Blade Worth Calibration within the UMLRR

Introduction

The reactivity worth associated with a small change in the position of a control blade is a function of the reference position of the blade (see Refs. 1-2 for a general discussion of partially inserted control rods). In practice, the differential worth, $d\rho/dz \approx \Delta\rho/\Delta z$, within the UMLRR tends to follow a slightly bottom-skewed bell-shaped curve:

> The bell-shaped profile is due to the higher neutron flux at core center relative to the axial endpoints of the fuel, and the fact that neutrons in this central region contribute more to the system's criticality (i.e. they are more important) than neutrons near the periphery -- since a larger portion stay in the core rather than leak out of the fueled region.
>
> The slight downward skew is associated with the remaining control blades that are partially inserted into the upper portion of the core to offset any excess fuel reactivity that may be present (this changes as a function of burnup). This partial insertion causes a slightly bottom-peaked flux distribution and differential blade worth profile.

Integration from 0 to z of the differential worth profile gives the integral worth curve. Formal measurement of the differential and integral worth curves (that is, plots of $d\rho/dz$ versus z and ρ versus z) are required for all four control blades and for the low-worth regulating blade within the UMLRR. Knowledge of these worth profiles is essential for proper operation and control of the facility, for the measurement of experimental sample reactivities, etc.. In fact, the first task to be accomplished each time a new core configuration is established is the calibration of the control blades within the new core arrangement. This is an essential ingredient needed in the day-to-day operation of the UMLRR.

The basic approach for measuring the desired worth curves involves the measurement of the reactivity induced due to a small movement of a blade. For example, a blade that is suddenly withdrawn a small amount translates to a positive reactivity addition, which causes a critical system to go slightly supercritical. This results in an increase in power and, after a short transient time to allow the reactor to reach a stable positive period, one can easily measure the doubling time and convert this to reactor period, τ. If the power is increasing exponentially with a stable period, then

$$P(t) = P_o e^{t/\tau} \tag{1}$$

Evaluating this expression at the doubling time, t_d, gives

$$\frac{P(t_d)}{P_o} = 2 = e^{t_d/\tau} \tag{2}$$

which gives $\tau = t_d/\ln 2$.

Finally, using the reactivity equation (or inhour equation) based on the generation time formulation of point kinetics (see Refs. 3-5 for further discussion and explanation of the notation used), we can express the reactivity in terms of the reactor period, or

$$\rho = \omega\Lambda + \sum_{i=1}^{6} \frac{\beta_i \omega}{\omega + \lambda_i} \tag{3}$$

where $\omega = 1/\tau$. With eqn. (3), we can easily convert the observed doubling time into a "measured" reactivity change.

Then, knowing the actual blade movement, Δz, around the mid blade position, z_i, for the i^{th} experimental point, we can compute an experimental data point for use in generating the differential worth curve,

$$\left.\frac{d\rho}{dz}\right|_{z_i} \approx \left.\frac{\Delta\rho}{\Delta z}\right|_{z_i} = \left.\frac{(\rho - \rho_o)}{\Delta z}\right|_{z_i} = \left.\frac{\rho}{\Delta z}\right|_{z_i} \tag{4}$$

where $\rho_o = 0$ if the initial system is critical (which, of course, is an implicit assumption of the reactivity equation anyway).

Gathering several estimates of $\left.d\rho/dz\right|_{z_i}$ at different axial points, z_i, allows one to plot the experimental differential worth curve. Usually, a mathematical model is fit to the experimental data, giving a continuous representation of $d\rho(z)/dz$. This expression can then be formally integrated to give a continuous formula for the integral worth profile, $\rho(z)$.

Typical Experimental Procedure

The above overview for generating the necessary data for the differential and integral blade worth curves can be formalized with the following experimental procedure:

1. Select the blade of interest (Blade N, for example) and place this blade in some initial position (nearly fully inserted) with the remaining blades at a suitable position to give a critical system with a power level of about 50 W -- where a low power level is specified so that temperature effects will not interfere with subsequent reactivity measurements. The primary pump should be ON, but the secondary pump and cooling fans should be OFF. This arrangement, coupled with low power operation, should give nearly constant core temperatures throughout the experiment.

2. After the system has been at steady state for several minutes, the reactor staff will withdraw Blade N an amount Δz that leads to a doubling time between 1-3 minutes, with a target value close to 2 minutes. The blade should be withdrawn as rapidly as possible since the assumption inherent in eqn. (3) is that a step change in reactivity was made. The regulating blade should be in Manual Mode during this step.

   Note: A suitable Δz can be anywhere from a fraction of an inch to several inches, depending on the blade of interest and the current blade location, z. Of course, to specify this properly, one must have prior knowledge of the approximate blade worth curves. This information is readily available to the operations staff from previous experimental data.

3. After the blade has reached its final position, one should wait a couple of minutes before taking the doubling time measurement (to allow the system time to reach a stable reactor period). The measured doubling time, t_d, and the initial and final blade positions for the current data point are then recorded. Note that the time between reaching 20% and 40% or

30% and 60% (after one rescaling) on the linear power channels usually gives a good measure of doubling time (recall that the linear power channels in the UMLRR indicate the “percent of range” and that auto scaling is performed as the level for the current range reaches its lower or upper endpoints at 0% and 100%, respectively).

4. After each measurement (when the reactor has reached about 650-700 W), the reactor operator then puts Blade N in its next desired approximate position and brings the reactor back to critical near the reference power level by manipulating the other blades, as appropriate. Note that the initialization process required before the next blade movement is made can take as long as 15-20 minutes.
5. Steps 2 through 4 are repeated to get a minimum of 6-7 points for generating the desired differential and integral blade worth curves for Blade N (10-12 data points spread across the 26 inch span for the UMLRR blades usually gives good results).

Delayed Neutron Data for the UMLRR

Converting the measured reactor period to reactivity via the use of eqn. (3) requires a set of delayed neutron data appropriate for the UMLRR. During the conversion from HEU to LEU fuel, the values of β_{eff} and Λ were computed for the new LEU core to be 0.0078 and 6.45e-5 seconds, respectively (see Ref. 6). These values, along with delayed neutron information for U235 fission from the ENDF/B-V data files, have been combined and summarized in Table 1 to give a complete set of kinetics parameters for use with eqn. (3). These data can be used to relate reactivity to the measured doubling time.

Table 1 UMLRR kinetics and delayed neutron data.

Generation Time (sec)	6.45e-5	$\bar{I} = \beta_{eff}/\beta$	1.137
Delayed Neutron Data			
Precursor Group	**Decay Constant (1/sec)**	**Delayed Neutron Fraction**	**Effective Delayed Neutron Fraction**
1	0.013	0.00026	0.00030
2	0.032	0.00146	0.00166
3	0.116	0.00129	0.00147
4	0.311	0.00279	0.00317
5	1.400	0.00088	0.00100
6	3.870	0.00018	0.00020
Total		0.00686	0.00780

Curve Fit for Differential Worth

A particular mathematical model for the differential worth, that combines a low-order polynomial with a sinusoid, was proposed several years ago (see Ref. 7). This combined model seems to give a somewhat better fit than a simple 4th, 5th or 6th order polynomial model, and this model has been used for analysis of the UMLRR blade worths since the startup of the new LEU core in summer of 2000. In particular, this new model uses the following cubic polynomial plus sinusoidal dependence to model the differential worth distribution within the UMLRR:

$$\frac{d}{dz}\rho(z) = c_1 + c_2 z + c_3 z^2 + c_4 z^3 + c_5 \cos\left(\frac{2\pi z}{H}\right) \quad (5)$$

where z is the distance withdrawn and H is the maximum blade traverse (H = 26 inches for the UMLRR). This distribution allows modeling the slightly bottom peaked differential worth profile that is observed for the UMLRR control blades.

Integrating this expression gives the integral worth curve,

$$\rho(z) = c_1 z + \frac{1}{2}c_2 z^2 + \frac{1}{3}c_3 z^3 + \frac{1}{4}c_4 z^4 + c_5 \frac{H}{2\pi}\sin\left(\frac{2\pi z}{H}\right) \quad (6)$$

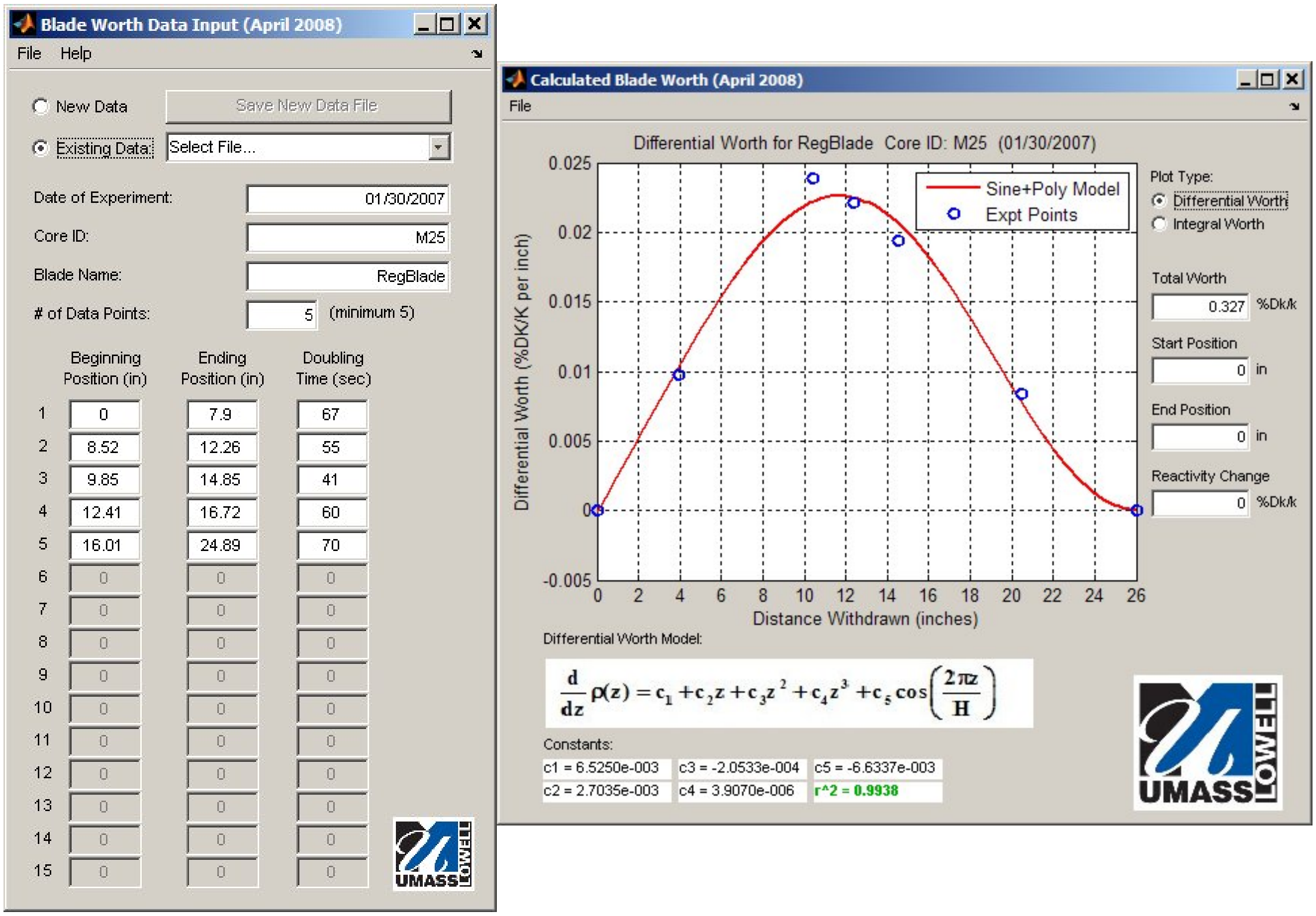
The blade_worth GUI

A graphical user interface was developed in Matlab to display the differential and integral blade worth curves for all the control blades within the UMLRR. The user interface for **blade_worth_gui** is split between two screens as shown in Fig. 1 -- the GUI screen on the left allows primary user control over the measured data and the one on the right displays the selected experimental and curve fit results. In the data control window, the user can enter new experimental data and save the measured data to a new file, or he or she can open an existing data file (series of *.dat files containing previous experimental data). The results window shows either the differential or integral worth curve (based on the selected plot type), the resultant model coefficients for the curve fit, and the r^2 correlation coefficient (near unity usually implies a good fit). This window also has two edit boxes where the user can enter a start and end value for simulated movement of the control blade, and the estimated reactivity worth is displayed qualitatively in the plot and quantitatively in a text box. An indication of the total blade worth is also given.

The **blade_worth** GUI can be used to get a good understanding of typical differential and integral worth curves and it can also be used to convert raw measured data from a blade calibration experiment within the UMLRR into useful graphical data. It is also a very useful tool for estimating the worth associated with a particular change in blade location. Finally, it also gives the user access to the model coefficients, which are often needed in a variety of other applications that require quantitative information concerning the blade worth. Overall, the **blade_worth** GUI can be useful as both an educational tool and as a convenient way for obtaining quantitative blade worth data for a variety of other applications.

References

1. J. R. Lamarsh, ***Introduction to Nuclear Engineering***, 2nd Edition, Addison-Wesley Publishing Company (1983).
2. J. J. Duderstadt and L. J. Hamilton, **Nuclear Reactor Analysis**, John Wiley & Sons (1976).
3. K. O. Ott and R. J. Neuhold, **Introductory Nuclear Reactor Dynamics**, American Nuclear Society (1985).
4. A. F. Henry, **Nuclear Reactor Analysis**, MIT Press (1975).
5. J. R. White, “One-Speed Point Kinetics Equations,” part of a series of Lecture Notes for the Nuclear Power Fundamentals Program at UMass-Lowell.
6. “FSAR Supplement for Conversion to Low Enrichment Uranium (LEU) Fuel,” Document submitted for review by the NRC for conversion of the UMass-Lowell Research Reactor (May 1993).
7. J. R. White, et. al., “Calculational Support for the Startup of the LEU-Fueled UMass-Lowell Research Reactor,” Advances in Reactor Physics and Mathematics and Computation, Pittsburgh, PA (May 2000).



○ New Data

● Existing Data: Select File...

Date of Experiment: 01/30/2007

Core ID: M25

Blade Name: RegBlade

# of Data Points: 5 (minimum 5)

	Beginning Position (in)	Ending Position (in)	Doubling Time (sec)
1	0	7.9	67
2	8.52	12.26	55
3	9.85	14.85	41
4	12.41	16.72	60
5	16.01	24.89	70
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0

Plot Type:

● Differential Worth

○ Integral Worth

Total Worth: 0.327 %Dk/k

Start Position: 0 in

End Position: 0 in

Reactivity Change: 0 %Dk/k

Differential Worth Model:

$$\frac{d}{dz}\rho(z) = c_1 + c_2 z + c_3 z^2 + c_4 z^3 + c_5 \cos\left(\frac{2\pi z}{H}\right)$$

Constants:

c1 = 6.5250e-003
c3 = -2.0533e-004
c5 = -6.6337e-003
c2 = 2.7035e-003
c4 = 3.9070e-006
r^2 = 0.9938

Fig. 1 Data control and results window for the blade_worth GUI.