Name: ___________________________

Final Exam – Part I: Closed Book (25%)

Instrumentation and Process Control
CHEN 4570 – Spring 2000

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1. *(3 pts.)* During several of the laboratory sessions, the dynamic response of a system (e.g., heat exchanger, CSTR reactor, etc.) to set-point changes was measured. Control Station was then used to fit the data to a FOPDT and/or SOPDT model.

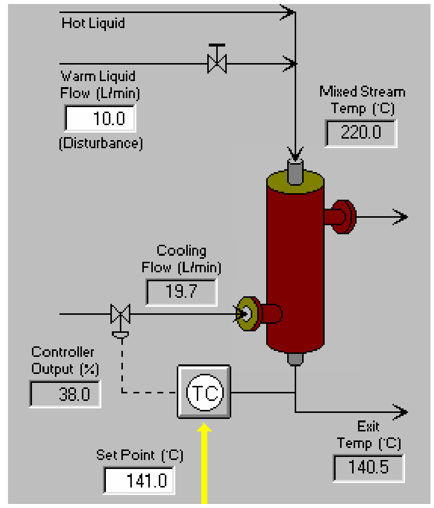
   a.) It is possible that the dynamics of such systems may have been higher than second order. Explain why FOPDT and SOPDT models provide good approximations for higher-order systems.

   b.) Will a SOPDT model always result in a better fit (i.e., lower SSE value) than a FOPDT model? Explain.

   c.) For the processes examined during lab, the SOPDT model provided a better fit than the corresponding FOPDT model. However, the FOPDT model was often used to determine controller settings. Why is a model with a poorer fit often used to find controller settings?

   Important Note: "The text only gave relations for controller settings based on an FOPDT model" will not be counted as a correct answer!

2. *(6 pts.)* To the right is a diagram depicting control system for a heat exchanger. On the following page are three sets of responses of the heat exchanger to changes in set points.



Each of the three cases depicted on the following page utilizes a different type of controller – one of the cases uses a P-only, another case uses a PI, and the remaining case uses a PID. For a given case, the responses shown on the left and right graphs were obtained by changing one of the controller parameters.

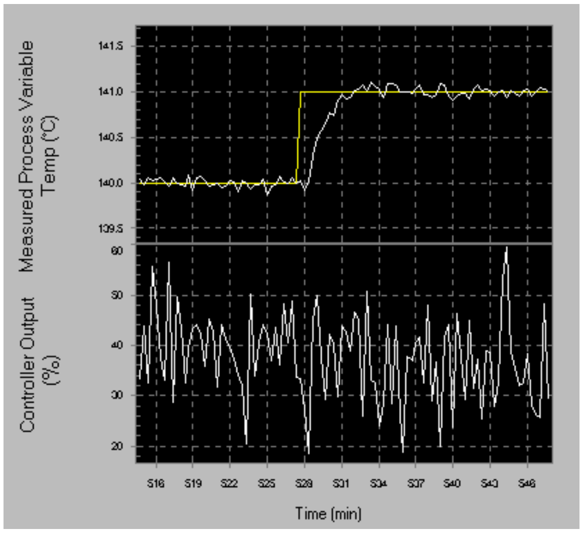
Based on these responses, answer the following questions.

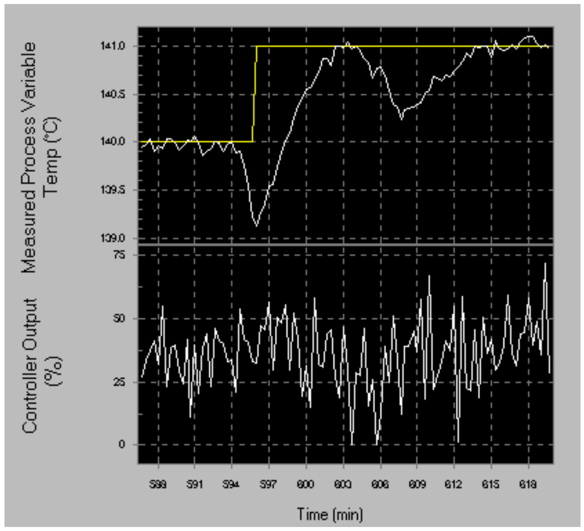
a.) Which of the three cases has a P-only controller? Explain. For this case, was the controller gain (K_c) of the leftmost response increased or decreased to obtain the response shown on the right? Explain.

b.) Which of the three cases is utilizing a PI controller? Explain. For this case, was the integral time constant (τ_I) of the leftmost response increased or decreased to obtain the response shown on the right? Explain.

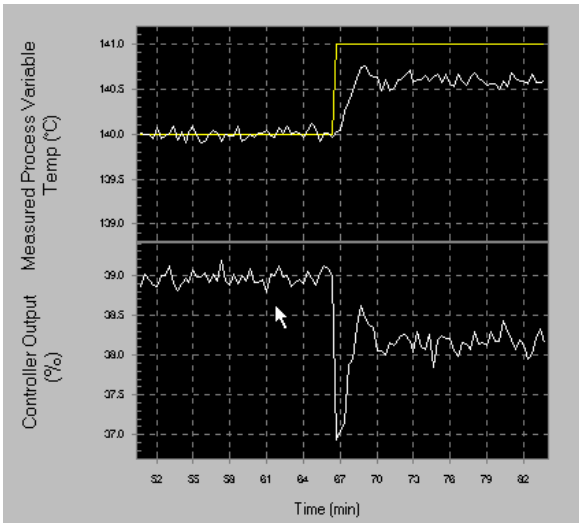
c.) Which of the three cases is using a PID controller? Explain. For this case, was the integral time constant (τ_D) of the leftmost response increased or decreased to obtain the response shown on the right? Explain.

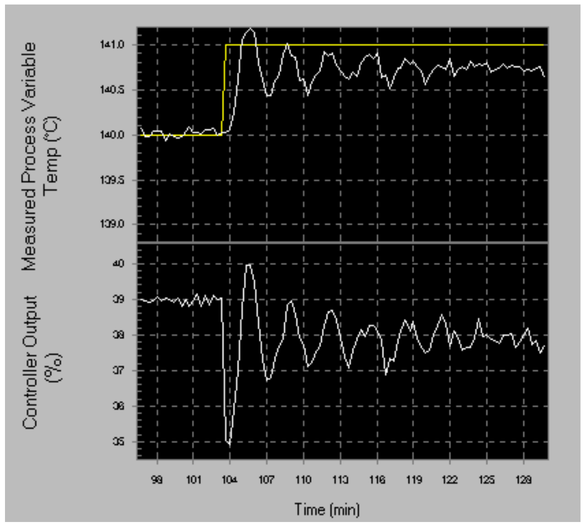
Case I:



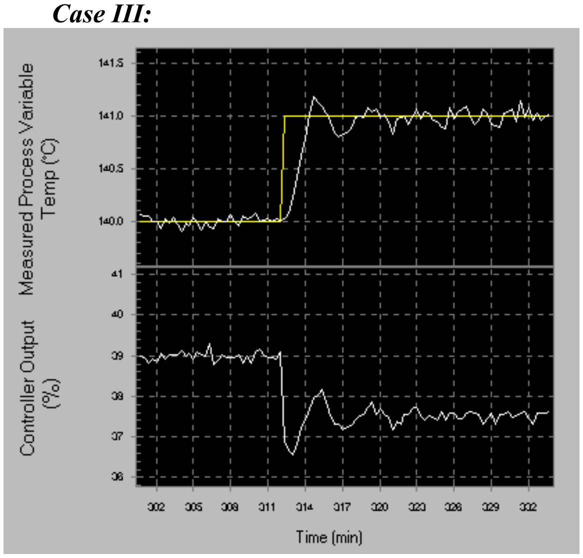


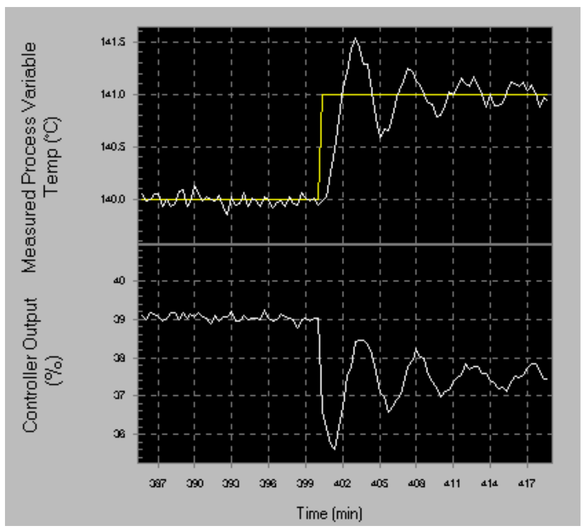
Case II:





Case III:





3. *(3 pts.)* Explain what type of situation would benefit most by the implementation of the following advanced control strategies.

   a.) Feedforward/Feedback Control

   b.) Smith Predictor

   c.) Cascade Control

4. *(5 pts.)* True/False

   ______ Given a perfect process model, a cascade control system can theoretically achieve perfect process control.

   ______ The phase angle associated with an open-loop transfer function is independent of the process gain and the controller gain.

   ______ A process model is required to implement a feedback controller (i.e., the process model is imbedded in the feedback controller).

   ______ Systems characterized by a negative process gain are physically possible.

   ______ When designing a controller using direct synthesis or internal model control, more conservative controller settings will result when the magnitude of the desired closed-loop time constant is increased.

   ______ A cascade control system should be implemented such that dynamics of the primary loop are much faster than those of the secondary loop.

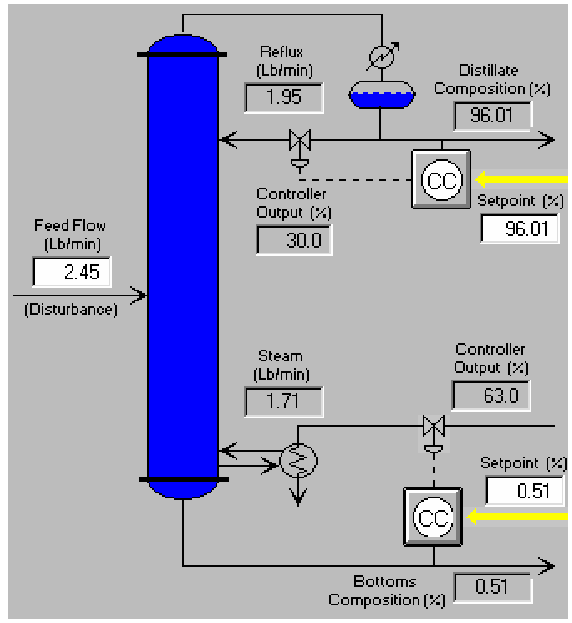
   ______ Given a physical processes in which the input is being varied in a sinusoidal manner, it is expected amplitude of the output will increase as the frequency of the input is decreased.

   ______ Systems characterized by a negative time constant are physically possible.

   ______ The dependence of the amplitude ratio and phase angle on frequency is shown explicitly on a Nyquist plot of the system.

   ______ The controller settings used in a Smith Predictor scheme are chosen according to the fitted process model without the dead time included.

5. (*8 pts.*) Consider the distillation column shown at the right.



a.) What are the controlled variables?

b.) What are the corresponding manipulated variables?

c.) Draw a block diagram representing this control scheme in the space below.

Final Exam – Part II: Open Book and Notes (75%)

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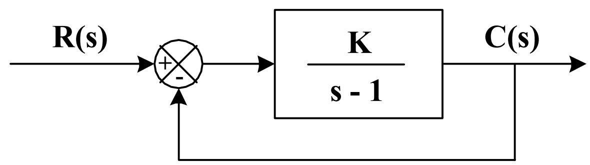
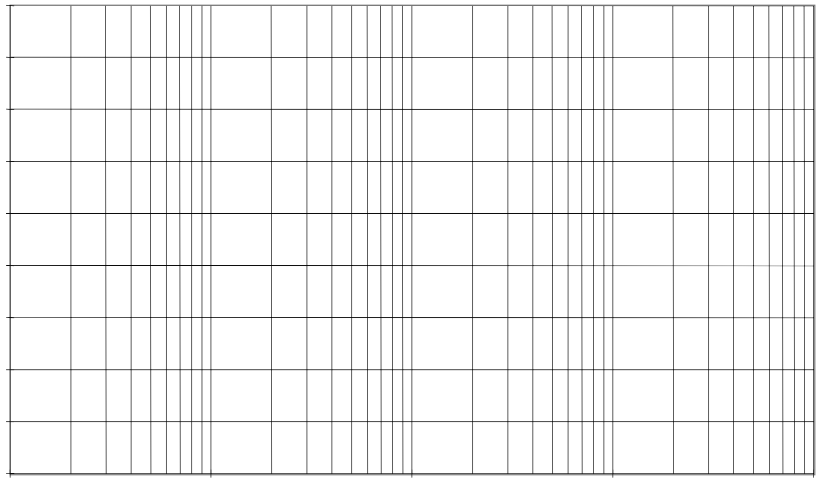
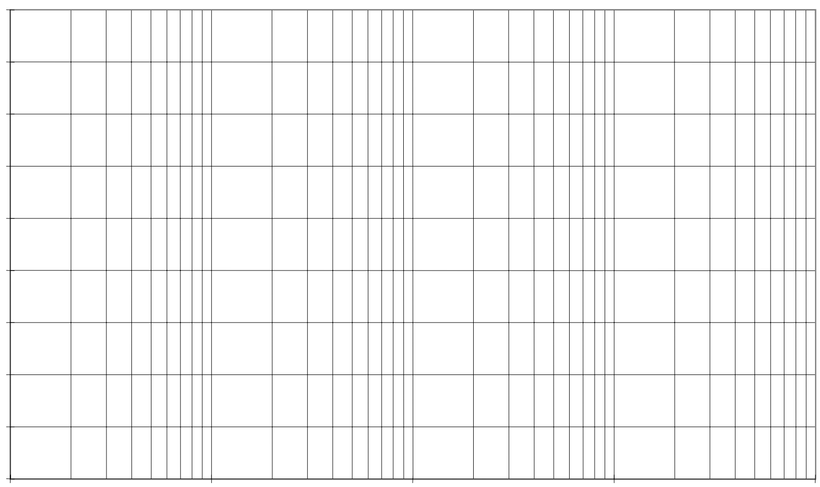
<u>Problem 1 (20 points)</u>

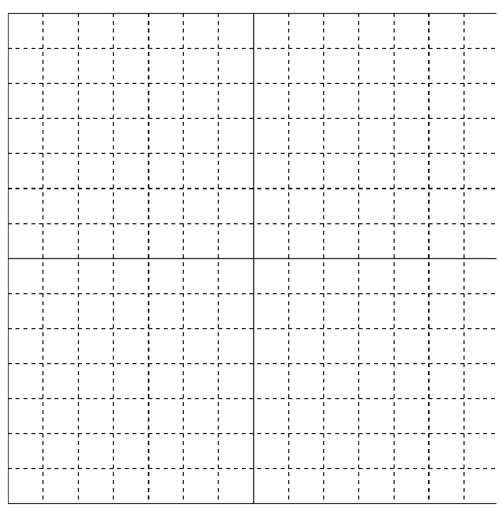


For the closed-loop system shown above:

a.) *(15 pts.)* For the open-loop transfer function (G_{OL}), sketch the Bode plots and Nyquist diagram using the graph paper on the following page. Be sure to label asymptotic values on the graphs.
b.) *(4 pts.)* Using the Nyquist stability criterion, determine the value of K at the stability limit.
c.) *(1 pt.)* Can the Bode stability criterion also be used to determine the stability limit? Explain.



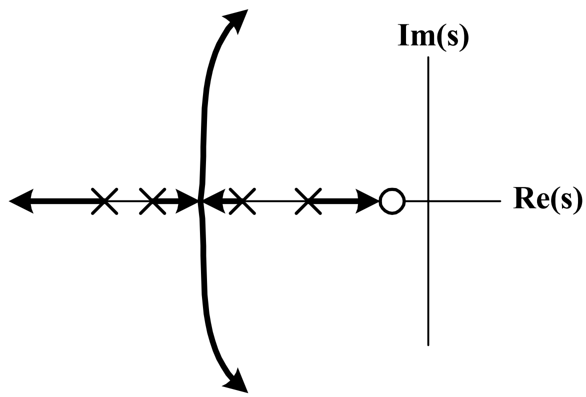




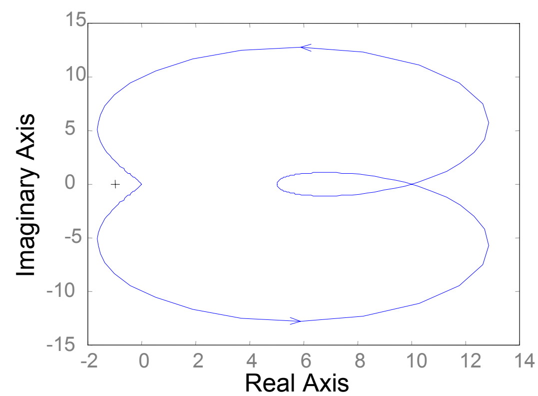
Problem 2 (15 points)

Below is a root locus, a Nyquist diagram, and Bode plots for three unrelated processes. These diagrams are based on the open-loop transfer functions ($G_{OL} = G_C \, G_V \, G_P \, G_M$) of the corresponding process. Answer the following questions for *each* diagram (i.e., answer each question for the process represented by the root locus diagram, and then answer the same set of questions for the process represented by the Nyquist diagram, and then similarly for the process associated with the Bode plots).

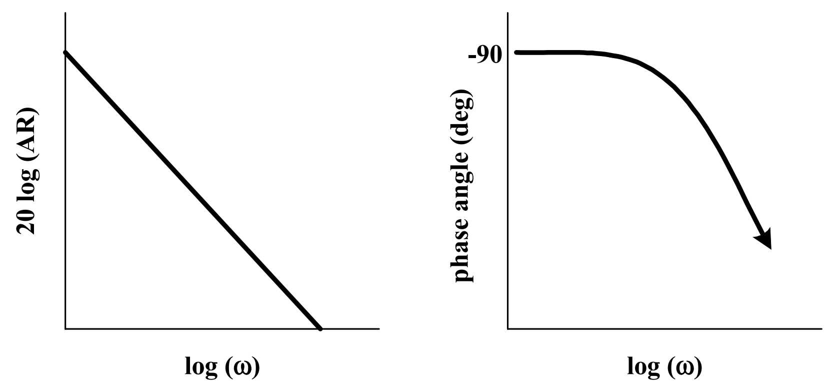
Important Note: There may not be enough information to answer some of the questions; if this is the case, write "cannot be determined based on given information"!



Process 1: *Root Locus Diagram*



Process 2: *Nyquist Diagram*



Process 3: *Bode Plots*

a) *(1 pt.)* Does the system have dead time associated with it? Explain.
b) *(1 pt.)* What is the order of the open-loop process? Explain.
c) *(1 pt.)* Is the system open-loop stable? Explain.
d) *(1 pt.)* Is the system closed-loop stable? Explain.
e) *(1 pt.)* How will closed-loop stability change as the controller gain is increased? Explain.

Problem 3 (15 points)

An experimental biotechnology process utilizes a microorganism M_1 for the batchwise manufacture of a vaccine. After each production cycle, most of the original mass of M_1 is recovered and reused, but after several cycles, a fresh supply of M_1 must be introduced and the "spent" batch of M_1 discarded. A special pond, cultivated as the natural habitat of a different microorganism M_2 is used for the disposal of M_1 because it is known that M_2 thrives and reproduces by feeding exclusively on M_1. However, if M_1 is left by itself in the pond, it will mutate somewhat and then begin to thrive and reproduce by feeding on lower forms present in the pond.

In monitoring the pond for the amount of M_1 and M_2 it contains, it is found, however, that contrary to initial expectations, the amount of M_1 does not decrease steadily with time; rather, it fluctuates in a distinctly periodic fashion. The same analysis uncovers another equally unsettling fact: that the amount of M_2 itself also fluctuates essentially with the same period as the M_1 fluctuations.

As a first step in understanding the observed phenomenon, the following mathematical model was developed for the dynamic behavior of the mass concentration of M_1 and M_2 in the pond:

$$\frac{dC_1}{dt} = a_1 C_1 - a_{12} C_1 C_2 + bW \quad \text{and} \quad \frac{dC_2}{dt} = -a_2 C_2 + a_{21} C_1 C_2$$

where C_1 and C_2 refer to the mass concentration (mg/L) of M_1 and M_2, respectively, W is the rate of introduction of M_1 into the pond (mg/hr) and a_1, a_2, a_{12}, a_{21}, and b are all constants that characterize the pond in question.

a.) *(5 pts.)* Show that the linearized approximation of this model in terms of deviation variables takes the general form:

$$\frac{dX_1}{dt} = \alpha_{11} X_1 - \alpha_{12} X_2 + bU \quad \text{and} \quad \frac{dX_2}{dt} = \alpha_{21} X_1 - \alpha_{22} X_2$$

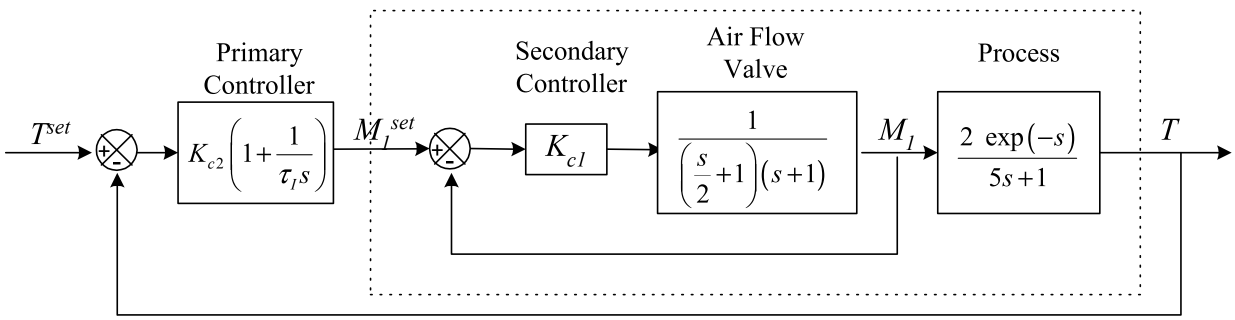
Provide explicit expressions for the quantities X_1, X_2, U, α_{11}, α_{22}, α_{12}, α_{21} in terms of the original model parameters.

b.) *(9 pts.)* Based on the simplified model given in part a, determine the response of X_2 in time to a step change in U? For the specific pond in question, the appropriate value parameters are estimated to be: $\alpha_{11} = 1.0$, $\alpha_{22} = 2.0$, $\alpha_{12} = 1.5$, $\alpha_{21} = 2.0$, and $b = 0.25$.

c.) *(1 pt.)* Comment on whether or not the predictions of this linearized model are consistent with the dynamic behavior observed via the pond monitoring system.

Problem 4 (25 points)

Your instructor is a stenotherm (last word-of-the-day!). In other words, she is only comfortable in a very narrow range of temperatures. Unfortunately, the feedback controller utilized in the Engineering Center does not provide tight temperature control. In particular, the air flow rate, which is used as the manipulated variable, is subject to significant disturbances and measurement noise in the upstream pressure supply. Out of gratitude, one of her students designs a cascade control system for her office! The block diagram of this system is depicted below.



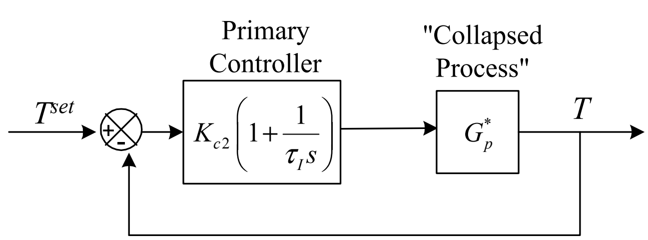
a.) *(2 pts.)* What are two possible approaches that the student may have used to determine the G_v and G_p? Describe (in a sentence or two) what these approaches entail.

b.) *(1 pt.)* Based on the models obtained for the G_v and G_p, is cascade control an appropriate choice for this process? Explain.

c.) *(2 pts.)* Did the student choose the most appropriate controller types for the primary and secondary loop? Explain.

d.) *(7 pts.)* The student plans to design the inner loop of the cascade controller such that it responds like a second-order process with a damping coefficient of 0.707. Is this a reasonable design criteria? Explain. Assuming that the process requires a reverse-acting controller, what is the resulting value of K_{c1} ?

e.) *(4 pts.)* Now the student needs to choose controller parameters for the primary loop. Due to the complexities associated with the inner loop, the general plan is to approximate the secondary controller, valve, and process (i.e., everything contained in the boxed region) with a simpler model (e.g., FOPDT or SOPDT). As a first step, the student simplifies the block diagram by collapsing the blocks contained in the boxed region into a single block, as shown below. What is the time-constant form of the resulting transfer function G_p^* ?



f.) *(2 pts.)* To approximate G_p^* as a FOPDT transfer function, the student first checks Control Station's "Custom Process" tool, but finds that the form of G_p^* is too complex to use this utility (i.e., the form of G_p^* does not take the general form required by Control Station). But alas (!), the student determines another method of modeling G_p^* as a FOPDT system. In a few sentences, describe this alternative method.

g.) *(7 pts.)* Suppose the student finds that G_p^* can be approximated by the following transfer function:

$$\frac{0.65\exp(-1.5s)}{5.8s+1}$$

The student wants to compare the primary controller settings obtained using two different criteria: ITAE performance index and Cohen-Coon relations. What values are obtained? Which criteria results in the most conservative controller parameters? Explain.