiment.

The use of this function (or any capability with similar functionality) during the actual experiment is very useful to predict the critical height as each new data point is obtained and to decide what change in height should be made on the next step (usually about one half the change predicted for criticality). Since the data in Figs. 1-3 are available in real time via the UMLRR Online link at the www.nuclear101.com website,[4] this experiment can be easily performed in real-time by students at remote sites. Of course, for the example given here, we have processed the data offline, but it mimics what was done during the actual experiment on July 13, 2005.

As an illustration, the Matlab session for the final step in the approach to critical process for the current experiment is illustrated below:

```
>> h = [6 10 14 15.4 16.5 17.2 17.6];
>> C = [12 17 42 68 124 240 455];
>> critical_height(h,C);
```

and the results returned by the function are given in Table 2 and Fig. 4 below.

As apparent, the final predicted critical height was about 18.1 inches withdrawn -- which was validated by actually going critical just a little above this value. In the early stages of the experiment, the predictions are not particularly good because of the lack of linear behavior. However, as one approaches the critical condition, the linearity assumption becomes a better approximation of the behavior of 1/M vs. blade height, and the predictions generated by **critical_height.m** are generally quite good (also see a similar discussion in Ref. 2).

Table 2 Screen output from the critical_height sample run.

```
             Summary Data for 1/M Plot and Estimate of Critical Height

     Expt. Pt    Blade Pos.    Count Rate    M = Ci/Co      1/M      Est. Crit. Ht.
               (inches out)    (cps)                                (inches out)
         0        6.000          12            1.00        1.000
         1       10.000          17            1.42        0.706        19.600
         2       14.000          42            3.50        0.286        16.720
         3       15.400          68            5.67        0.176        17.662
         4       16.500         124           10.33        0.097        17.836
         5       17.200         240           20.00        0.050        17.948
         6       17.600         455           37.92        0.026        18.047
```

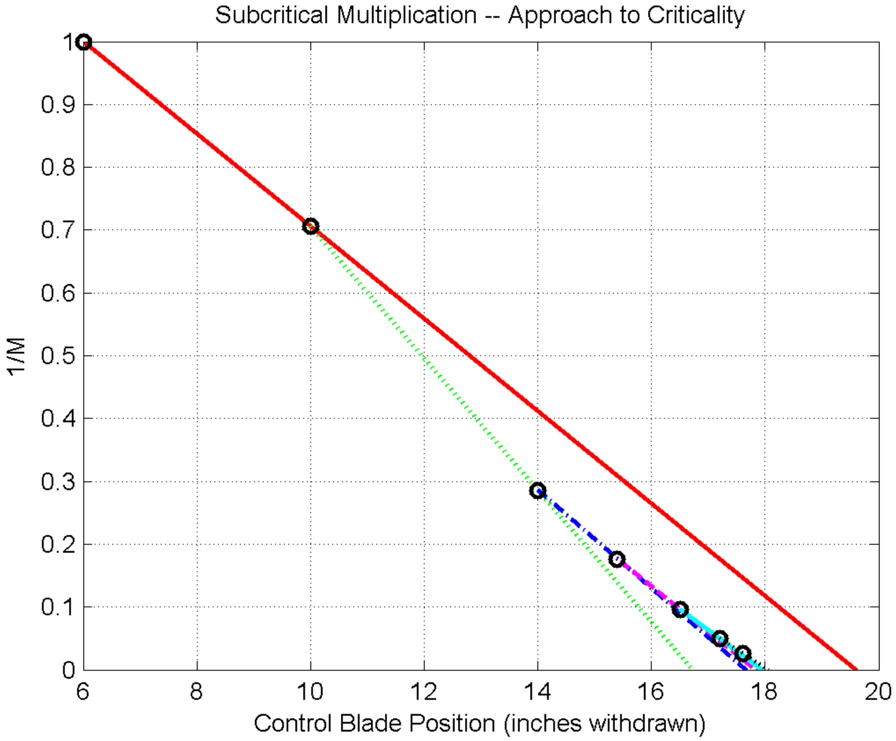

Fig. 4 1/M plot for the Blade #4 approach to critical experiment performed July 13, 2005.

Summary/Conclusions

This report summarizes the reactor operations data and key results from the **Blade #4 Approach to Critical Experiment #1** performed in the UMLRR on July 13, 2005. The goal of the experiment was to illustrate several theoretical concepts associated with subcritical systems (i.e. the subcritical multiplication factor, M, the behavior of 1/M as criticality is approached, etc.) and to use these to predict the critical height of a given control blade under the conditions of this particular experiment. As seen from the above results, the physical experiment and prediction analysis scheme were indeed successful, with a predicted and actual critical height of about 18.1 inches withdrawn. This experiment is relatively easy to perform and analyze and it is also quite informative. It can also be easily varied (different control blade of interest, different heights for the fixed blades, different reactor temperature conditions, etc.) to present each group of students with a new set of data each time the experiment is run. Finally, with the real-time UMLRR Online capability[4] now available, an approach to critical experiment similar to the one illustrated here can be easily performed by a remote group of students via internet communications from essentially anywhere in the world -- this is what our Reactor Sharing Program at UMass-Lowell is all about! In particular, any instructor interested in having their students perform and analyze an experiment within the UMLRR (such as the one illustrated here) should contact Prof. J. R. White directly at John_White@uml.edu. Even if you don't perform and analyze the experiment yourself, hopefully the data, results, and discussions presented here will help in your overall understanding of this subject…

References

1. J. R. White, "Understanding Subcritical Multiplication via an Approach to Critical Experiment," part of a series of Demos & Expts. available at www.nuclear101.com.
2. J. R. White, "Subcritical Multiplication," part of a series of Lecture Notes available at www.nuclear101.com.
3. A listing of the **critical_height.m** file is not given here since some instructors may want their students to write a similar function file or to perform hand computations and plotting as part of the learning experience associated with their Approach to Critical Experiment. Instructors interested in a copy of this relatively simple Matlab function can email Prof. J. R. White directly at John_White@uml.edu to request a copy.
4. J. R. White, A. Jirapongmed, and L. M. Bobek, "A Web-Based System for Access to Real-Time and Archival Research Reactor Data," ANS Annual Meeting, Pittsburgh, PA (June 2004).