Protect Centrifugal Pumps From Low Flows

Operation of centrifugal pumps below their minimum flow requirements is the primary cause of premature pump failure. Hydraulic instability occurs at low flows, causing cavitation, surging, and excessive vibration in the pump. This instability is more restrictive in setting the minimum allowable flow than using the temperature rise, which was used in the past. If you are the system design engineer, you should consider providing a protective system during the preparation of the piping and instrumentation diagrams (P&ID's). Not all pumps is to determine which pumps do and which do not, and decide the type of system to employ. This decision must be made as early as possible in the development of the P&IDs to avoid costly rework. This article gives guidelines on when to provide a protective system and offers examples of appropriate designs.

Why provide protection ?

Protection against operation below the safe low-flow limits is required for the following reasons :

1. To prevent damage due to overheating ;
2. To prevent cavitation and vibration due to excessive internal recalculation ;
3. To prevent damage due to excessive radial reaction ;
4. To prevent damage due to cycling between two points if the performance curve is humped ; and
5. To prevent overloading of drives for certain types of pumps (axial flow, mixed flow, and regenerative turbine) which have horsepower curves that rise toward shutoff.

The extent and type of damage to a pump depends on how long low flow persists and on the magnitude of the forces and vibrations that are generated. Failure of the mechanical seals is the most common problem, followed by failure of the bearings. Loss of efficiency due to wear of the impellers by cavitation is usually a slower process.

The cost of pump maintenance amounts to about 40% of the total for many process plants (1). If the addition of a low-flow protection system can reduce these costs and also reduce plant upsets, then the cost of the system is more than justified.

When to provide protection

Every pump should be examined to determine whether or not low-flow protection is required. To make the decision, you must be familiar with the modes of operation of the plant and the effect the control systems may have on the pump operation. The following operating modes should be examined.

1. Is the plant designed for stable operation during prolonged turndown conditions, e.g., 50% of capacity ?
2. Is the plant to be started up slowly at reduced flow rates?

3. Is the flow reduced when there is a plant upset?
4. Is the pump flow controlled by a level controller (or a flow controller reset by level)?
5. Can the flow rate be cut back or stopped by a downstream user?
6. Is the pump in critical service?
7. Are two pumps with different head/capacity curves operating in parallel in the same system with a common control?
8. Is the fluid at its bubble point or does it contain dissolved gas?

If the anticipated flow rate for any of these modes of operation is less than the minimum required for stable operation of the minimum required for stable operation of the pump, then a low-flow protective system is warranted. Capital and operating costs, reliability, are maintainability are factors to consider.
Applications that frequently are provided with low-flow protective systems are :

- Feed pumps ;
- Product pumps ;
- Intermediate transfer pumps on level control ;
- Boiler feed water pumps on level control ;
- Steam condensate pumps on level control ;
- Firewater pumps ;
- Utility water pumps ;
- Drinking water pumps ; and
- Pumps operating in parallel with different head/capacity characteristics.

Applications that normally do not require minimum flow protection are :

- Circulating cooling-water systems ;
- Circulating heating or cooling medium systems ; and
- Any system with a fixed flow rate.

Setting minimum flow rate

In the past, temperature rise in the pump was considered to be the limiting factor setting the minimum flow requirements (2). The minimum flow was set at 10-15% of design based on a temperature rise of about 20°F. This resulted in few pumps being provided with minimum flow protection systems and many pump failures. Due to research over the past 30 years (3-6), it has been realized that the minimum flow requirements can be as high as 70% to prevent excessive internal recalculation causing vibration, cavitation, and surging. This can occur even with considerable excess available net positive suction head (NPSH). Pump vendors now specify the low-flow limit for both thermal limitations and hydraulic stability.

Since pump vendors usually have not been selected during the initial phase of P&ID development, the specified minimum safe flow is unknown. It is impossible to determine the low flow limit for hydraulic stability without having specific information on the internal design of the pump. The guidelines in Table 1 may be useful in deciding whether or not to provide a minimum flow protection system. These guidelines are based on articles by Taylor (7) and Makay (8). If the recommended minimum flow limit is above any of the anticipated low-flow modes, then the addition of low-flow protection may be justified.

The percentages in Table 1 are based on the design flow (normal flow) of the pump, which are usually 5% below the flow at maximum efficiency (best efficiency point or BEP). The BEP is normally halfway between the design and rated flows. It is common practice to specify the rated capacity as 110% of design. In some cases the rated flow may be 125% of the design flow. In these instances the minimum flow listed in Table 1 should be increased proportionally. Pump vendors normally quote the minimum flow based on the BEP. Unstable flow conditions can also occur if the pump is operated much above its rated capacity, that is, >110% of design. If pre-selection of the pumps for a project can be made, a better estimate of the low-flow limit may be obtained.

The recommended minimum ratio of $NPSH_a$ to $NPSH_r$ is also given in Table 1. During the hydraulic calculations for the P&IDs, you must set the heights of the suction vessels to provide adequate NPSH for the pumps. As indicated, it is general practice to provide a safety factor for the NPSHa which is based on experience. It is normally not necessary nor economical to provide more than the recommended minimum.

Figure 1 shows typical operating ranges for centrifugal pumps in different services. It should be noted that there is a limit for operation at too low a flow as well as too high a flow. In general, the safe operating range for high-capacity (over 1,000gpm), high head (over 250 psi), high-horsepower (over 300 hp) pumps is less than for small, low-head pumps.

The required minimum turndown for a pump may be specified to the pump vendors. Generally, it is normally not economical nor possible to purchase a specially designed pump that can over the required range of conditions. However, there are some special cases where this has been justified for improved safety and reliability.

At the time the pumps are purchased and the manufacturer's recommended minimum flow rates are received, the low-flow requirements should be reviewed. This is normally before the issue of the P&IDs but after many of the piping drawings have been prepared. It is cost-effective to provide the protective systems on the P&IDs as early as possible – that is, do it right the first time.

Finally, during the process hazards review of the P&IDs, the need for protective systems for the pumps, and the design of the protective systems should be analyzed. Lack of protective systems or faulty designs have resulted in many disruptions to operations.

Table 1. Guidelines to determine when a low-flow protection system is needed.

Type of Service	Recommended Minimum Flow, % of Design	$NPSH_a/NPSH_r$
Hydrocarbons, single-and double-suction	25-50	1.1
Water and water solutions, single-suction	40-70	2.0
Water and water solution, double-suction*	70-85	2.0
Pumps with domed head/flow curves	Below shutoff head	1.1-2.0

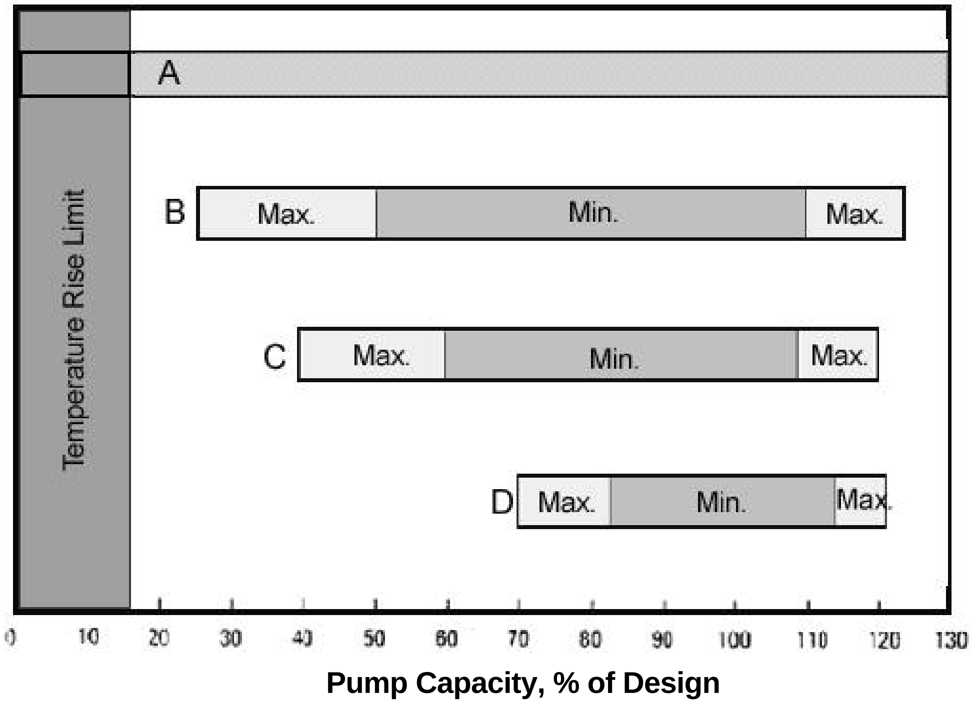
* Generally above 1,000 gpm.

Nomenclature

ARC = automatic recalculation valve
FC = flow controller
FI = flow indicator
HLL = high liquid level
LC = level controller
LLL = low liquid level
NLL = normal liquid level
$NPSH_a$ = net positive suction head available, ft
$NPSH_r$ = net positive suction head required, ft
PC = pressure controller
PT = pressure transmitter
RO = restriction orifice
SV = solenoid valve

Table 2. Guidelines for using low-flow protection systems.

Protection System	High Power Cost Pump Size, hp	Low Power Cost Pump Size, up
Continuous bypass	<15	<30
On/off bypass	10-15	20-30
Automatic recalculation valve	>15	>35
Modulating control valve	>15	>30



Safe Operating Range

A Full range of pump head/capacity curve

B Safe range for hydrocarbon pumps

C Safe range for single-suction water pump

D Safe range for double-suction water pumps

Minimum is the safe operating range.

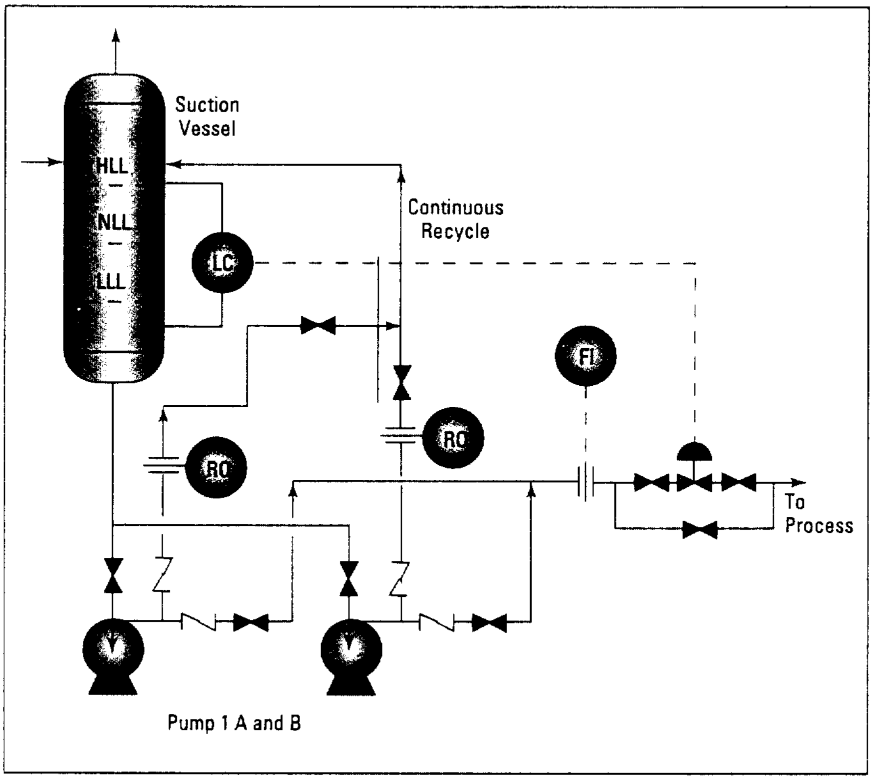
■ **Figure 1. Safe operating range.**

Recalculation systems

There are three basic types of by-pass systems for low-flow protection ; continuous, on/off, and variable flow. Which type to select depends on the service, capital, and power cost. Table 2 gives guidelines for each application. In the table, high power costs are 8₵/kWh and low costs are 3₵/kWh.

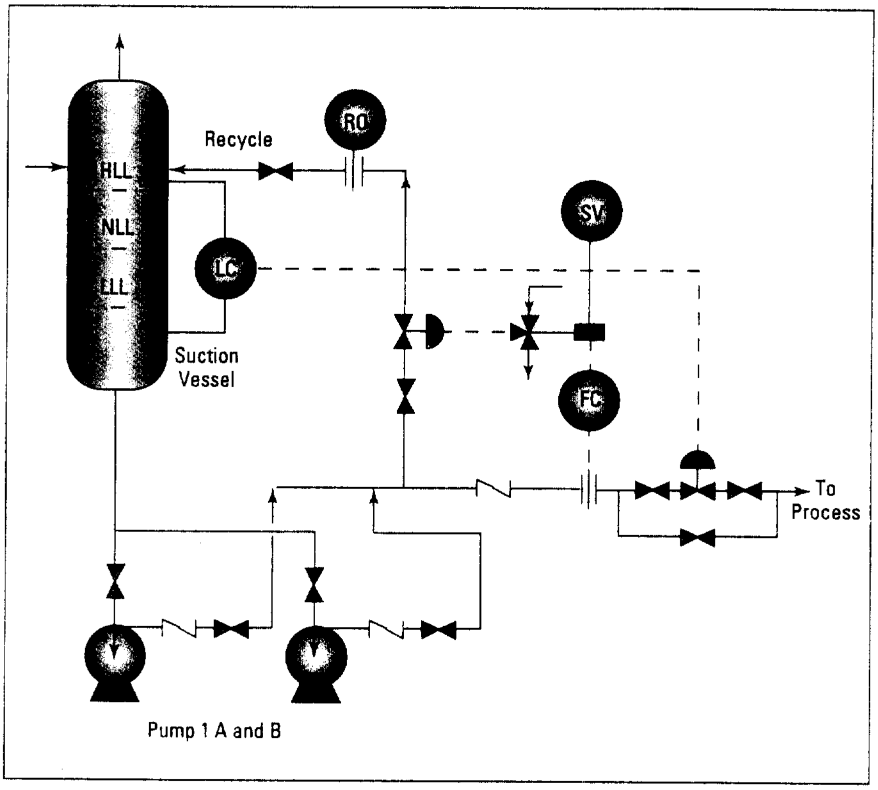
The recycle line should return to the vapor space of the suction vessel. If this is not possible, then recycle through a cooler and return to the suction line. If this alternative is not feasible and the recycle is short-term, that is, of a few minutes' duration, then return the recycle to the suction line as far upstream as practical. The design of these different protective systems is now considered.

Continuous recalculation (Figure 2) – This is the least expensive low-flow protection system. A fixed orifice in the bypass line controls the minimum flow. The continuous by-pass must be added to the normal flow to set the design capacity of the pump. Thus there is a continuous waste of energy when the pump operates above the minimum required flow.



■ Figure 2. Continuous recycle system.

Recalculation with an on/off valve (Figure 3) – This is the next least expensive system. The on/off valve in the recalculation line opens wide whenever the flow element in the main line drops below the safe minimum flow. A fixed orifice controls the recalculating flow. A disadvantage of this system is that when the on/off valve opens or closes it can cause sufficient hydraulic shock to upset sensitive systems. This type of system is not generally recommended. It should only be used if the minimum recommended flow is less than 30% of the design flow.

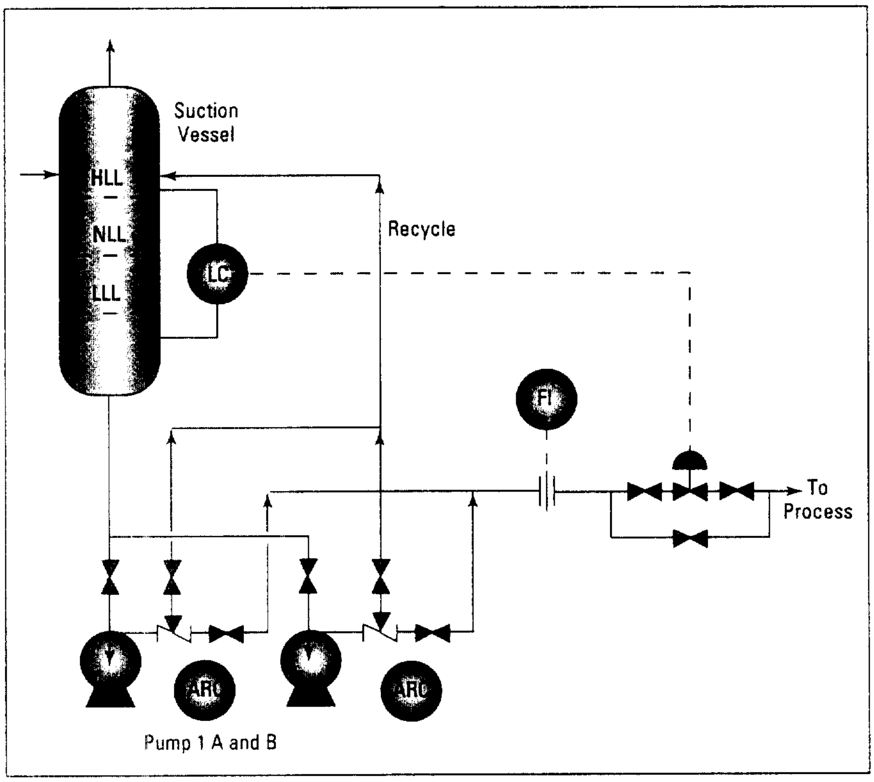


■ **Figure 3. On/off recycle system.**

Some experts will disagree with providing a single recycle system,. as shown in Figure 3 and 5, for a pump and its spare. When a single recycle system is provided, it is incumbent on the operators to be aware that only one pump at a time should be operating. This is accepted as the normal practice in many oil refineries and chemical plants.

A check valve is provided in the main process line downstream of the bypass branch. This check valve is required to prevent reverse flow from any downstream source returning to the suction drum via the recycle line in case of pump failure. There is a check valve at the discharge of the pumps for added insurance against reverse flow through the pump.

Automatic recalculation valve (Figure 4) – The automatic recalculation (ARC) valve has been used for many years to control the minimum flow for pumps in clean service, such as for boiler feed water and steam condensate. More recently, it has been used in many chemical and hydrocarbon services. It is a combination of a check valve and modulating control valve. The spring-loaded check valve acts as a flow-sensing element. Its position controls the opening of the bypass port. It is factory set to begin opening the bypass port when the flow drops to the minimum recommended rate.

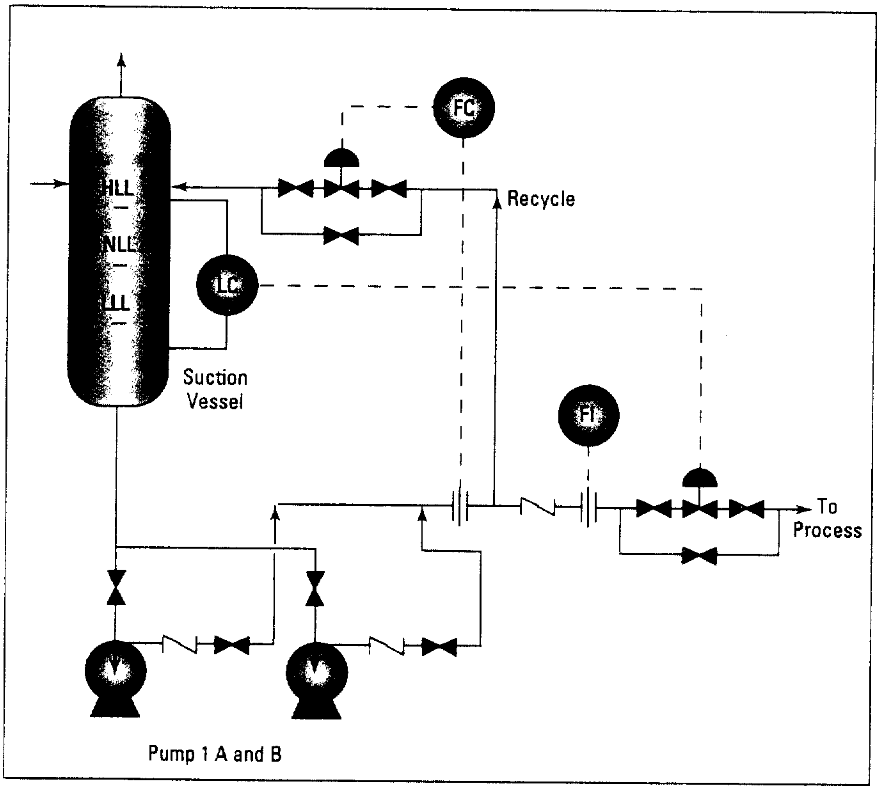


■ **Figure 4. Automatic recirculation system with ARC valve.**

The bypass is fully open when the forward flow stops and the check valve is in the closed position. An orifice in the bypass port limits the by-pass flow to that required for safe operation. The ARC valve allows smooth operation over the full capacity range of the pump.

The total of an ARC valve installation to protect one pump and its spare is about the same as for a single control valve recycle system up to 3 in. For 4 in. and over, the latter system is less expensive. ARC valves can also be purchased with the dual function of protecting with the dual function of protecting against low flow and excessively high flows. This system is particularly useful when two or more pumps subject to low flow are operated in parallel.

Modulating control valve (Figure 5) – This is the most commonly used system in process plants. It is used in services where the presence of scale or solid particles makes the use of ARC valves unsuitable. The recycle valve is frequently controlled by a flow element on the discharge of the pump. Other methods are also used, such as pressure control, differential temperature across the pump, and motor amperage. Figure 6 shows an example of a pressure controlled system. The controller is set to begin opening at a pressure corresponding to the minimum flow requirement. In general, pressure control of the bypass is not as good as flow control because it is not as sensitive to flow changes.

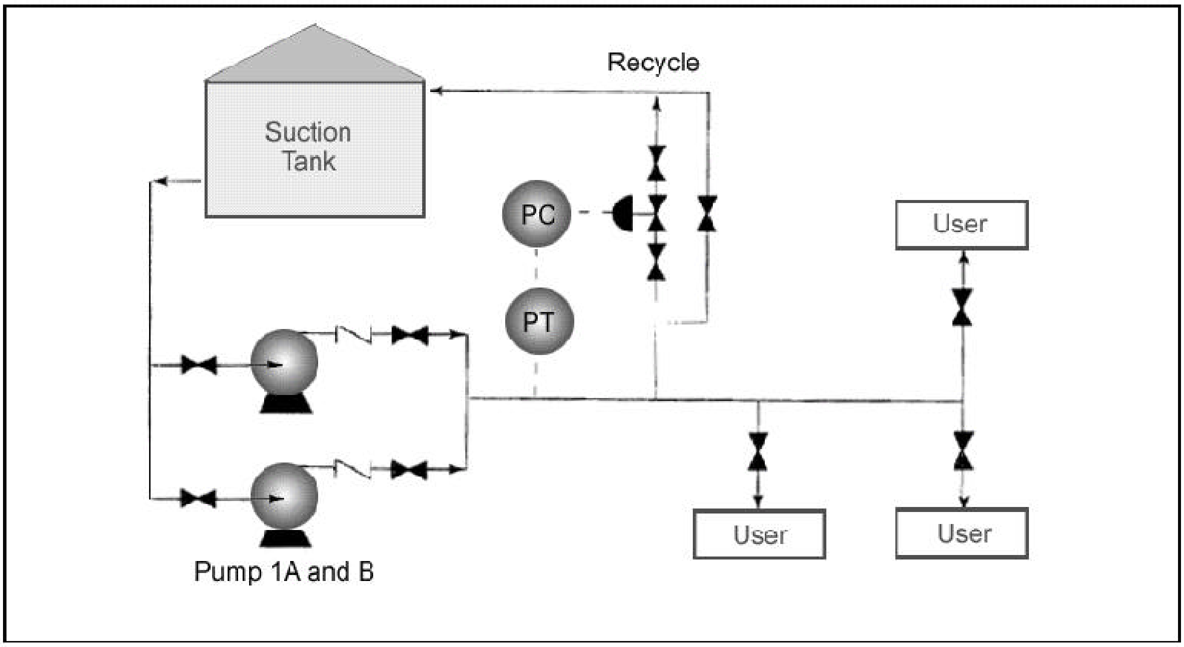


■ **Figure 5. Flow-controlled recycle system**

The system shown in Figure 5 is for the case where there are two pumps, one of which is spare. The flow controller is set to begin opening when the discharge flow falls below the minimum recommended rate. If both pumps are operating, the minimum flow setting should be doubled or the control system changed to protect both pumps, for example, change to pressure control if applicable.

Existing units

If a pump in your processing plant has excessive failures, it may be the consequence of periodic operation outside the safe limits for low or high flow. Find out from the operating staff if there are any periods of low or high flow, either short-or long-term. If this is the potential cause of the failures, consider increasing the NPSH available, modifying the operating procedures or providing a low or high-low protection system. Check the pump specification for the recommended range for stable flow. If it is not listed, ask the manufacturer for its recommendation.



■ **Figure 6. Pressure-controlled recycle system**

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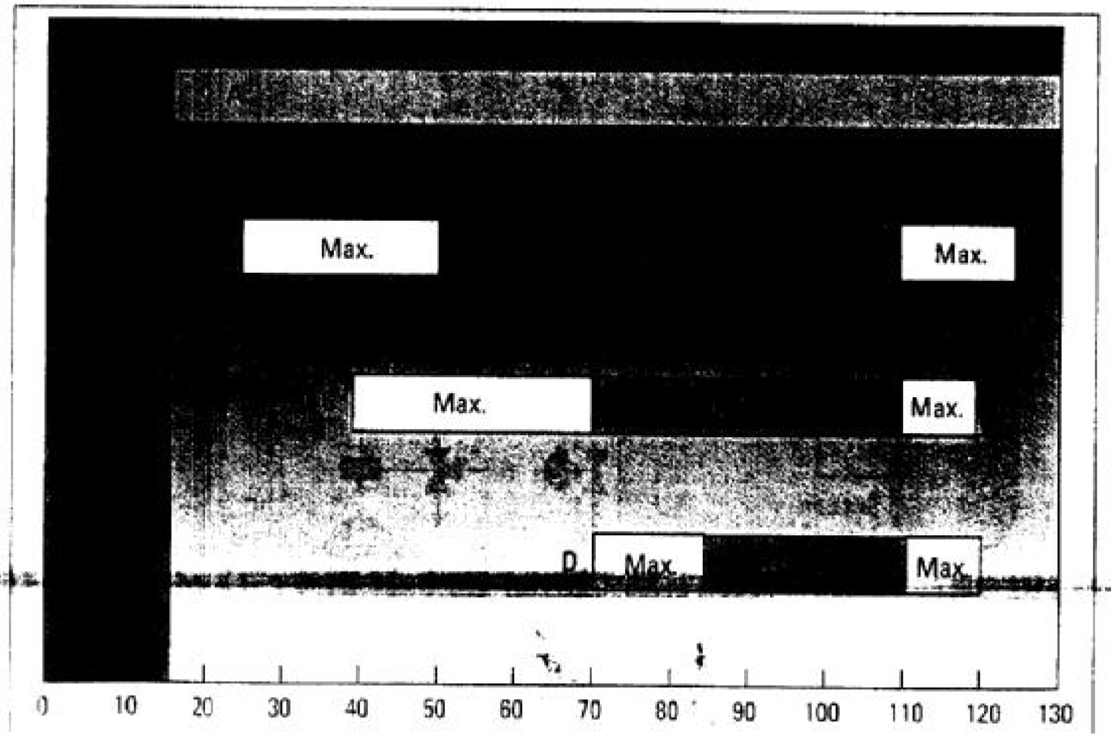
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