

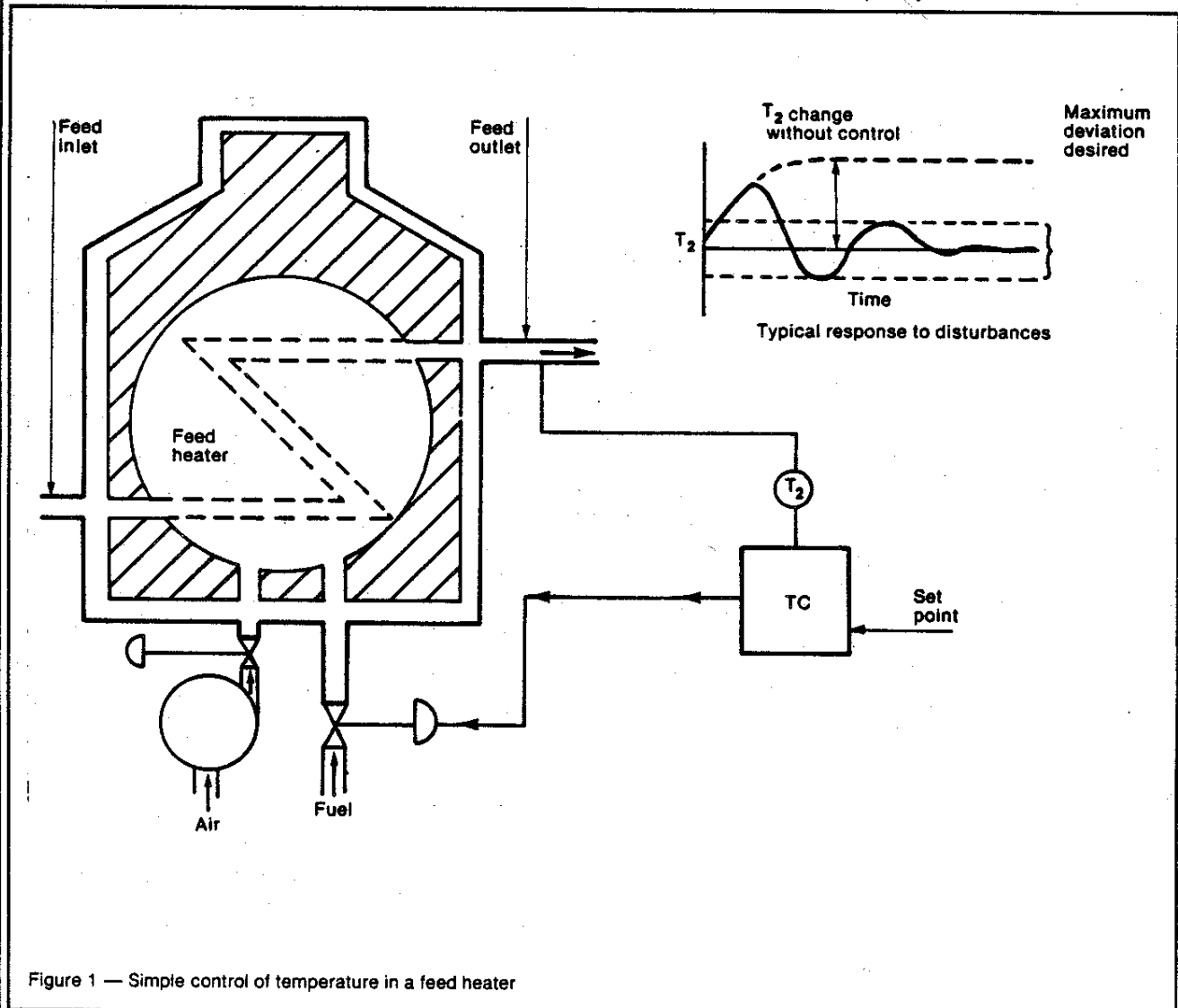
Cascade Control

Why Cascade Control?

Sometimes a simple feedback control loop cannot keep a controlled variable near the set point even with the best possible controller adjustments. The simple loop includes one measuring element, one controller, one final control element. For example, it may include a thermocouple, a pneumatic

three-mode controller, and a valve. The temperature may show large deviations from the set point and may be slow to return when it does deviate. Changes in some process conditions disturb the temperature so much that the system is unable to control it acceptably. Corrections cannot be made soon enough. Figure 1 shows simple temperature control of a feed heater. Figure 2 shows the control loop in block form.

When the measured temperature deviates from the set point, the temperature controller will adjust the fuel valve. If all characteristics of the fuel stay constant—including, for example, its pressure—control can be good. But wide variations in fuel pressure will rapidly change the flow even for one position of the valve stem. The temperature in the heater will consequently



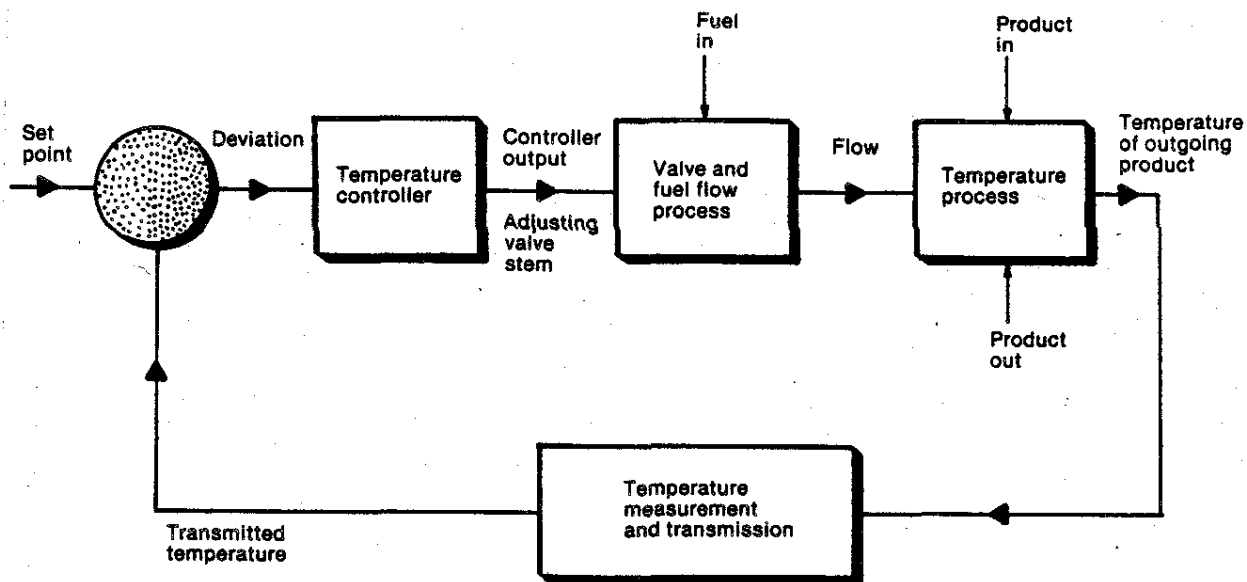


Figure 2 — Block diagram of the control loop as the signal transmitting system for Figure 1

change, though relatively slowly.

When the news of the temperature change reaches the controller, the controller readjusts the valve as though the valve opening had been wrong. Time elapses before the controller knows that any correction is needed, additional time before it knows how much, and still more time before its correction of the valve position can return the temperature toward the set point.

The temperature process, relating flow to temperature, involves negligible dead time but some lags. These are represented by the "process" block in Figure 2. Though the flow changes very fast, the temperature changes comparatively slowly. The temperature is hard to control because the valve adjustment is not made until the temperature has changed. Continued disturbances in pressure will not only result in continued and unnecessary valve correction, but they can make close control unobtainable.

The system is designed to control by valve adjustment. Yet *heat supply*, not valve adjustment, actually determines the temperature. If the quality of fuel is constant, flow can then determine the temperature. Flow is not controlled. Flow is of only secondary interest, but its fluctuations will affect the variable which is of primary interest - the temperature.

In fact, secondary interest is in flow because it represents heat supply and is therefore related to temperature. The most desirable control system would give best control of net heat input (heat input minus heat losses) and therefore of product temperature. In any temperature application, any condition which determines heat input is of interest, important because it affects temperature. Such secondary conditions include not only flow but fuel characteristics such as Btu content or steam temperature.

Ignoring other possible factors, consider only the disturbing flow changes caused by fuel pressure disturbances. If valve adjustment could be made as soon as any disturbing condition caused a change in flow, the effects of the disturbance would then be controlled faster. Fast repositioning of the valve would prevent the disturbance from having time to appreciably affect the temperature. Control of flow can usually be fast; liquid flow changes at once and gas flow changes fast when upstream pressure changes. Fast transmitters and controllers permit fast readjustment of the valve.

But the reason for controlling the flow is to *keep the temperature at the desired value*. Constant flow may not do it. It will not if there is any change in fuel quality or in furnace load. Changes in flow must still be called for by deviations in temperature.

If the temperature controller is made to adjust the flow set point, then the temperature will be issuing the commands. The flow controller can obey the command by adjusting the valve. For flow changes, the flow controller will be able to make fast corrections without waiting for any effects to be felt in the temperature.

The two controllers in series then act to keep the temperature constant. The temperature controller commands, the flow controller obeys. *This controller arrangement is defined as cascade control.*

In brief, *this is the combination of conditions when cascade control should be considered:*

1. Under control by a simple system, the variable is slow to respond to disturbances or corrections, and its deviations sometimes become undesirably large.
2. Some change in a process condition causes serious upsets in the controlled variable.
3. The value of some other variable (pressure, flow, temperature) is affected by the disturbance and is definitely related to the value of the controlled variable.
4. The secondary variable can be controlled, responds rapidly to disturbances or corrections, and needs to be controlled at the command of the primary variable.

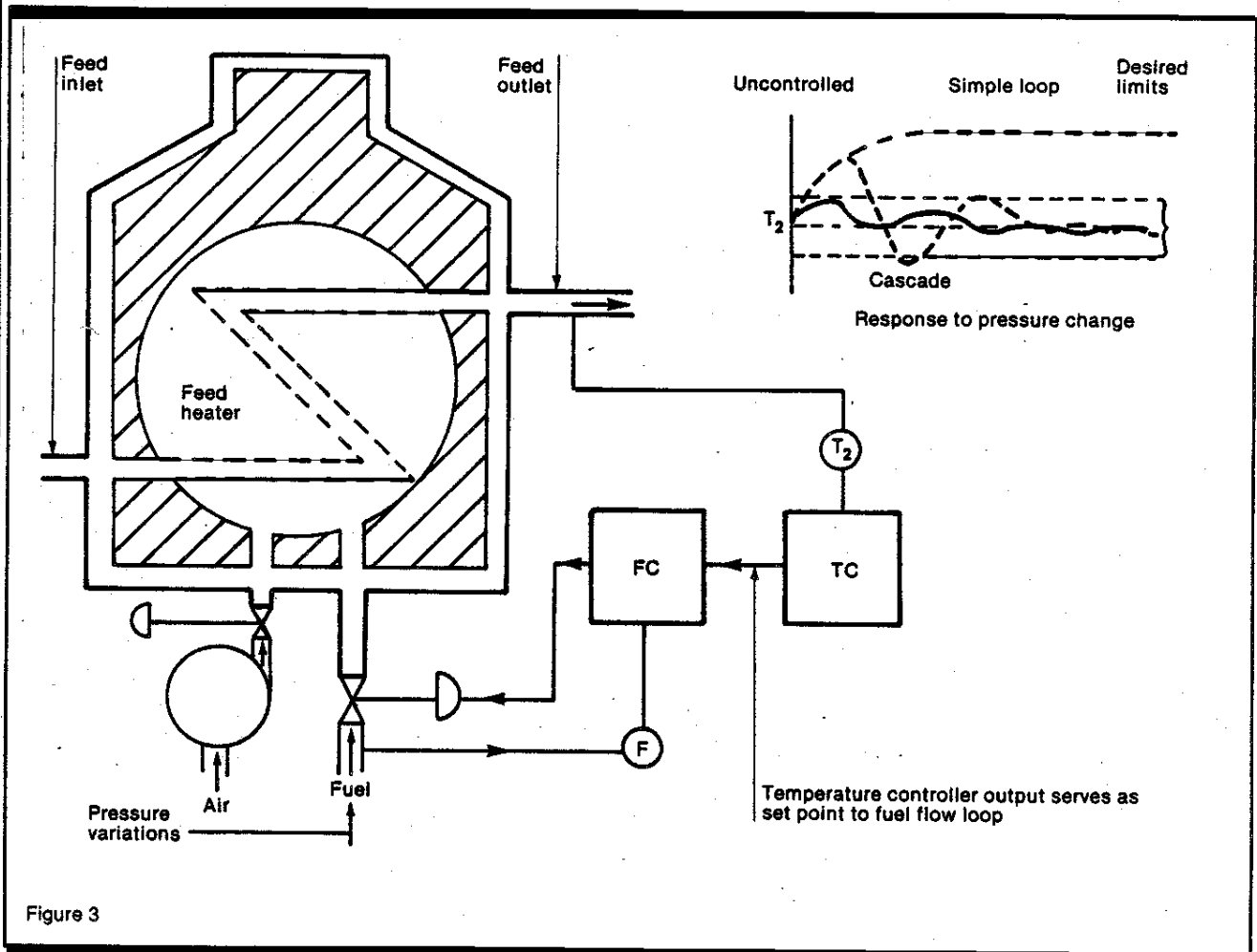


Figure 3

The Cascade Arrangement

Figure 3 shows cascade control of the feed heater of Figure 1.

If the temperature rises, the temperature controller output must call for less heat. Instead of doing it by reducing the valve opening, it lowers the set point of the fuel flow controller. The flow controller, responding to comparison of the measured flow to the flow set point, adjusts the flow by reducing the valve opening.

By its set point, the flow controller obeys the command of the temperature controller. By responding to flow deviations, it adjusts the flow after a flow disturbance, returning the flow to the set point. The most likely flow disturbing condition is fuel pressure fluctuations.

This system cannot make fast corrections for any variations in net heat input which are not reflected in flow. For clearest view of its usefulness, it must be shown in block diagram form, as in Figure 4.

Figure 4 is typical of the block diagrams

of all cascade control systems. Except for the possible addition of more "process" blocks, the diagram for any other cascade system will be identical with Figure 4 except in names of variables and disturbances.

These are the significant points:

1. Two items of instrumentation have been added beyond that needed for the simple loop — the secondary controller and the secondary measuring transmitter device. The control element is unchanged and is part of the secondary loop.
2. The secondary controller (also called the "slave controller") has one special characteristic — its set point can be adjusted by a transmitted signal. The signal comes from the primary controller (also called "master controller").
3. The process is shown as having separable parts — the fuel flow process (relating flow to valve stem position) and the temperature process (relating temperature to flow).

4. Two control loops are identifiable, the complete secondary loop acting as a component of the primary loop. The secondary loop is the fast loop in which corrections are made rapidly for any disturbances which enter it. The

primary loop includes the slower part of the process (the change in temperature as related to change in flow or valve position). Some disturbances enter the secondary loop (fuel pressure disturbances). The others enter the primary (fuel heat content or load disturbances).

For any cascade control system, all of those conditions will be true, though the words in parenthesis would have to be changed. Cascade arrangements are most used for temperature control because the temperature process is apt to be relatively slow, and a secondary condition (such as fuel flow or pressure) actually determines heat flow. But cascade control is also suitable for other relatively slow "processes," such as gas analysis or a slow-changing tank pressure. What makes a process seem "relatively slow" is desire for faster, closer control.

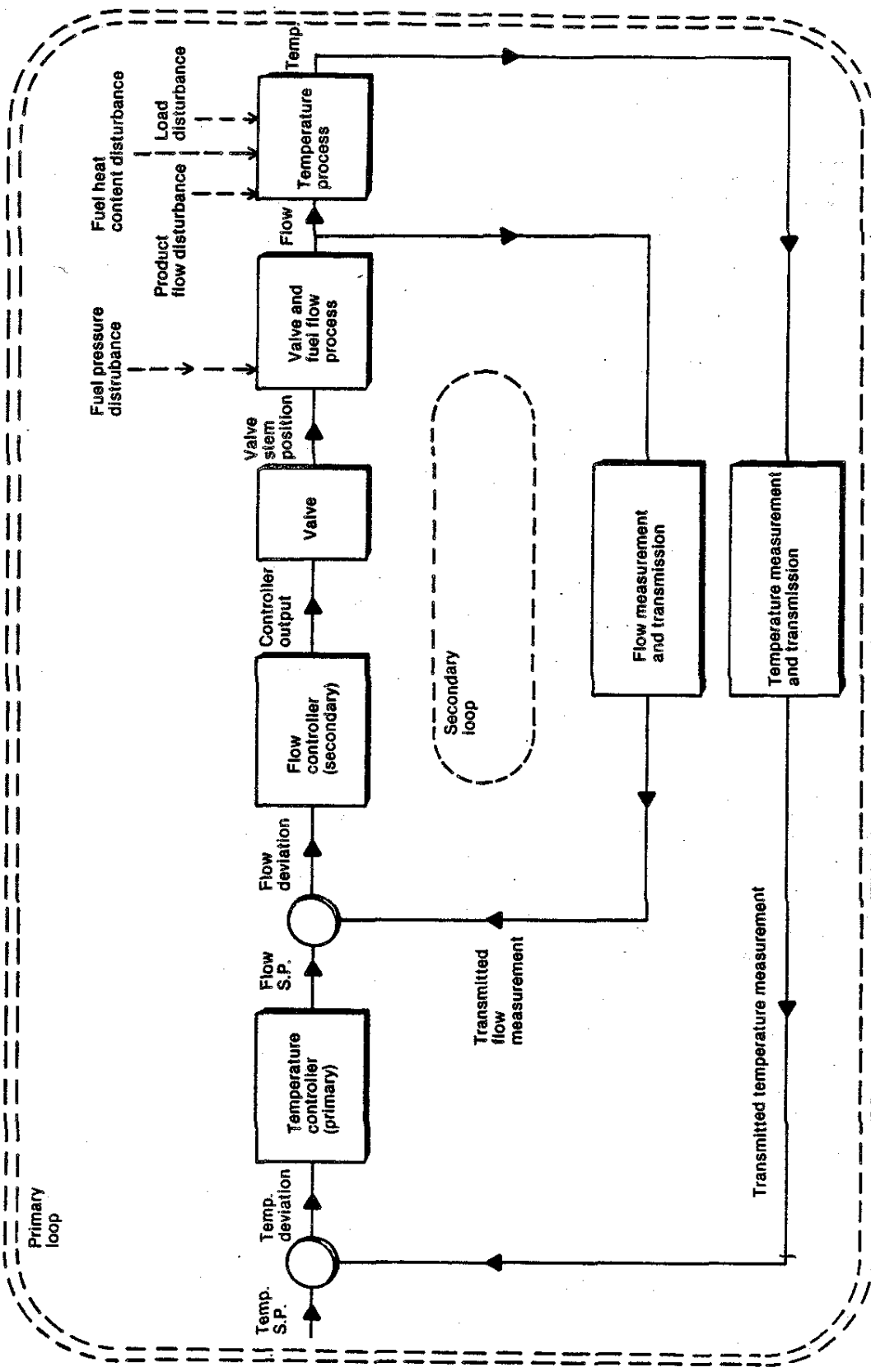


Figure 4 — Block diagram of cascade control of temperature with secondary control of fuel flow to a feed heater

How It Can Improve Control

Any well planned cascade control system will give closer control of the primary variable. (It is usually relatively unimportant that it also control the secondary variable.) Compared to simple-loop control, it has two major advantages - decrease in deviations and increase in speed of lineout of the primary variable after distur-

bances. The improvement actually obtainable with the specific cascade arrangement will depend upon process and disturbance relationships as discussed in "Rules of Thumb." Possible improvements are summarized under the first two points below, though the maximum improvement will not be obtainable in *all* cascade arrangements. The cascade control system also offers the advantage described under the third point - additional protection for product and equipment by simple high and low limiting of the secondary set point.

1. *Decrease in Deviations of Primary Variable*

Cascade control can reduce the peak deviations of the primary variable

and reduce the area under the deviation curve.

For disturbances entering the secondary loop, the peak deviations can be reduced at least to half height and possibly by factors of tens, the area under the curve by factors of hundreds. The control valve is readjusted before the disturbances in the secondary variable can severely affect the primary variable.

For disturbances entering the primary loop, peaks can be reduced to half height and the area reduced by a factor of five or six. The whole system responds faster because the response within the secondary loop is so fast.

2. *Faster Line-out of Primary Variable*

The primary variable will nearly always line out faster after any disturbance. Normal controller adjustments usually result in a transient cycling period of not more than two or three cycles, and the time they take can be reduced to half as long even for disturbances which enter

the primary loop. Not only will secondary-loop corrections be fast, but line-out of the primary variable will also usually be speeded up for disturbances entering anywhere.

3. *Additional Protection for Product and Equipment*

High and low limits on the index of the secondary controller can serve to protect the product or process equipment from extreme conditions. The limits can be set mechanically or electrically without restricting the available motion of the final control element. Flow set point, for example, can be held at a minimum value needed for satisfactory operation of process equipment or at a maximum value to avoid spoiling the product.

Rules of Thumb for Designing a Cascade Control System

The most useful cascade control will be obtained only with wise choice of the secondary variable. This is the vital requirement in successful cascade system design. How much improvement will actually be obtainable will depend on locations of disturbances and response speeds of system components.

But rules of thumb can be used in designing the system. They can also increase understanding of system performance.

To use the rules, *start by drawing a block diagram*. It clarifies reasons for choices. Allow three separate blocks for the process though two may prove to be enough. Otherwise, make the diagram identical with Figure 4, but with no lettering except the "SP" for set point inputs to the two controllers and with the secondary loop measuring point not yet chosen. Then letter the diagram to show the instrumentation of the specific system and to define the specific process blocks. Each block represents one of the physical relationships which actually exist between the "position" of the final control element and the value of the primary variable. Examples of such blocks are given in Figure 5.

Then plan possible alternates for placement of the secondary measuring ele-

ment and selection of the secondary variable, using these five rules of thumb:

1. *Make the secondary loop include the input point of the most serious disturbances.*

It is the effects of these disturbances which the cascade system will be most successful in controlling.

2. *Make the secondary loop fast by including only minor lags of the complete control system.*

This requires understanding something about the speed of response of the secondary loop or of the blocks which are its components. To follow this rule of thumb it is necessary to compare response speeds of T_s and T_P as defined in Figure 5.

The higher the ratio T_P/T_s , the more the cascade system will reduce deviations resulting from disturbances entering the secondary loop. The ratio should preferably be at least 3 and it is advantageous to have it higher - 5 or 10.

One rule of thumb sometimes given is that the secondary loop should be closed around the second-longest lag in the system. For large reduction in deviations resulting from distur-

this rule will be good only if the ratio T_P/T_s can still be kept high. This normally means that the second-longest lag would have to be only 1/2 to 1/3 as long as the longest lag.

In instrumenting the secondary loop, keep it fast by using measuring, transmitting, and controlling hardware with short time constants or high natural frequencies.

3. *Use a Secondary Variable with Set Point Values Definitely and Usefully Related to Values of the Primary Variable.*

In *undisturbed* operation of the system, at line out, the relation between secondary set point and primary variable should be representable by a single line. If the line is straight rather than curved, this will simplify the adjustment of the primary controller.

Aside from disturbances, the value of the secondary variable will then determine the value of the primary variable: if the secondary can be kept near its set point, the primary will stay near a corresponding point. When the secondary set point is adjusted, it can then act to control the primary variable, raising it or lowering it as needed.

Typical physical relationships between the secondary and primary variables are shown in Figure 6. The

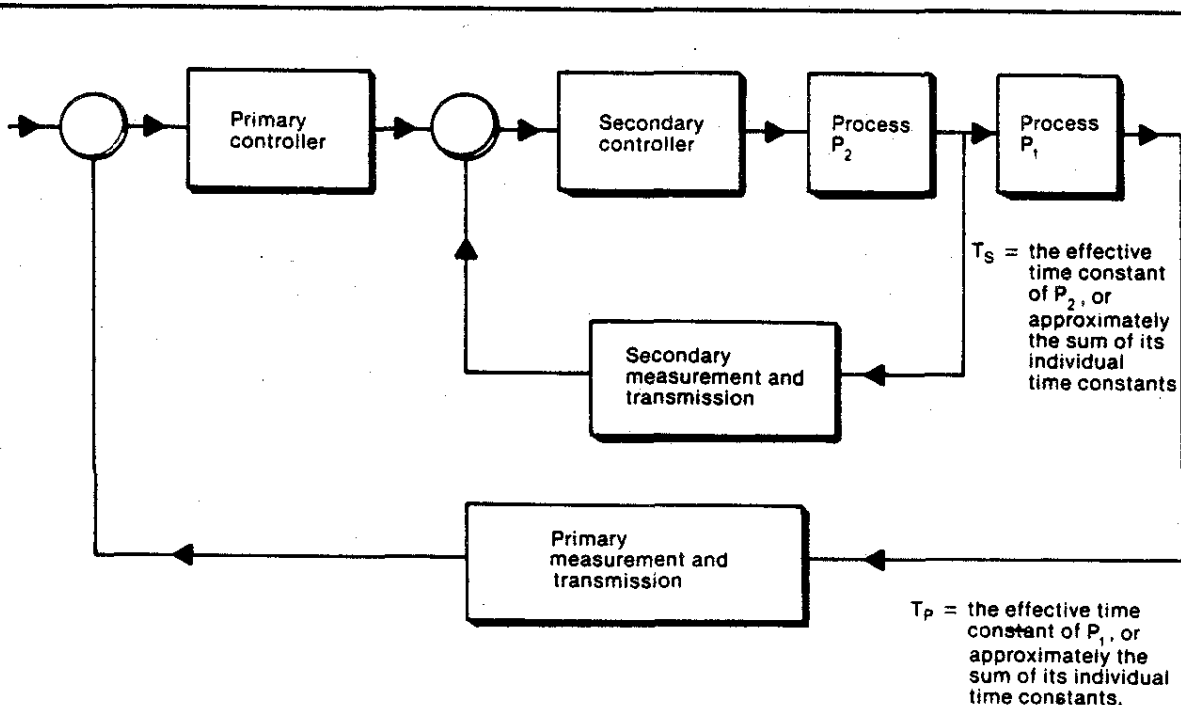


Figure 5 — Cascade control loop and the most significant time constants

recorder-controller measuring range of the primary variable is fixed by the total range over which measurement and control are desired. The required recorder-controller range for the secondary variable depends on the physical relation between the two variables. The secondary controller should be able to make corrections even at the extremes of set points required under steady-state operation. This effect on the secondary span is indicated in both sketches of Figure 6, where the secondary recorder span is wider than the required range of set point.

Always, it is desirable that the secondary variable (controlled by its set point) be the principle factor in determining the value of the primary variable. Any other factor which determines the value of the primary variable must be recognized as a disturbance.

4. If it can be done with the secondary loop still kept relatively fast, make

the secondary loop include as many of the disturbance inputs as possible.

This will more strikingly improve the control for more disturbances. In addition, by closing a loop around more of the process, it will have maximum effect in speeding up the cycling during line-out with a well-planned loop. The cycling of the primary variable can be twice as fast if dead time is negligible and will be faster than simple control even if dead time is appreciable.

Any shorter, lower cycling can result in marked improvement even for disturbances entering the primary loop.

5. *Choose the secondary variable which will provide stable performance with the narrowest proportional band (the highest gain) in the secondary controller, if the other rules of thumb are satisfied.*

The improvement in closeness of control for disturbances within the secondary loop will be roughly related to the

proportional band settings of both controllers. (This assumes all process equipment to be the same in both cascade systems, and both transmitters to have the correct range for full, accurate transmission.) If M_P is the gain

$$\text{of the primary controller} = \left(\frac{100}{PB_P} \right)$$

M_S the gain of the secondary controller, and M the gain of the single-loop controller, peak deviations after disturbances within the secondary loop will be lower than those under simple control by a factor of $\frac{M_S M_P}{M}$. The comparative effectiveness of alternate cascade designs can be measured by the relative values of the product $M_S M_P$.

Blind use of rules of thumb is impossible in designing any control system. Judgement will always have to be applied, based on knowledge of the actual system, the actual disturbances, and the performance most desirable in control of the specific variable.

Figure 6a — Straight-line relation between primary variable and secondary set point
Secondary recorder-controller span can be chosen so that needed percent change in set point equals percent change in primary variable.

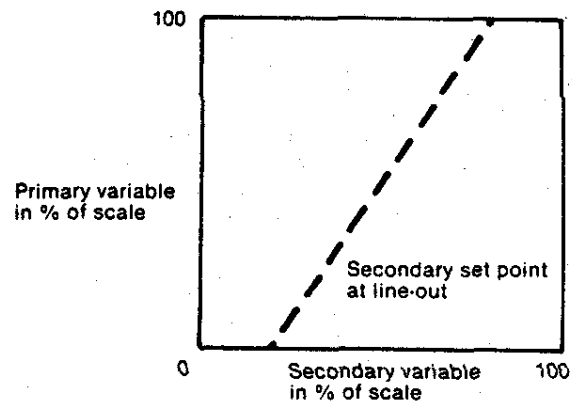


Figure 6b — Curved-line relation between primary variable and secondary set point
Secondary span can still be chosen to permit correction at extremes of set point, but required percent change in set point for percent change in primary variable will depend upon primary set point.
For set points near B, relatively large changes in set point will be needed for a specific change in primary variable. Near A, small changes will be required. Short lines show straight-line approximations to the actual curve at A and B.

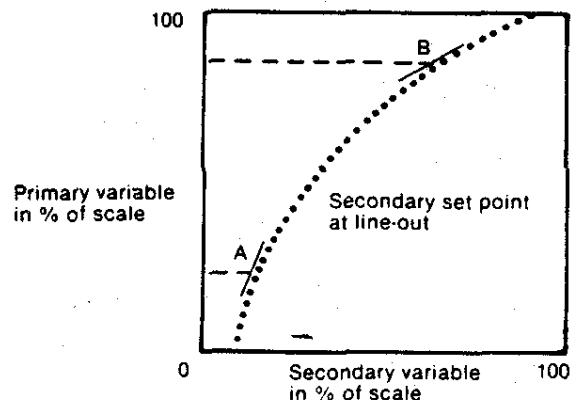


Figure 6 — Typical physical relationships between secondary set point and recorded value of primary variable (0 and 100% are minimum and maximum recorded values of the two variables)