

PRINCIPLES OF INJECTOR OPERATION

By Jeffrey G. Hook July 4, 1996 Revised May 29, 2016

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"An Injector is an apparatus in which a gaseous jet impinges and is condensed by a fluid mass whose final kinetic energy exceeds that of a jet of similar form and density discharging under the initial pressure of the motive jet." The foregoing from Chapter 3 of Practice and Theory of the Injector by Strickland L. Kneass, edition of 1910.

"An injector is an instrument by means of which a jet of steam acting on a stream of water with which it mingles, and by which it is condensed, can impart to the resultant jet of water a sufficient velocity to overcome a pressure that may be equal to or greater than the initial pressure of the steam. Thus, steam from a boiler may force feed-water into the same boiler, or into a boiler having a higher pressure. The mechanical energy of the jet of water is derived from the heat energy yielded by the condensation of the steam-jet." The foregoing from Chapter 18 of Thermodynamics of the Steam Engine by Cecil H. Peabody, edition of 1909.

"In order that an injector shall deliver water against the steam pressure in a boiler its velocity [of the resultant water jet] must be greater than would be impressed on cold water by a head equivalent to the boiler pressure." The foregoing also from Chapter 18 of Thermodynamics of the Steam Engine by Cecil H. Peabody, edition of 1909.

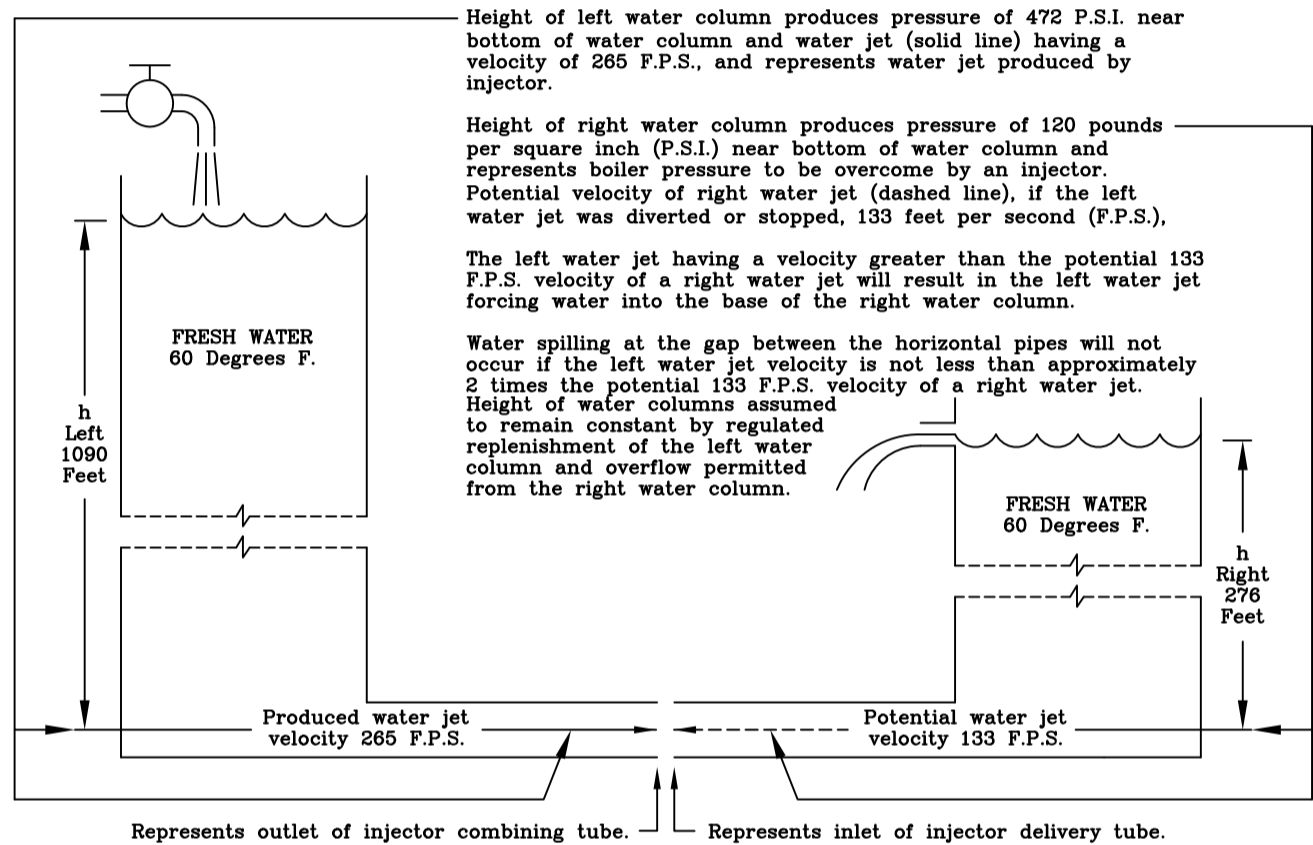
To view S. L. Kneass's and C. H. Peabody's complete works see Lake Forest Live Steamers Railway Museum suggested technical and historical reading list at www.lflsrm.org

Note: C. H. Peabody uses S. L. Kneass's earlier edition of 1898 as a reference.

The following drawings have been produced to assist in illustrating the principles outlined above. The values are approximate and have been derived from formulas presented in C. H. Peabody's work. The phrases jet of steam or steam jet may be used interchangeably. The phrases jet of water and water jet may be used interchangeably. The phrase draft tube and suction tube may be used interchangeably.

Drawing -A-

Illustration of pressure and potential water jet velocity produced by given height, or head, of water column.



Formula -1-

$$P = wh/144$$

where:

P = Pressure at bottom of water column in pounds per square inch.
w = Weight of water* taken as 62.4 lbs. per cubic foot.
h = Height of water column in feet.

Formula -2-

$$V = \sqrt{2gh}$$

where:

V = Velocity of water* jet in feet per second.
g = Acceleration due to gravity taken as 32.2 feet per second per second.
h = Height of water column in feet.

* Fresh water at 60 degrees Fahrenheit.

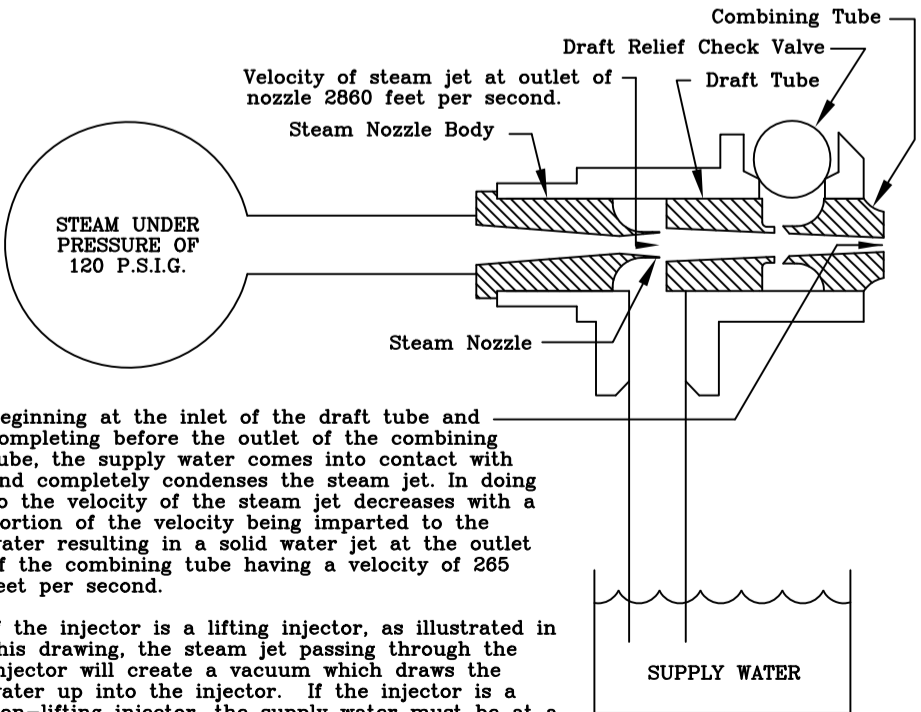
Drawing -B-

Illustration of portion of injector that produces high velocity water jet.

Steam nozzle, draft tube and combining tube

sections of lifting injector Drawing -D-, Page 2.

Pressure and velocity values from C. H. Peabody's work Page 455 Paragraph 5.



Beginning at the inlet of the draft tube and completing before the outlet of the combining tube, the supply water comes into contact with and completely condenses the steam jet. In doing so the velocity of the steam jet decreases with a portion of the velocity being imparted to the water resulting in a solid water jet at the outlet of the combining tube having a velocity of 265 feet per second.

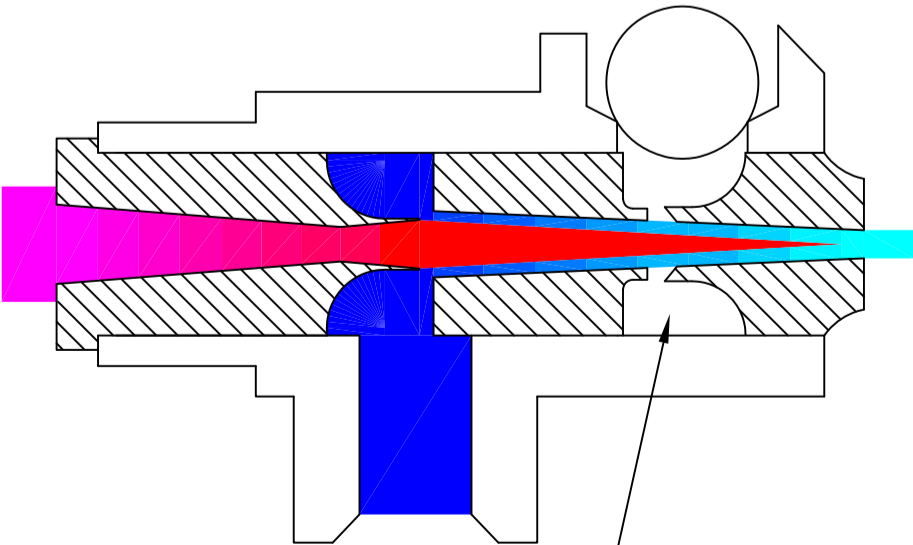
If the injector is a lifting injector, as illustrated in this drawing, the steam jet passing through the injector will create a vacuum which draws the water up into the injector. If the injector is a non-lifting injector, the supply water must be at a level above the injector which will allow the water to flow into the injector by gravity.

Drawing -C-

Illustration of action in steam nozzle and draft and combining tubes under stable conditions after starting.

Shape and length of steam jet as condensed by supply water in draft and combining tubes theorized by the author.

Supply water in blue color.
High pressure moderate velocity steam from boiler in magenta color.
Resulting high velocity low pressure steam jet in red color.
Resulting high velocity low pressure water jet in cyan color.

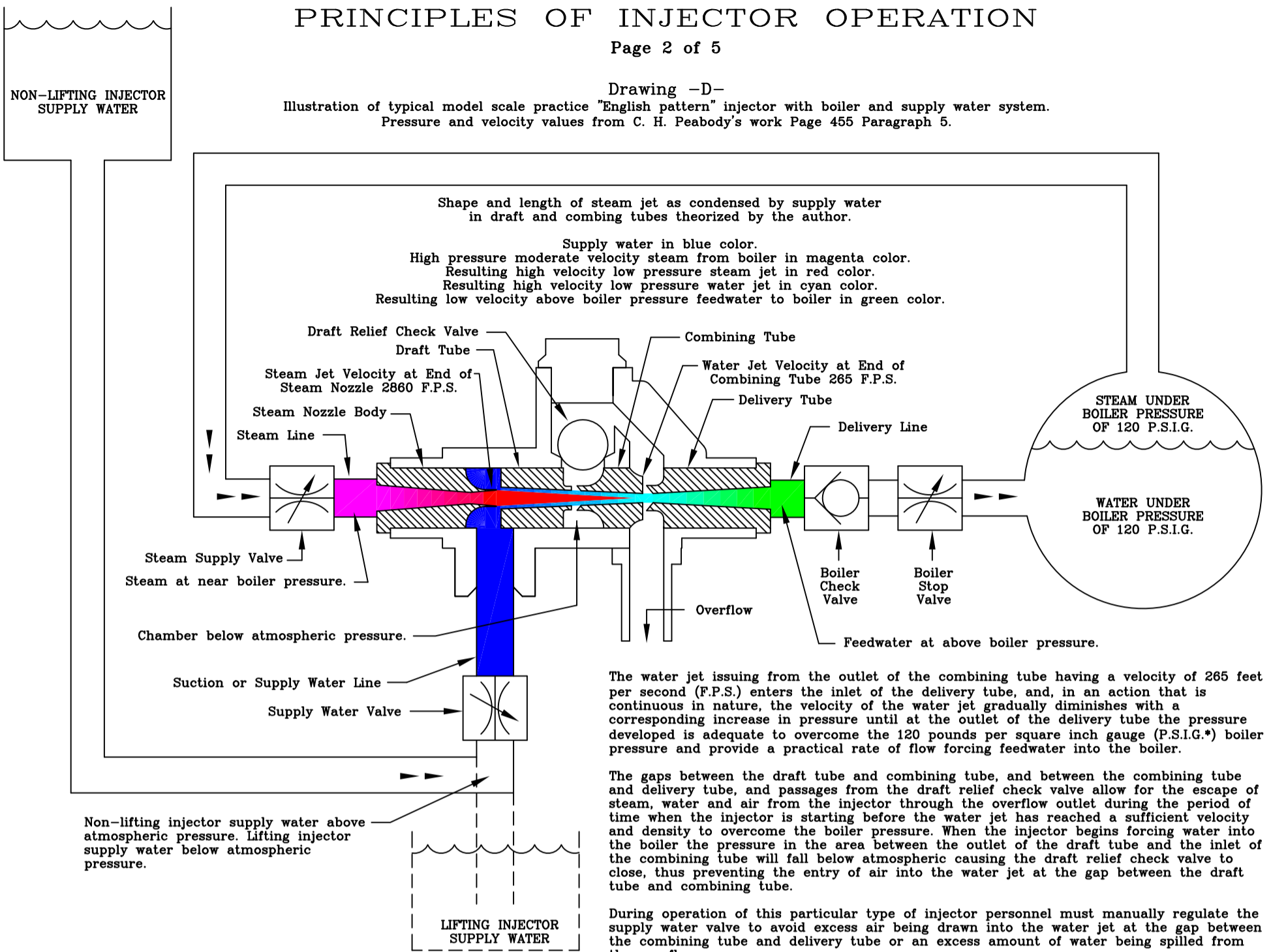


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Drawing -D-

Illustration of typical model scale practice "English pattern" injector with boiler and supply water system.
Pressure and velocity values from C. H. Peabody's work Page 455 Paragraph 5.



The water jet issuing from the outlet of the combining tube having a velocity of 265 feet per second (F.P.S.) enters the inlet of the delivery tube, and, in an action that is continuous in nature, the velocity of the water jet gradually diminishes with a corresponding increase in pressure until at the outlet of the delivery tube the pressure developed is adequate to overcome the 120 pounds per square inch gauge (P.S.I.G.*) boiler pressure and provide a practical rate of flow forcing feedwater into the boiler.

The gaps between the draft tube and combining tube, and between the combining tube and delivery tube, and passages from the draft relief check valve allow for the escape of steam, water and air from the injector through the overflow outlet during the period of time when the injector is starting before the water jet has reached a sufficient velocity and density to overcome the boiler pressure. When the injector begins forcing water into the boiler the pressure in the area between the outlet of the draft tube and the inlet of the combining tube will fall below atmospheric causing the draft relief check valve to close, thus preventing the entry of air into the water jet at the gap between the draft tube and combining tube.

During operation of this particular type of injector personnel must manually regulate the supply water valve to avoid excess air being drawn into the water jet at the gap between the combining tube and delivery tube or an excess amount of water being spilled from the overflow.

Full scale practice modern injectors always, and most other model scale practice injectors, include a check valve located before the overflow outlet that functions in a manner similar to the draft relief check valve. The overflow outlet check valve closing when the pressure in the area between the outlet of the combining tube and the inlet of the delivery tube falls below atmospheric, thus preventing the entry of air into the water jet at the gap between the combining tube and delivery tube.

The gap between the draft tube and the combining tube and the draft relief check valve provide for a feature where the injector automatically restarts after the supply water has been restored after an interruption. For a given injector the diameter of the outlet of the combining tube and/or the gap between the outlet of the combining tube and inlet of the delivery tube is generally not sufficient to allow the full flow of the uncondensed steam jet to escape from the injector without causing a pressure above atmospheric to develop in the chamber that surrounds the steam nozzle. The foregoing preventing supply water from entering the injector. The gap between the outlet of the draft tube and the inlet of the combining tube and the passages to the overflow outlet via the draft relief check valve provides the additional area necessary for the escape of the fully uncondensed steam jet thus allowing supply water to enter the injector.

Normally the steam and supply water valves are the only valves that are required to be manipulated by personnel in order to control the operation of the injector.

The boiler check valve operates automatically to prevent the flow of water from the boiler into the injector when the injector is not operating and during the period of time when the injector is being started.

The boiler stop valve is normally left open and is closed only if the boiler check valve fails to close properly when the injector is stopped.

Injectors may be designed to function as either lifting or non-lifting. The supply water for a non-lifting injector installation is shown above by solid lines. The supply water for a lifting injector installation is shown above by dashed lines. Injectors designed as lifting may generally be used in lifting or non-lifting installations. Injectors designed as non-lifting must only be installed as such.

In 1:8 scale model practice it is recommended to use non-lifting design injectors or to install lifting design injectors in the manner of a non-lifting installation. A non-lifting installation regardless of the design of the injector allows for the flow of cold supply water through the injector by gravity. Lifting injector installations may experience difficulties in starting, also referred to as priming, if the injector has become overheated thereby preventing the injector from creating a sufficient vacuum to draw the supply water up into the injector.

* For pressures stated in pounds per square inch gauge (P.S.I.G.) zero is equivalent to atmospheric pressure. For pressures stated in pounds per square inch absolute (P.S.I.A.) zero is equivalent to a perfect vacuum. Therefore a common rotating hand radial scale pressure gauge open to the atmosphere when reading zero P.S.I., or more correctly zero P.S.I.G., depending on the barometric pressure at its location, may also be considered as simultaneously indicating atmospheric pressure of approximately 14.7 P.S.I.A. The same gauge when reading 100 P.S.I., or more correctly 100 P.S.I.G., is simultaneously indicating approximately 114.7 P.S.I.A.

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Drawing -E-

Illustration of typical full scale practice "Penberthy" injector rated for lifting or non-lifting service.

Model scale practice "Ohlenkamp" 5/16 inch injector is a reduced scale replica.

Model scale practice "Super Scale Economy" 5/16 inch injector is similar in form and function.

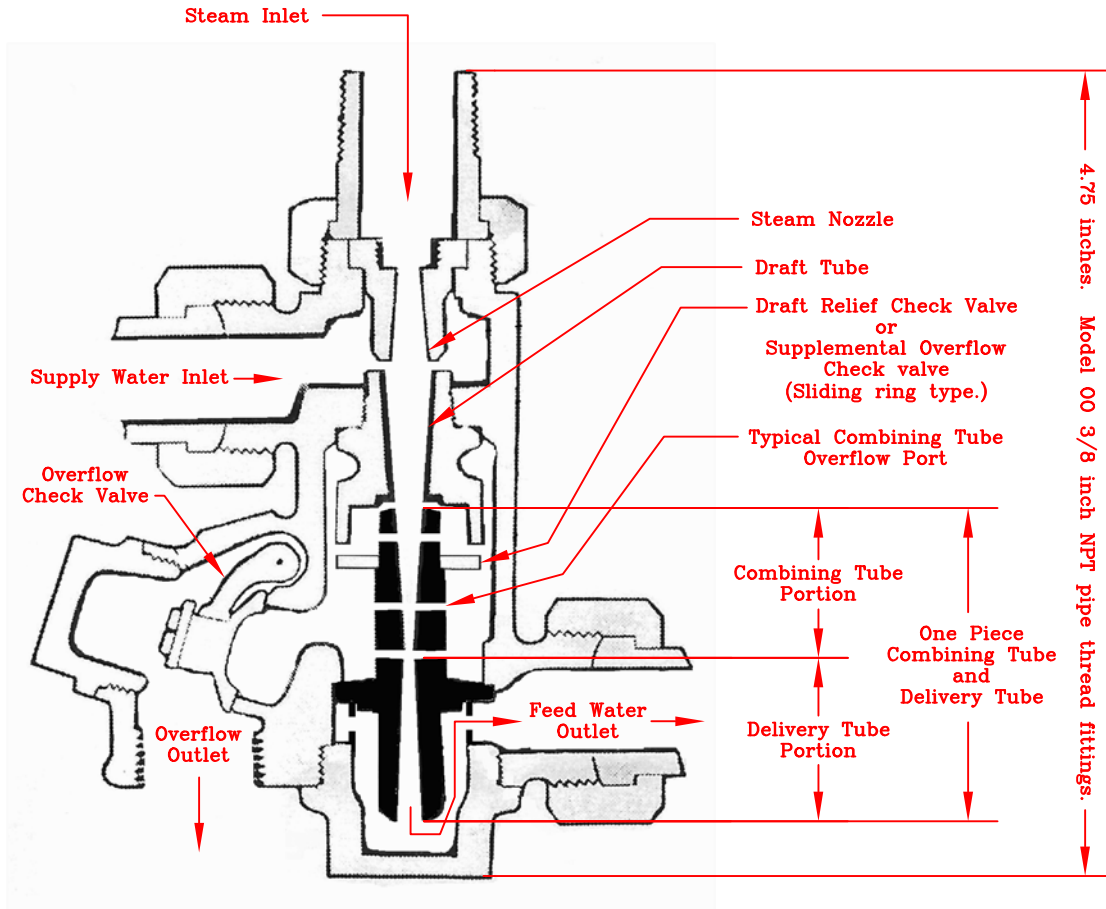


Image -A-

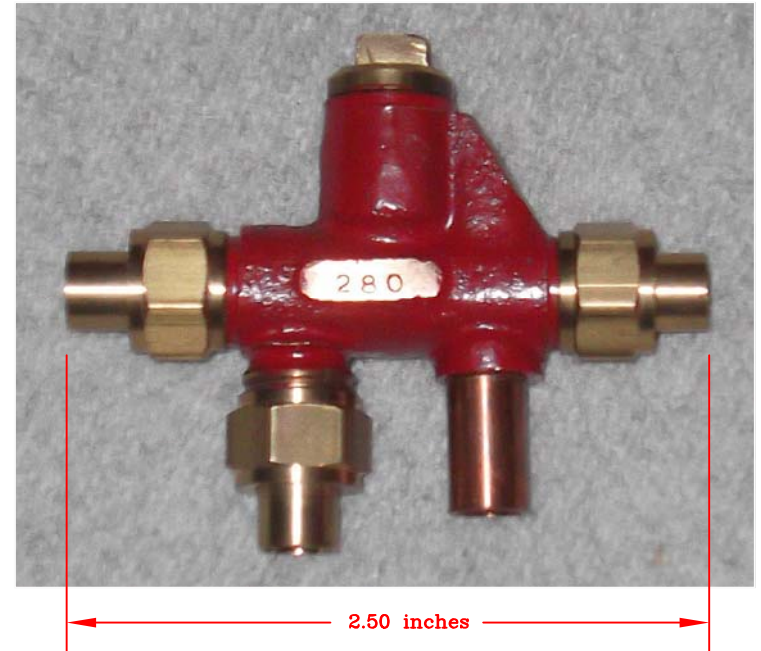
Typical model scale practice "English pattern" 1/4 inch injector.

Rated for:

Lifting or non-lifting service.

Maximum boiler pressure 100 P.S.I.G.

4 pints per minute @ 100 P.S.I.G. non-lifting.



The following excerpts are from Chapter 7 of Practice and Theory of the Injector by Strickland L. Kneass, edition of 1910. To view S. L. Kneass's complete work see Lake Forest Live Steamers Railway Museum suggested technical and historical reading list at www.lflsrm.org

"NOTWITHSTANDING the fact that much has been written upon this subject, the action of the injector still appears mysterious to many of those who are familiar with its operations. It is strange that the reason for its working is not more generally understood, even by those accustomed to operate it daily, especially as this method of feeding is now so universally employed for locomotive and stationary boilers.

The simplest method of considering the theory of the injector is to eliminate the more complicated sides of the question and consider it solely from a mechanical point of view; simply as an apparatus in which the momentum of a jet of steam is transferred to a more slowly-moving body of water, producing a resultant velocity sufficient to overcome the pressure of the boiler.

The high velocity attained by a jet of steam has been calculated, and diagrams have been given that show the fall of pressure and increase in velocity as the volume is increased according to the laws under which the steam expands. Suppose that a nozzle connected with a reservoir containing steam at 120 lbs. pressure discharges 1 lb. of steam per second; at its minimum diameter, the steam will have reached a velocity of 1407 feet, but when the terminal pressure is 22" vacuum, the velocity will be 3446 feet per second. Let us suppose that this jet flows into a combining tube, which is able, by means of the great conductivity of its walls, to abstract sufficient heat to completely condense the steam at a final pressure of 22", or 4 lbs. absolute. This reduces the steam to a solid jet of water having a cross section 1/774 the area of the steam while passing through the steam nozzle, and yet does not in any way affect the velocity, as the contraction of the jet is entirely lateral. A jet of water issuing from the delivery tube, forced out by the pressure of the boiler, would have a velocity nearly equal to that due to the head, or approximately, 133 feet per second, only 1/25 of that of the jet of condensed steam; but an injector is required to perform useful work, forcing a supply of feed water into the boiler; therefore a certain weight of feed water must be added which will take the place of the cold walls of the tube for the purpose of condensation. This mass of water receives the energy of the moving steam, condenses it, and the two fluids move along together through the delivery tube with a terminal velocity greater than a jet of the same density issuing from the boiler. If the weight of water supplied is too great, the steam will not have power enough to give the required velocity of 133 feet; if there is an insufficient supply, the volume of the steam will not be reduced sufficiently to pass through the tubes, and in neither case will the injector work properly."

"It is thus seen that the whole action of the injector depends upon the fact that the velocity of a jet of steam discharging into the combining tube, is 20 to 25 times that of a jet of water issuing from a boiler under the same pressure, and that the enormous reduction of the volume during condensation concentrates the momentum of the jet upon an area which is but a small fractional part of the orifice from which it issues, leaving a large margin of available energy which may be applied to useful purposes. As condensation plays such an important part in the operation, it is seen that any condensable gas may be substituted for the motive steam, if the inherent conditions are properly considered, but some modifications of the proportions of the parts as used in the steam injector might be found necessary in order to work satisfactorily under the new conditions."

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OPERATING PROCEDURES FOR A TYPICAL 1:8 SCALE MODEL PRACTICE NON-LIFTING INJECTOR INSTALLATION

A. Starting: 1. Open supply water valve to provide adequate flow of water into injector and out of overflow pipe; 2. Quickly open steam supply valve fully; 3. If water is spilling from overflow gradually close supply water valve until water spilling diminishes or stops; 4. As boiler pressure decreases due to injection of cool feedwater into boiler, monitor overflow and repeat step No. 3 if required.

B. Stopping: 1. Close steam supply valve quickly; 2. Close supply water valve.

C. Injector breaks (stops forcing water into boiler) with strong flow of steam from overflow pipe: 1. Close steam supply valve quickly; 2. Ensure supply water valve is opened sufficiently to provide an adequate flow of water into injector and out of overflow pipe; 3. Continue at starting step No. 2.

D. Injector operating with strong flow of water from overflow pipe: 1. Close steam supply valve quickly; 2. Wait for normal adequate flow of water to appear again out of overflow pipe as when starting; 3. Continue at starting step No. 2.

E. Injector stopped with flow of steam and hot water out of overflow pipe: 1. Close boiler stop valve; 2. Open supply water valve to provide adequate flow of water into injector and out of overflow pipe; 3. Quickly open steam supply valve fully; 4. Strong flow of water should appear at overflow pipe due to injector having primed correctly with boiler stop valve closed; 5. Open boiler stop valve fully; 6. If water is spilling from overflow gradually close supply water valve until water spilling diminishes or stops; 7. As boiler pressure decreases due to injection of cool feedwater into boiler, monitor overflow and repeat step 6 if required.

INJECTOR OPERATING PRINCIPLES TO KEEP UPPERMOST IN MIND

The pressure that an injector develops at its feedwater outlet, when greater than the steam pressure supplied to it, is described by S. L. Kneass as the back pressure. A fundamental characteristic of a given injector under given operating circumstances is the maximum or limiting back pressure it can produce without spilling water at the overflow outlet. The foregoing being discovered by placing the injector under test operating conditions where a pressure gauge is installed in the delivery line near the feedwater outlet of the injector and the delivery line is then gradually restricted by means of a valve located beyond the point of installation of the pressure gauge.

Injectors being governed by the laws of physics and subject to the efficiencies resulting from the shape and dimensional proportions of their manufacture will generally develop a maximum or limiting back pressure without spilling water at the overflow outlet of not less than 120% of the normal rated steam pressure supplied to the injector. The foregoing subject to the temperature and absolute pressure of the supply water entering the injector.

Most injector failures can be attributed to circumstances that result in either the normal operating back pressure not being achieved, or if the normal operating back pressure is achieved, it is insufficient to overcome abnormal restrictions in the delivery line.

Observation of the outlet of the overflow pipe of an operating injector may, and must, be used by personnel to ascertain if the injector is operating normally. Consideration should always be given to the fact that if the steam supply and supply water valves to an injector are open and there is no steam and/or water spilling from the overflow outlet, feedwater is being forced into the boiler unless there is a leak in the delivery line or the overflow outlet is closed and steam is being forced back into the supply water tank. With the steam supply valve open, water spilling at the overflow pipe of an injector most likely indicates that it is not developing normal feed water back pressure or flow rate into the boiler.

The following is an outline of common injector failures or operating issues:

1. Steam pressure at entrance to steam nozzle or velocity of steam jet reduced from normal.
(Strong flow of water at overflow pipe.)
 - a. Steam supply valve not fully open.
 - b. Steam supply line restricted by debris.
 - c. Steam nozzle or steam nozzle strainer restricted by debris.
 - d. Steam supply line restricted by kinks or flattened spots in piping.
 - e. Steam leaks at loose or broken pipe fittings.
 - f. Water carried over from boiler into injector steam line.
2. Steam jet not fully condensed by supply water resulting in water jet of lesser mass and/or velocity than normal.
(Strong flow of steam or alternating strong flow of steam and water at overflow pipe.)
 - a. Tender tank empty or low water level.
 - b. Supply water valve not open sufficiently.
 - c. Supply water line restricted by debris.
 - d. Tender tank suction line strainer restricted by debris.
 - e. Supply water line restricted by kinks or flattened spots in piping or hoses.
 - f. Elevated temperature of injector disrupting normal efficiency of condensation of steam jet.
 - g. Elevated temperature of supply water disrupting normal efficiency of condensation of steam jet. Generally a result of overheating tender supply water during freezing weather conditions by using injector steam supply.
Note: Extra care must also be taken to avoid damaging hose connections when using injector steam supply as tender supply water heater.
3. Air entrained in supply water resulting in water jet of lesser mass and/or velocity than normal.
(Alternating strong flow of steam and water at overflow pipe.)
 - a. Tender empty or low water level.
 - b. Leak in supply water valve stem packing.
 - c. Leak in supply water line piping or hoses.
 - d. Supply water valve of another injector is open allowing air to enter through its leaking overflow check valve into a supply water system common to more than one injector.
4. Water jet velocity diminished although steam jet velocity is normal.
(Strong flow of water at overflow pipe.)
 - a. Draft tube restricted by debris.
 - b. Combining tube restricted by debris.Note: Extra care must be taken to avoid damage to the interior of injector tubes when attempting to remove debris from them.
5. Excessive delivery line restrictions cannot be overcome by normal back pressure developed.
(Strong flow of water at overflow pipe.)
 - a. boiler stop valve closed or not open sufficiently.
 - b. Boiler check valve stuck closed or not opening sufficiently.
 - c. Delivery line restricted by debris.
 - d. Delivery line restricted by kinks or flattened spots in piping.
 - e. Delivery tube restricted by debris.Note: Extra care must be taken to avoid damage to the interior of injector tubes when attempting to remove debris from them.
6. Rate of water supplied to injector is greater than required for existing boiler pressure,
(Water moderately spills at overflow pipe with injector steam valve wide open.)
 - a. Throttle supply water valve to reduce supply water rate until overflow stops or diminishes.
7. Air cannot escape from injector at starting.
(Supply water does not run out of overflow pipe after opening supply water valve.)
 - a. Injector overflow check valve stuck closed.
8. Strong flow of water at overflow pipe.
 - a. Draft relief check valve not closing after injector primes.
See operating procedure D.
9. Lifting injector installation supply water suction lift failure.
 - a. Combination of height of lift of supply water, elevated supply water temperature and/or elevated temperature of body of injector causes supply water to vaporize before reaching steam jet issuing from steam nozzle. See also No. 2(g).

Excerpt from Practice and Theory of the Injector by S. L. Kneass, Edition of 1910, Page 121 Data for Penberthy Injector

The following tests of an injector of this pattern have been furnished by the manufacturers, but were made by disinterested experts—height of lift = 3 feet:

Limiting feed temperature at 65 lbs. steam, 128°, delivery 200°						
“ “ “ 75 “ 121° “ 196°						
“ “ “ 85 “ 117° “ 200°						
“ back pressure without overflow at 65 lbs., 92 lbs.						
“ “ “ “ 75 “ 103 “						
“ “ “ “ 85 “ 112 “						

The author wishes to thank B. M. Caughron and E. B. Pappert for their suggestions on content for, and the proof reading of, this article.

FOR ADDITIONAL 1:8 SCALE MODEL PRACTICE STEAM RAILWAY ENGINEERING INFORMATION SEE W W W . L F L S R M . O R G

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IMAGES SHOWING NON-LIFTING INJECTOR INSTALLATION ON
DEERFIELD AND ROUNDABOUT RAILWAY ENGINE NO. 442



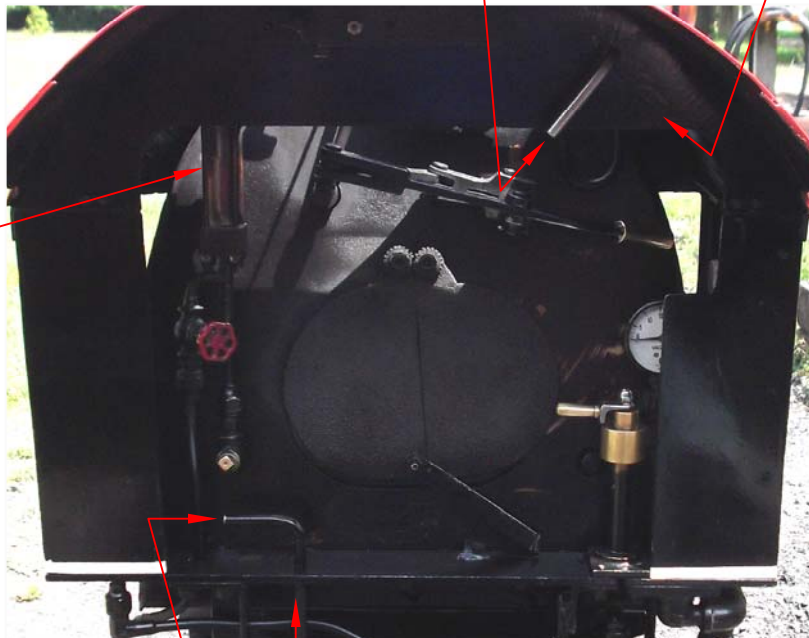
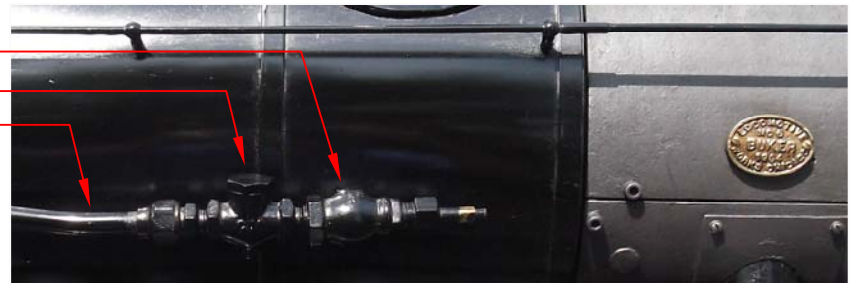
Boiler stop valve operated when
required with adjustable wrench.

Boiler check valve.
Feedwater delivery
line from injector.

Injector steam valve operating
handle shown in closed position.

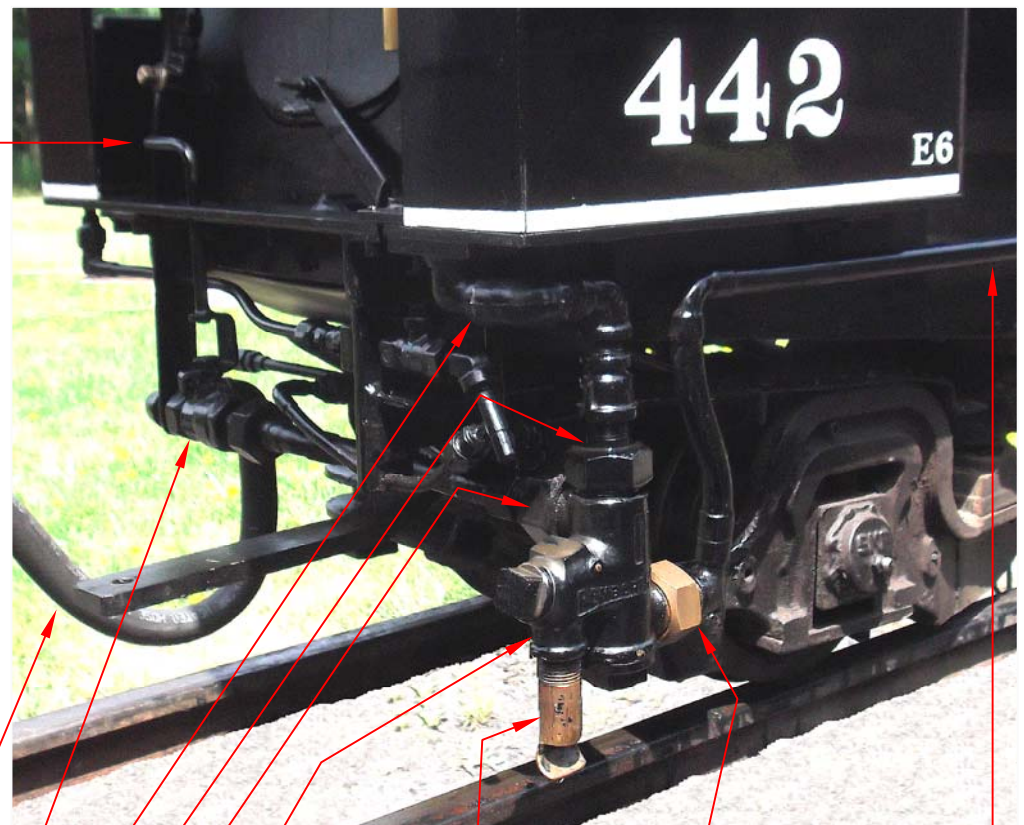
Steam valve is 90 degree rotating
ball type and located near
boiler steam turret.

Operating handle
position when open.



Operating handle position when open.

Injector supply water valve operating
handle shown in closed position.



Injector supply water flexible
hose from tender tank to
supply water valve.

Injector supply water valve.
90 degree rotating ball type.

Injector steam line
from steam valve.

Injector steam inlet.

Injector supply water inlet.

Injector overflow
outlet and
diverter pipe.

Injector
feedwater
outlet.

Feedwater delivery
line to boiler
check valve.

Penberthy model OO injector with 3/8 inch NPT pipe fittings.
Referred to as "STOCK MODEL SUCTION LEFT - DELIVERY BACK."

Not shown in above images, although of great importance, is the fine mesh
stainless steel filter screen located below the tender filling hole.



The Most Important
Window in a Train

FOR ADDITIONAL INFORMATION SEE LAKE FOREST LIVE STEAMERS RAILWAY MUSEUM WEB SITE AT

W W W . L F L S R M . O R G