APPENDIX B

Lambda Tuning Procedure

Lambda (λ) is the desired closed-loop time constant of an assumed linear first-order process. The following controller tunings are applied to achieve the desired response:

$$K_c = \frac{1}{PG}\left(\frac{1}{\lambda + DT}\right) \quad \text{(B.1)}$$

$$I = TC \quad \text{(B.2)}$$

where:

K_c = Controller gain (% controller output / % change in error)
I = Integral (seconds per repeat)
λ = Closed-loop time constant (seconds)
PG = Process Gain (% change in process variable / % change in controller output)
TC = Time Constant (seconds)
DT = Dead Time (seconds)

Lambda is chosen by the user so that:

$$\lambda \geq DT \text{ or } \lambda \geq TC$$

The open-loop process gain, time constant and dead time were determined by a applying a 5% controller output step change into the simulator. The PG, TC and DT parameters were estimated by a least squares fit to the data generated. Tests were performed at minimum flow conditions and therefore represent system dynamics at this region of operation.

Output Linearization Procedure

The procedure used for determining linearization curves in this study is:

1. Normalized discharge pressure curves are first determined using the simulator by plotting normalized discharge pressure against controller output. Data is generated for 1, 2 and 3 operating pumps.
2. A smooth curve is fit to the data using either polynomial or power functions. The following power function was found to be convenient for fitting normalized pressure data as it is constrained to pass through the [0, 0] and [100, 100] points, and is easily inverted.

$$y = 100\left\{1 - \left[1 - \left(\frac{x}{100}\right)^c\right]^a\right\} \quad \text{(B.3)}$$

   The two parameters ‘a’ and ‘c’ must be fit by nonlinear least squares.

3. The linearization curve is the inverse of the normalized discharge pressure curve. It can be determined in one of two ways:
   - A polynomial can be fit to 1/(Normalized Discharge Pressure) values
   - If a power function of the form [B.3] has been fit to the Normalized Discharge Pressure curve, the linearization curve is determined by Equation B.4:

$$y = 100\left\{1 - \left[\left(1 - \frac{x}{100}\right)^{1/a}\right]^{1/c}\right\} \quad \text{(B.4)}$$

4. Once linearization curves are determined, the gain curves for the modified process are redetermined. Lambda tunings are generated for this process using the maximum gain found over the entire operating region.