which this higher velocity can be produced in the drive pipe will decrease; hence, the combined efficiency of the ram will decrease with an increase of pumping head.

If all other conditions remain constant, there is one pumping head for which the efficiency of the ram will be a maximum.

Length of Drive Pipes.—Other things remaining constant, the efficiency with which a given velocity can be produced in the drive pipe decreases as the length of drive pipe increases. This is due to pipe friction. The time required to attain a certain velocity with a given head increases as the length of drive pipe.

The efficiency during the retardation period is theoretically independent of the length of drive pipe. Practically, however, on account of the slip in the check valves and the loss in waste valve closure, it is not. The slip depends upon the frequency of the valve action, which, other things being fixed, depends upon the length of drive pipe. The longer the drive pipe, the fewer the strokes and less the slips.

The proportion of loss due to slip increases with the pumping head, both on account of the greater tendency to slip and the shortening of the delivery stroke. Therefore, a longer drive pipe is required for high heads than for low ones.

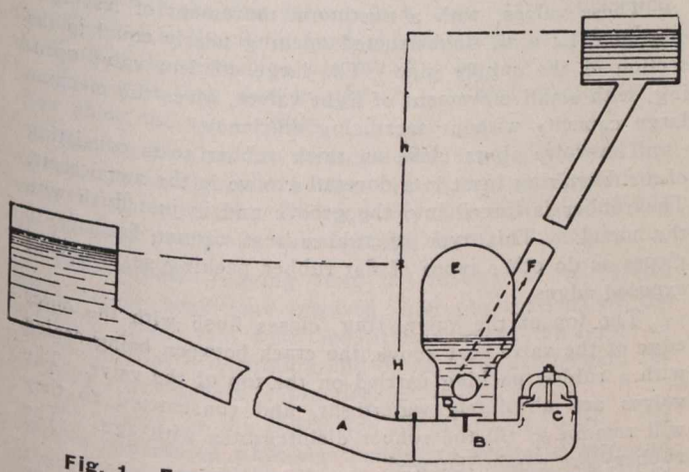

Fig. 1.—Essential Features of the Hydraulic Ram.

If the drive pipe is too long the friction is excessive, and if too short the slip is abnormal, hence there is for each size of ram with each combination of supply and delivery head a certain length of drive pipe that will produce the maximum efficiency.

There is also another working factor involved in the operation of the ram that has an influence on the minimum practical length of drive pipe. If the drive pipe is too short, or steep, the surging and vibration of the water column may interfere with the smooth operation of the valves, and the interfering waves will decrease the efficiency if the stroke is not carefully synchronized with the pressure vibrations. If too long a drive pipe is used, with the ordinary upward discharge, the automatic air supply will not work.

Size of Drive Pipe.—The main loss during the acceleration period is the pipe friction. During the retardation period the pipe friction is a minor loss. The efficiency of the ram will be increased by using the larger pipe, or a greater capacity will be secured with the same efficiency. The larger the size of the ram, with corresponding size of drive pipe, the greater the efficiency of the machine.

Strokes Per Minute.—Under any given conditions the capacity of the ram depends upon the velocity obtained in the drive pipe, and that depends upon the number of strokes per minute with which the machine is operating. The fewer the strokes, the greater the capacity, and the greater the number of strokes, the less the capacity.

A long, slow stroke allows the water to attain a greater velocity at each stroke and a corresponding greater average velocity, or flow through the pipe and ram.

For any given set of conditions there is a certain number of strokes that will produce the maximum efficiency. The efficiency increases with the number of strokes to a certain point, after which it decreases.

With a given supply head the efficient number of strokes increases with the pumping head to a maximum, and then decreases.

Limiting Factors.—The physical possibilities of the hydraulic ram are limited—first, by natural laws governing its operation, and, second, by human ingenuity in devising ways to make practical its possibilities.

Fundamental Limitations.—There seems to be no law law directly limiting the height of supply head that can be used, except that it must always be less than the lift above the ram. Let us, then, consider the pumping head. As stated before, the amount of pressure that can be developed by the sudden stoppage of water in the ordinary pipe is about 60 lbs. per sq. in. per second-foot of velocity stopped. Hence, the problem resolves itself into one of velocity obtainable in the drive pipe. In small pipes the limiting, or critical, velocity is soon reached. For example, a velocity of about 5.5 ft. only per second can be attained in a 1-in. pipe with a slope of 10 to 1, while in a 12-in. pipe with the same slope a maximum velocity of nearly 18 ft. per second could be attained. The practical operating velocity would probably be about two-thirds the maximum.

Thus it is apparent that, while a one-inch ram is limited to about a 400-ft. lift, under ordinary conditions, a 12-in. ram should be able to lift water at least 1,000 ft. The drive head that can be used must in each case be considerably less than the lift above the machine for practical operation. It is apparent that the fundamental limiting factors are beyond all practical requirements; hence, the problem resolves itself into one of practical design and mechanical construction.

Mechanical Limitations.—The design and operation of the waste valve seems to be the vital point. The ordinary hydraulic ram has an upwardly discharging waste valve of the disc type. The force of gravity—that is, the weight of the valve—is depended upon to open it and hold it open until it is forced shut, as previously described.

Machines of this type naturally have their limitations. Fifty feet seems to be the limit of the height of supply head that can be used. In the first place, the static head against which the valves will open is limited. They will not open with a long drive pipe or small ratio of heads. A moderate velocity will close them. For small rams, however, they answer very well. As the size of the disc valve increases, the area exposed to ram pressure increases as the square of the diameter, while the waterway around the circumference only as the first power. Thus the practical limit as to size is soon reached. This limit seems to be about 8 inches.

Certain manufacturers have lately cut the centres out of their discs and introduced light springs to assist the operation. This was quite an improvement, and they were enabled to increase the size of their machines, so that 12-in. rams may now be secured.

A Progressive Step.—Daniel W. Mead, now professor of Hydraulics at the University of Wisconsin, was the first to depart from the old rule-of-thumb design.

In 1895 he built and installed (under conditions that no ram manufacturer would attempt) a machine for the village of West Dundee, Illinois. In fact, no ram on the market today would operate under the same conditions.