Recommendations for New Parameters for Specifications of Steam Locomotive Water Systems

By Sanjay Das---10/29/23

Introduction

At the present time, the ORTS steam model assumes that all steam locomotives have one live steam injector and one exhaust steam injector, and calculate their assumed feed-rates based on the ***.eng** file boiler and cylinder parameters. While this arrangement was a common arrangement, it is mostly prevalent in the UK and Europe, and is not representative of all locomotives. For example, in the United States, many of the larger, latter-day steam locomotives had one live-steam injector, and one feedwater heater system, while older and smaller locomotives have only two live-steam injectors. There needs to be a way for the user to specify the type of water system the locomotive has, as well as its boiler-feeding capacity, based on known specifications rather than going off of assumptions.

Basic Locomotive Water Supply Theory

Regardless of the equipment used to supply a locomotive boiler with water, the theory behind it is the same, generally there are 3 rules that designers had to bear in mind when designing a locomotive's water supply system:

1. Water must be supplied to the boiler as fast as the boiler evaporates it, according to the locomotive's boiler and cylinder horsepower,
2. The pressure of the water entering the boiler must be raised to significantly higher than the current boiler pressure in order to force the check valves open, and
3. Ideally, there should be some means of pre-heating the water to avoid “chilling” the boiler with relatively cold water and reducing its steaming capacity

These parameters are some things to keep in mind as we make locomotive water systems in ORTS more user-customizable.

Water Equipment Definition Parameters

While locomotive water systems vary greatly with location and era, there is, in reality, a few generic terms that can be used to describe the equipment and how it operates. My proposal is to define water systems using the following parameters:

ORTSSteamWaterSystem1EquipmentType (x)
ORTSSteamWaterSystem2EquipmentType (x)

These parameters are equivalent in function to the pre-existing **BrakeEquipmentType** parameter used to define brake equipment in ***.wag** and ***.eng** files, and **(x)** represents one or more of the following terms to describe the equipment in the water system, which can be used to load a default model for the equipment type specified:

Tag	Definition	Typical US Examples
Lifting_live_steam_injector	Locomotive is equipped with a lifting live steam injector. A lifting injector, located above the lowest water level in the tender or tank, has the ability to suck water from the bottom of the tank to	Nathan Simplex, Sellers Class N, Ohio

	approximately the boiler's center-line.	
Nonlifting_live_steam_injector	A non-lifting live steam injector cannot suck water to a higher elevation, and must be placed below the lowest possible water level in the tank.	Nathan 4000C, Sellers Class K and S, Ohio
Lifting_inspirator	Locomotive is equipped with a lifting inspirator. An inspirator differs from an injector in that it can deliver water to the boiler at a higher temperature and in greater capacity than a regular injector. Operates on live steam only.	Hancock
Nonlifting_inspirator	Same as above, but analogous to "Nonlifting_live_steam_injector".	Hancock MNL
Exhaust_steam_injector	Locomotive is equipped with an exhaust steam injector (these are always of the non-lifting type). Usually started on live steam and changed over to exhaust steam automatically.	Elesco
Combined_exhaust_and_live_steam_heating_injector	Effectively two non-lifting injectors in series, the first using exhaust steam to heat the water, the second being used to force water into the boiler.	Sellers Exhaust Feedwater Heating Equipment
Reciprocating_cold_water_pump	Locomotive is equipped with a live-steam-driven double-acting single-cylinder piston-type pump. It is usually used in conjunction with a feedwater heater, and the pump is placed somewhere between the tank and the heater.	Early Elesco
Duplex_reciprocating_cold_water_pump	Same as above, but with two steam cylinders (simple expansion) and two water cylinders, effectively doubling the water feeding capacity.	Later Elesco
Centrifugal_cold_water_pump	Locomotive is equipped with a live-steam turbine-driven centrifugal pump. It is usually used in conjunction with a feedwater heater (or sometimes an exhaust injector), and the pump is placed somewhere between the tank and the heater (or injector).	Coffin, Worthington S ans SA, some Elesco systems
Closed_type_feedwater_heater	Locomotive is equipped with a feedwater heater where exhaust steam surrounds a system of serpentine or coiled tubing in which water from the tender and pump flows.	Elesco, Coffin
Open_type_feedwater_heater	Locomotive is equipped with a feedwater heater where exhaust steam and incoming water are mixed directly.	Worhtington
Reciprocating_hot_water_pump	Locomotive is equipped with a live-steam-driven double-acting single-cylinder piston-type pump and is used in conjunction with a feedwater heater. The pump is placed somewhere between the heater and boiler check valve.	Worthington S, SA
Centrifugal_hot_water_pump	Locomotive is equipped with a live-steam turbine-driven centrifugal pump and is used in conjunction with a feedwater heater. The pump is placed somewhere between the heater and boiler check valve.	Wilson Water Conditioner
Reciprocating_combined_cold_and_hot_water_pump	Locomotive is equipped with a live-steam-driven double-acting single-cylinder reciprocating pump which is used in conjunction with a feedwater heater, on which the cold and hot water pistons share a common piston rod.	Worthington BL
Centrifugal_combined_cold_and_hot_water_pump	Locomotive is equipped with a live-steam-turbine-driven centrifugal pump which is used in conjunction with a feedwater heater, on which the	Hancock Turbo Feedwater Heater

	cold and hot water impellers share a common shaft.	
Condensate_drain_to_tender	Used in conjunction with closed feedwater heaters, any exhaust steam that condenses back into water is recirculated through the system by depositing it into the tender water tank, usually passing through an oil-skimming chamber in the tender along the way to remove cylinder lubricants and prevent contamination of the feedwater.	Coffin, Elesco
Condensate_drain_to_pump_suction_line	Same as above, but the condensate gets recirculated directly through the pump's suction (intake) line instead of flowing back to the tender. A centrifugal oil separator is placed in the condensate pipe to prevent cylinder lubricants from contaminating the feedwater.	Coffin, Elesco
Motion_pump	Locomotive is equipped with a single-acting reciprocating mechanical water pump driven by the motion of the locomotive, either by means of the piston rod crosshead, a wheel or an axle. Usually used in the days before the injector was introduced in the 1870s.	Early and mid 19th century locomotives

Keep in mind that this is only a partial list of possible water equipment types. It should also be noted that water systems, like brake equipment and triple valve features, have a seemingly endless array of variations, many of which may need to be added to ORTS later on down the road (see the Elvas Tower forum post, "Wishes for Improvements to Braking Systems"). However, the parameters described in this document should form the foundation for future support for locomotive water systems of other types that may be introduced later.

Water System Controls and Parameters

The following will give a summary of the various water systems used on US/North American locomotives and how they can be modeled in ORTS and defined in a locomotive ***.eng** file.:

Old-Time Water Supply—Motion Pumps

Prior to the 1870s, steam locomotives had two mechanical water pumps attached to the locomotive frame. They were motion-driven, usually deriving their motion from the main piston rod crosshead, but sometimes they were driven from a crank or an eccentric on a driving wheel or axle. These pumps were single-acting, with suction on one stroke and delivery on the other--when the pump piston rod moves away from the pump body, it primes the pump with fresh water from the tank or tender, and when the pump piston rod changed direction, moving toward the pump body, the water in the pump was delivered into the boiler.

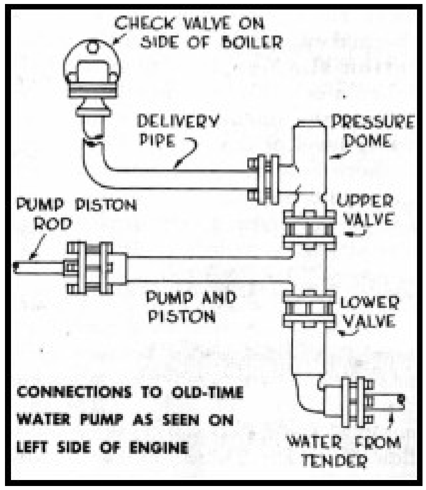


Image of old-time motion-driven water pump. The piston rod of this type of pump was usually connected to the crosshead of the main cylinder's piston rod. Courtesy of Kalmbach Books.

The maximum rate at which the pumps can deliver water is governed by the locomotive speed, so the following parameter can be used to specify that rate:

ORTSSteamMotionPumpMaxWaterFeedRateAtMaxDrivingWheelRPM (x)

In this case, **(x)** represents the feed rate of the pumps at the maximum driving wheel RPM, determined by the **MaxVelocity** parameter in the Engine section of the ***.eng** file using the following formula:

$$\mathbf{MaxWheelRPM = (((\mathit{v}/63660)/3600)/(2\Pi \mathit{r})/60)}$$

Where ***v*** is the **MaxVelocity** value (MPH assumed), ***r*** is the driving wheel radius (inches assumed), 63360 is the miles-to-inches conversion factor, 3600 the hours-to-seconds conversion factor and 60 being seconds-to-minutes. (Note: Those of you in metric territory please bear with me, as I'm pretty sure you have equivalent unit conversion factors).

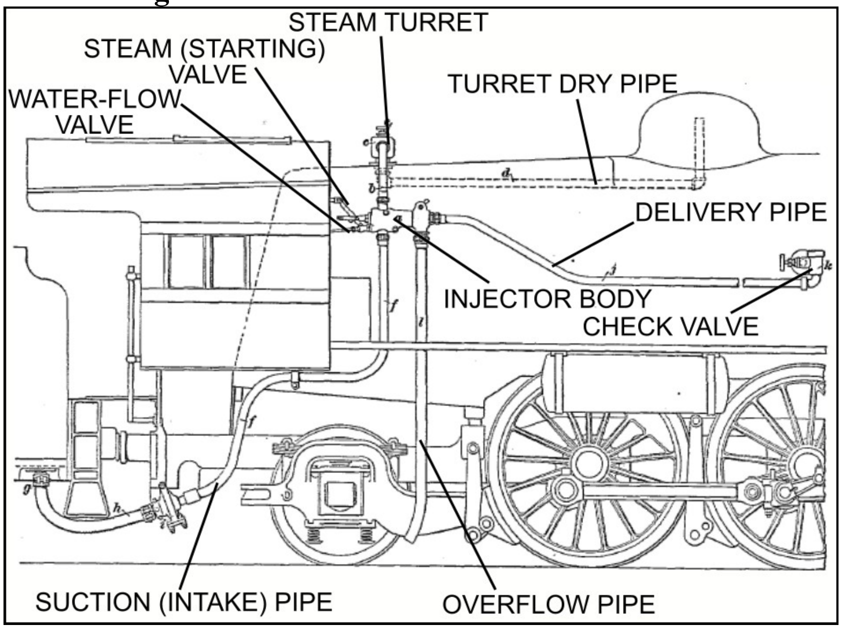
Having calculated the maximum wheel RPM from the above formula, ORTS can use this and the **ORTSSteamMotionPumpMaxWaterFeedRateAtMaxDrivingWheelRPM** parameter to interpolate and/or extrapolate (if locomotive speed should exceed the **MaxVelocity** parameter value due to coasting downhill) the water feed rate accordingly.

In addition, each feed pump had a water-regulating valve to fine tune the amount of water entering the boiler. Since this is analogous to the water-flow controls on injectors, then the only cab controls needed are the water valves, since the steam valves are not needed:

Increase Water Flow For Motion Pump 1 = K
Decrease Water Flow for Motion Pump 1= SHIFT + K
Increase Water Flow For Motion Pump 2 = L
Decrease Water Flow for Motion Pump 2= SHIFT + L

Suitable cabview control tokens would be either **ORTS_WATER_MOTIONPUMP1** or **ORTS_WATER_MOTIONPUMP2**.

Live-Steam Injectors—Lifting



Typical lifting live-steam injector installation. Courtesy of International Correspondence Schools.

Live-steam injectors come in two general varieties: lifting and non-lifting. A lifting injector is capable of raising water up into the injector body. It is usually placed about a foot higher than the highest water level in the tank or tender, so when the tank or tender is full, the water need not travel very far.

In order for a lifting injector to work properly, it must be *primed*, or filled with water, before it can be used to feed the boiler. (This operation of priming an injector IS NOT to be confused with the priming of the locomotive cylinders that is the result of too much water being fed into the boiler!) To do this, the engineer or fireman pulls the injector steam starting valve slightly. This allows, when opened, a small trickle of steam through the main nozzle and combining and delivery tubes. This action creates a vacuum that raises the water from the tank up into the injector body. When water starts to discharge out of the overflow pipe, the injector has been primed and the injector steam valve can be fully opened to force water into the boiler.

The basic functionality of injectors obviously has been modeled in both MSTS and ORTS. However, with the newly introduced ORTS steam model, the injector capacities and feed rates are based on assumptions calculated from boiler and cylinder parameters, which is unrealistic. In reality, the specifications of the injector(s) are tailor-made for a particular locomotive.

Here are some tables, reproduced from a circa-1920s American Locomotive Company (Alco) Standards and Practices manual, showing the correlation between cylinder horsepower, boiler pressure and injector feed rates, for various makes and models of both lifting and non-lifting injectors:

Cylinders	Steam	Maximum Steam Consumption per Cylinder HP Hour	
		Pounds	Gallons
Simple	Saturated	27.0	3.24

	Superheated	20.8	2.50
Compound	Saturated	23.3	2.82
	Superheated	19.7	2.36

Fuel	Service	% Maximum Steam Consumption Supplied By One Injector
Other than Oil or Pulverized Coal	Road	75%
	Switching	60%
Oil or Pulverized Coal	Road	87%
	Switching	70%

Table of Capacities of Injectors at 200 PSI Boiler Pressure

Size Number	Nathan			Sellers	Ohio		Hancock	Average Capacities, Gallons (US), per Hour
	Monitor and all Non-Lifting Except Simplex	Simplex Lifting & Non-Lifting Except HW	Simplex Non-Lifting HW	All	Standards A, B & E	Standards C & D	Types A, B & D	
7	1920	1950	1950	—	1800	—	2040	1932
7½	—	—	—	2010	—	—	—	2010
8	2340	2580	2580	—	2300	2700	2710	2535
8½	—	—	—	2587	—	—	—	2587
9	2940	3240	3240	—	2900	3200	2980	3083
9½	—	—	—	3187	3150	—	3300	3212
10	3750	3800	3800	—	3400	3800	4060	3768
10½	—	—	—	3952	3600	—	—	3776
11	4150	4550	4550	—	3800	4200	4420	4278
11½	—	—	—	4725	—	—	—	4725
12	4430	5200	5500	—	4200	4600	—	4790
12 5/16	—	—	—	5700	—	—	—	5700
13	—	6000	6000-7000	—	—	—	—	6250
13 5/16	—	—	—	6800	—	—	—	6800
14	—	7500	—	—	—	—	—	7500

For boiler pressures less than 200 PSI, use the percentages of capacities in above table as follows:

Boiler Pressure (PSI)	Percentage
150	92%
160	94%
170	96%
180	98%

190	100%

With the above tables in mind, here are some new parameters for specifying injector capacity. First, determining the flow rate:

ORTSSteamInjectorFeedRatePerUnitOfBoilerPressure (x)

Where **(x)** determines the maximum flow rate of the injector relative to each unit of boiler pressure (example: US Gallons Per Hour per PSI). Giving an example from the above table, to use a Nathan size 14 Simplex lifting injector, then the formula would be:

7500 g-us per hr/200 psi = 37.5 g-us/hr/psi

Alternatively, the following parameter can be used:

ORTSSteamInjectorWaterDeliveredPerPressureOfSteam (x)

Where **(x)** is the weight of water delivered for each unit of boiler pressure, determined by the following formula:

Water Delivered = (h-d)/(d-f)

Where **h** is the equivalent heat value of the steam at a given pressure (for example, one pound of saturated steam at 200 PSI has a heat value of 1197.6 BTU's), **d** represents the delivery temperature of the water (this is dependent on steam pressure) and f is the water's temperature at the point of intake (usually the same as the ambient air temperature).

To specify the steam usage of the injector, the following parameter can be used:

ORTSSteamInjectorMaxSteamUsage (x)

Where **(x)** is the steam usage rate used by the injector when feeding the boiler.

When an injector is used to feed water into the boiler, the steam heats the water in the process. However, the water entering the injector cannot be too hot, or it will spill out the overflow. To specify this **Highest Operating Temperature**, then this parameter can be used:

ORTSSteamInjectorMaxIntakeWaterOperatingTemperature (x)

Where **(x)** is the maximum temperature of the water to be fed into the injector. If this temperature is exceeded, then the water will be "wasted" out the overflow pipe.

An overview of various makes and models of injectors used on US locomotives reveals that there are various control schemes, and consequently, ORTS needs to account for that. So there are many options for controlling lifting injectors. The first is the legacy ORTS/MSTS controls:

Injector 1 Steam Toggle = I
Injector 2 Steam Toggle = O

Injector 1 Water Flow Increase = K
Injector 1 Water Flow Decrease = SHIFT + K
Injector 2 Water Flow Increase = L
Injector 2 Water Flow Decrease = SHIFT + L

However, as stated earlier on, a lifting injector has to prime in order to get water into the injector body before it will feed water into the boiler. If a lifting injector cannot prime, it will not operate. Consequently, the steam starting valve has to be made variable so that the valve can be opened slightly to prime the injector before being opened fully to force water into the boiler. Thus the control scheme would be:

Injector 1 Steam Valve Increase = I
Injector 1 Steam Valve Decrease = SHIFT + I
Injector 2 Steam Valve Increase = O
Injector 2 Steam Valve Decrease =SHIFT + O
Injector 1 Water Flow Increase = K
Injector 1 Water Flow Decrease = SHIFT + K
Injector 2 Water Flow Increase = L
Injector 2 Water Flow Decrease = SHIFT + L

In order to let ORTS know that the injector has to be primed before it will operate, then the following binary parameter can be added:

ORTSSteamLiftingInjectorMustBePrimedToOperate (x)

Where **(x)** is equal to either:

0 = The injector operates off the legacy ORTS/MSTS injector control scheme (which is what will be assumed if the parameter is omitted entirely), or
1 = The injector has a variable steam valve and must be primed before it will operate.

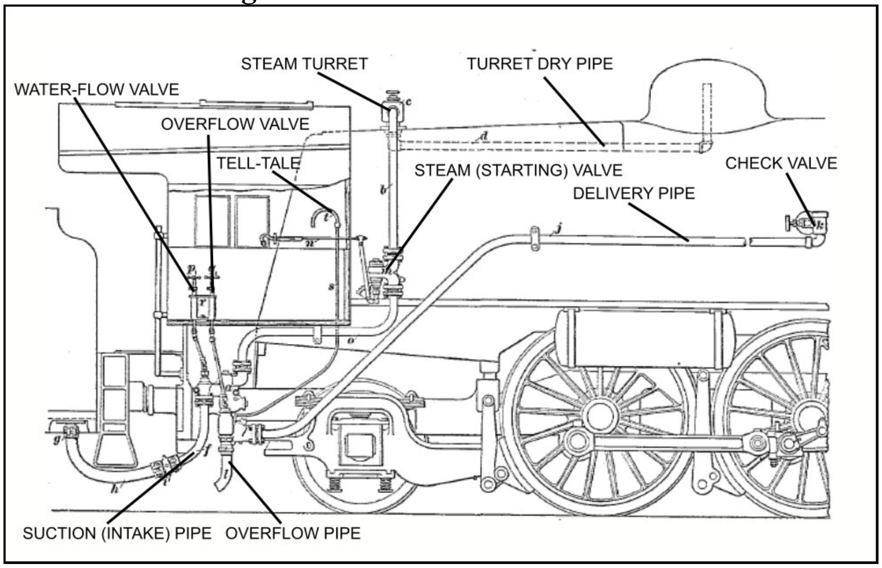
If this parameter is omitted, then the ORTS will assume that the injector operates off of the legacy injector control scheme.

Furthermore, to specify the height that the water must travel in order to use the new injector-priming function, then the following parameters can be used:

ORTSSteamLiftingInjectorToTenderHighWaterLevel (x)
ORTSSteamLiftingInjectorToTenderLowWaterLevel (x)

Where **(x)** is the distance between the injector body and either the highest or lowest water level in the tank or tender. This is used to calculate the time it takes for the injector to prime before it can feed water into the boiler. If the tank or tender water level is anything more than 0% but less than 100%, ORTS will interpolate the distance relative to the high and low water levels accordingly.

Live-Steam Injectors—Non-Lifting



Typical non-lifting live-steam injector installation. Courtesy of International Correspondence Schools.

A non-lifting injector cannot raise water like a lifting injector can, and therefore the injector is mounted so its intake pipe is below the lowest water level in the tank or tender. However, the advantages for non-lifting injectors include:

1. Larger water capacity for any given size,
2. it can be located so as to make repairs easier (by workers on the ground),
3. it will start working almost immediately, without having to wait for the injector to prime, (because of its location relative to the water source),
4. it works with less water in the tank or tender and with water at higher temperatures, and
5. the ratio of the quantities of steam and water can be more precisely regulated.

Non-lifting injectors have similar water-delivery characteristics to lifting injectors, so most of the parameters for feed rate, the temperature the water is heated to, etc., are the same as previously described for the lifting injector, and thus will not be repeated here. However, the principal difference is in the control schemes and parameters.

Firstly, since it is unnecessary to prime a non-lifting injector (unless the water tank or tender is almost empty in some cases), the parameters for the priming functionality are not used. Since most if not all non-lifting injectors require their overflow valves to be manually opened and closed by a crewmember, additional controls and keyboard commands are needed, and a parameter that lets ORTS know what control scheme to use, like this one:

ORTSSteamNonLiftingInjectorOverFlowOperation (x)

Where **(x)** represents one of three labels:

(None) = Overflow functionality is disabled and injector operates off of the ORTS/MSTS legacy injector controls,
(Manual) = The overflow valve must be opened manually by the player or AI fireman before starting

the injector, and manually closed once it is feeding water into the boiler.
(Automatic) = The injector has an automatically-controlled overflow valve, usually used in conjunction with single-control injectors like the Sellers Class S (explained later).

Thus, in the case of a non-lifting injector having manual overflow control, the control scheme would thus be:

Injector 1 Steam Toggle = I
Injector 2 Steam Toggle = O
Injector 1 Water Flow Increase = K
Injector 1 Water Flow Decrease = SHIFT + K
Injector 2 Water Flow Increase = L
Injector 2 Water Flow Decrease = SHIFT + L
Injector 1 Overflow Open = CTRL + I
Injector 1 Overflow Close = SHIFT + CTRL + I
Injector 2 Overflow Open = CTRL + O
Injector 2 Overflow Close = SHIFT + CTRL + O

Suitable ***.cvf** cab view control tags would be either **ORTS_OVERFLOW_INJ1** or **ORTS_OVERFLOW_INJ2**. Suitable ***.eng** file **EngineControllers** tags include **ORTSInjector1Overflow** and **ORTSInjector2Overflow**.

As mentioned earlier, non-lifting injectors do not necessarily need to be primed before they will operate. However, a study of US locomotive injector controls reveals that in many times, the steam starting valve was still made variable, so the steam to the injector could be increased gradually instead of suddenly. On some injectors, the steam starting valve is made variable so that, when opened only slightly, can allow the injector to act as a pre-heater for the water before it is forced into the boiler. To replicate this functionality, the following binary parameter can be used:

ORTSSteamNonLiftingInjectorSteamValveHasHeaterFunction (x)

Where **(x)** is either:

0 = The Injector Steam Valve DOES NOT have a heater function (this is also what will be assumed if the parameter is omitted entirely), or
1 = The injector steam valve IS equipped with a heater function.

A suitable ***.eng** file controller notch script would be:

```
Injector1Steam ( 0 1 0.5 0
        NumNotches( 3
               Notch( 0 1 Dummy ) Comment ( *** OFF *** )
               Notch( 0.5 1 Dummy ) Comment (  *** Injector Functions as Water Heater *** )
               Notch( 1.0 1 Dummy ) Comment ( *** Injector Forces Water Into Boiler *** )
        )
     )
```

Without a doubt, having multiple controls to operate an injector is a bit cumbersome and inconvenient.

In the interest of simplifying operation, injector manufacturers began devising non-lifting injectors that could be operated by only one control lever. Both Sellers (the Type S Non-Lifting Injector) and Nathan (The Model 4000C Automatic Restarting Injector) offered such devices.

To operate these injectors, the crew member pulls on a latched quadrant-type lever similar to a locomotive throttle or reverse/cutoff lever, which opens both the injector steam and water valves simultaneously, thereby throttling the steam supply and regulating the water flow. The overflow valve is controlled automatically by the pressures and vacuum in the injector body. To specify this type of control scheme, the following optional binary parameter can be used:

ORTSSteamNonLiftingInjectorDoesSteamAndWaterShareOneControl (x)

Where **(x)** is either:

0 = The Injector is controlled by two or three controls (this is also what will be assumed if the parameter is omitted entirely), or
1 = The injector steam and water controls operate simultaneously from one lever.

Thus the only controls needed in this scheme are:

Injector 1 Increase = K
Injector 1 Decrease = SHIFT + K
Injector 2 Increase = L
Injector 2 Decrease = SHIFT + L

Suitable ***.cvf** cabview control tags would be either **ORTS_COMBINED_INJ1** or **ORTS_COMBINED_INJ2**.

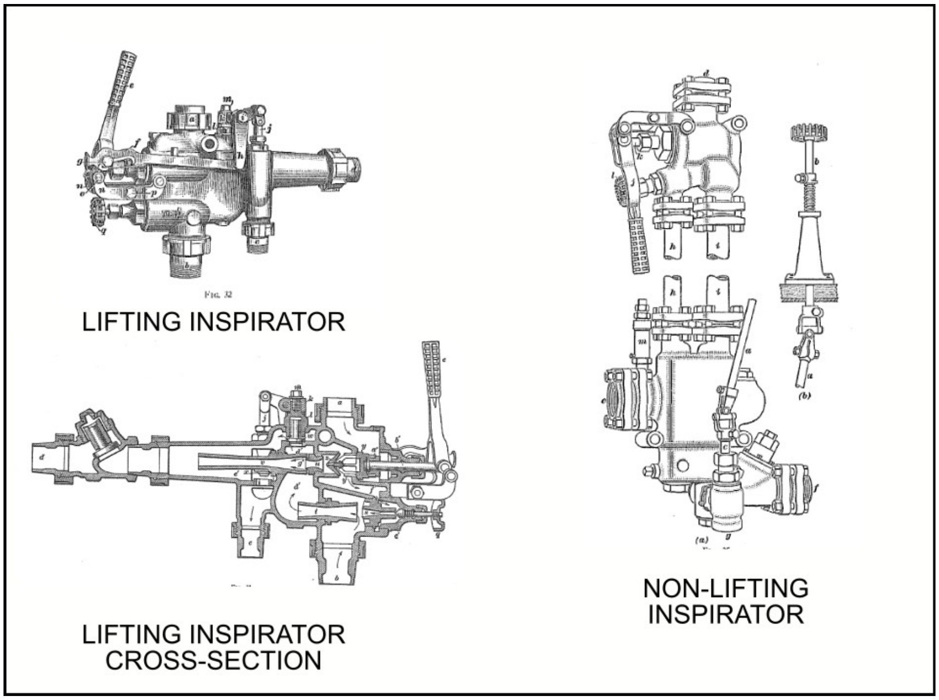
Also, instead of needing the following control script in the ***.eng** file:

```
Injector1Steam ( 0 1 0 )
Injector2Steam ( 0 1 0 )
Injector1Water ( 0 1 0.01 0
        NumNotches ( 0 )
)
Injector2Water ( 0 1 0.01 0
        NumNotches ( 0 )
)
```

...we can use something like this:

```
ORTSInjector1Combined ( 0 1 0.01 0
        NumNotches ( 0 )
)
ORTSInjector2Combined ( 0 1 0.01 0
        NumNotches ( 0 )
)
```

Inspirators



Examples of typical locomotive boiler-feeding inspirators. Courtesy of International Correspondence Schools.

An inspirator is essentially a heavier-duty version of an injector, capable of delivering water at a higher temperature than a conventional injector. The term "inspirator" comes from the verb "inspire" meaning "to inhale". The first device that would eventually evolve into a locomotive boiler-feeding inspirator was invented by John T Hancock in 1868, when he made some improvements to a device that could draw in air. Later on, he performed experiments using the device to lift water, followed by further improvements that allowed the device to not only lift water, but force it as well. Even though water was now used instead of air, the term "inspirator" was still used.

The higher capacity and water temperatures obtained with use of an inspirator are accomplished with the use of two steam tubes instead of just one, each with its own separate steam nozzle and control valve. One of the tubes is called the forcing tube, which is analogous to a combining and delivery tube in a conventional non-lifting injector, and used to force water into the boiler. The second tube, placed below the forcing tube, is called the lifting tube. It, too has both a combining tube and a delivery tube, but the whole lifting tube assembly is slightly shorter than the forcing tube. The lifting tube is used to lift water to prime the inspirator before it can force the water into the boiler.

With a boiler pressure of 200 PSI, and a water temperature of 75ºF in the tank, the water at the output of the lifting tube is at a pressure of around 31 PSI and at a temperature in the neighborhood of 110ºF by the time it reaches the entrance to the forcing tube. At this point, the boiling point of the water has raised to about 273ºF, at which point the steam passing through the forcing tube will condense until the water is raised to this temperature. However, the actual temperature of the water being delivered to the boiler is dependent on how the inspirator is regulated.

There is also a difference in how the overflow operates. In a two-tube injector or inspirator, cutting spillways in the tubes for overflow purposes (which is the case for regular injectors) will prevent the device from working properly. Thus, any surplus water during starting and priming the inspirator must be carried through the tubes. There are usually two overflow valves, one of which, known as the "final overflow", is placed in the forcing chamber. It is normally open, and when closed, it prevents the outgoing water from being discharged through the overflow pipe. On a lifting inspirator, this overflow valve is mechanically held closed when the forcing valve is moved to the full open position. The second overflow valve, known as the intermediate overflow valve, is normally closed, and placed between the lifting and forcing chambers. It prevents the passage of outgoing water backward into the lifting chamber, which would prevent the inspirator from working properly.

Inspirators, like regular injectors, come in two general varieties, lifting and non-lifting. The lifting inspirator is located above the highest water level in the tank or tender, and must be primed before it can force water into the boiler. The non-lifting inspirator has to be placed below the lowest water level in the tender or tank, and usually has a separate, manual overflow control.

Since injectors and inspirators are pretty much alike in operation, many of the physics parameters can be made identical and therefore will not be repeated here. However, when the **ORTSSteamWaterSystemEquipmentType** parameter(s) specify inspirators instead of injectors, the word "Injector" on all injector-related parameters must be replaced with the word "Inspirator". (Example: **ORTSSteam*<u>Inspirator</u>*MaxSteamUsage (x)**.)

As far as controls go, that's a whole different story. Keep in mind that some inspirators, particularly of they are of the lifting variety, have separate valves for the lifting and forcing tubes. Thus, additional keyboard commands are needed:

Inspirator 1 Steam Lifting Valve Increase = CTRL + I
Inspirator 1 Steam Lifting Valve Decrease = SHIFT + CTRL + I
Inspirator 1 Steam Forcing Valve Increase = I
Inspirator 1 Steam Forcing Valve Decrease = SHIFT + I
Inspirator 2 Steam Lifting Valve Increase = CTRL + O
Injector 2 Steam Lifting Valve Decrease =SHIFT + CTRL + O
Inspirator 2 Steam Forcing Valve Increase = O
Injector 2 Steam Forcing Valve Decrease =SHIFT + O
Inspirator 1 Water Flow Increase = K
Inspirator 1 Water Flow Decrease = SHIFT + K
Inspirator 2 Water Flow Increase = L
Inspirator 2 Water Flow Decrease = SHIFT + L

Suitable cab view ***.cvf** file control tags can potentially include:

- **ORTS_STEAM_LIFT_INSP1**
- **ORTS_STEAM_LIFT_INSP2**
- **ORTS_STEAM_FORCE_INSP1**
- **ORTS_STEAM_FORCE_INSP2**
- **ORTS_WATER_INSPIRATOR1**
- **ORTS_WATER_INSPIRATOR2**
- **ORTS_OVERFLOW_INSP1**
- **ORTS_OVERFLOW_INSP2**

Suitable ***.eng** file **EngineControllers** tags can potentially include:

- **ORTSInspirator1SteamLift**
- **ORTSInspirator2SteamLift**
- **ORTSInspirator1SteamForce**
- **ORTSInspirator2SteamForce**
- **ORTSInspirator1Steam**
- **ORTSInspirator2Steam**
- **ORTSInspirator1Water**
- **ORTSInspirator2Water**
- **ORTSInspirator1Overflow**
- **ORTSInspirator2Overflow**

On the other hand, most non-lifting inspirators have one control for both steam tubes, and thus the control scheme would be:

Inspirator 1 Steam Toggle = I
Inspirator 2 Steam Toggle = O
Inspirator 1 Water Flow Increase = K
Inspirator 1 Water Flow Decrease = SHIFT + K
Inspirator 2 Water Flow Increase = L
Inspirator 2 Water Flow Decrease = SHIFT + L
Inspirator 1 Overflow Open = CTRL + I
Inspirator 1 Overflow Close = SHIFT + CTRL + I
Inspirator 2 Overflow Open = CTRL + O
Inspirator 2 Overflow Close = SHIFT + CTRL + O

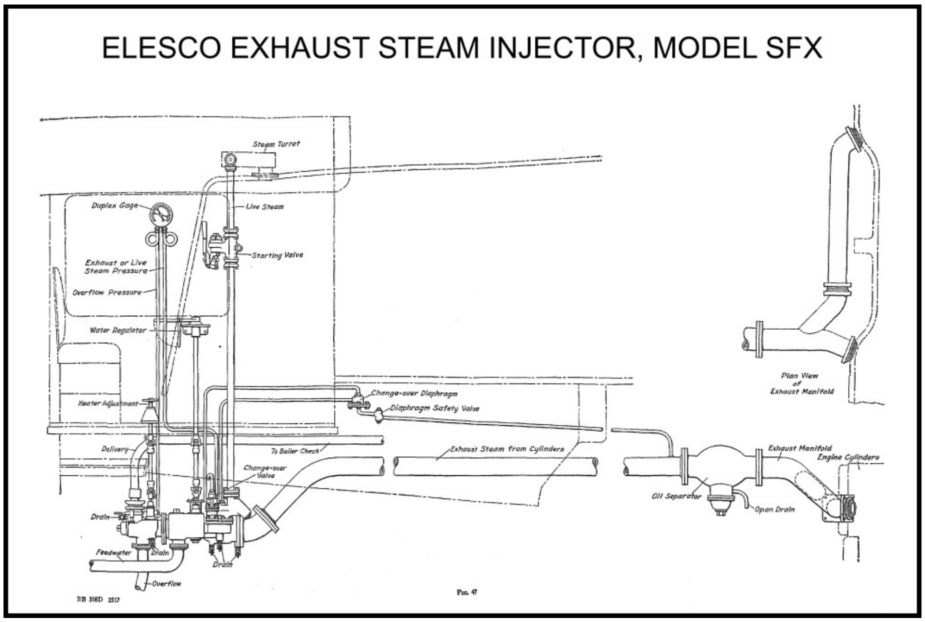
Thus, in terms of cab controls and **EngineControllers** tags, instead of needing **ORTS_STEAM_LIFT_INSPx**, **ORTS_STEAM_FORCE_INSPx**, **ORTSInspiratorxSteamLift**, and **ORTSInspiratorxSteamForce** for each inspirator, we only need one **ORTS_STEAM_INSPx** and one **ORTSInspiratorxSteam** tag for each inspirator.

By default, if a lifting inspirator is specified in the **ORTSSteamWaterSystemxEquipmentType** parameter, it will use separate controls for the lifting and forcing valves, whereas if a non-lifting inspirator is specified, it will use one control for both lifting and forcing.

Modern Water Supply—Exhaust Steam Injectors
Since all injectors effectively mix live steam from the boiler with the water to be injected into the boiler, the steam will heat the water to some degree, until the steam itself has re-condensed back into water. However, fresh live steam does take some additional time and fuel to generate, and since 99% of the time the live steam injectors use saturated rather than superheated steam, it is not necessarily efficient for the locomotive.

With the widespread adoption of the superheater in the late 1910s and early 1920s, it was discovered that superheated steam retained a significant amount of heat long after it had been exhausted from the steam chests and out the stack. Moreover, the heat from superheated exhaust steam required limited or no fuel to produce than the amount of fuel necessary to generate the same amount of saturated live steam. Consequently, locomotive builders and railroad-industry suppliers soon began developing devices that utilized exhaust steam as a heating medium for incoming boiler water, rather than having it all being “wasted” out the stack, which effectively increased the steaming capacity of the locomotive. Usually these devices replaced the live-steam injector that would otherwise be located on the fireman's side (on the left in North America) of the cab, while locomotives continued to have a live-steam injector on the engineer's side (right in North America).

One such device was the exhaust-steam injector. As its name would imply, it uses exhaust steam as the primary medium to force the water into the boiler. Perhaps the most well-known brand of exhaust steam injector was made by the Locomotive Superheater Company, or “Elesco” (the phonetic spelling of the acronym “L. S. Co.”) for short.



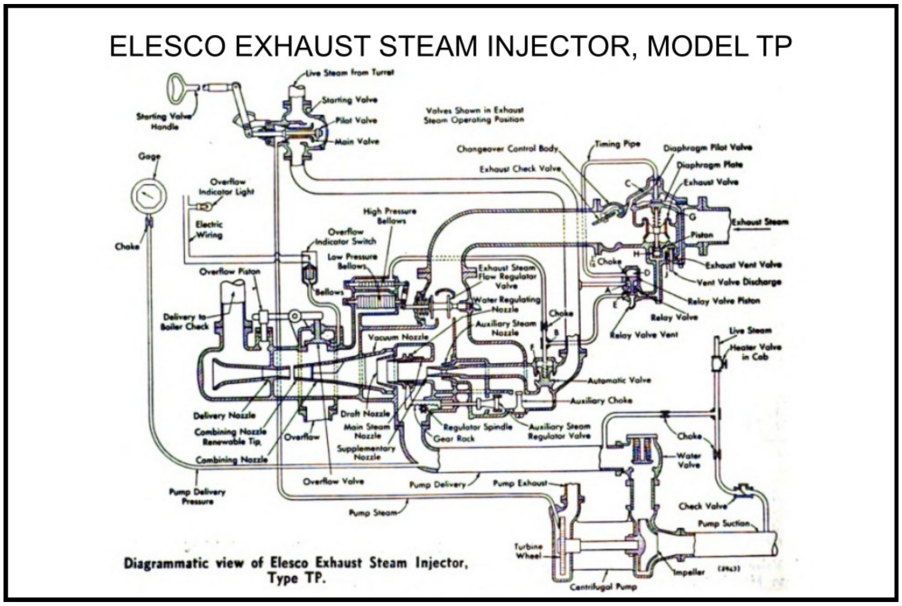
Typical Elesco exhaust steam injector installation. Usually located on left side of the locomotive. Courtesy of International Correspondence Schools.

The basic arrangement of one of Elesco's exhaust steam injectors is illustrated above. All exhaust steam injectors are of the non-lifting type, and therefore must be placed below the lowest point of the water tank. Exhaust steam from the main cylinders was conveyed to the injector by means of long pipes leading from the exhaust passages in the cylinder castings to the injector body. Along the way, the exhaust steam passes through an oil separator to filter out lubricants and other contaminants from the exhaust steam that may affect or even damage locomotive boilers if allowed to mix with the incoming boiler water.

The term “Exhaust Steam Injector” is actually more of a relative term. In normal operation the injector is indeed supplied with exhaust steam from the cylinders, provided the locomotive throttle is open. However, when the injector is first started, it must be started on live steam (at reduced pressure) and then switch over to exhaust steam once primed. On most exhaust-steam injectors, this changeover from live to exhaust steam is totally automatic, and accounts for the extra smaller pipes seen between the exhaust steam pipe and the injector body in the diagram. If the exhaust steam pressure was insufficient to allow the injector to operate, the injector would continue to operate on live steam until either the exhaust pressure increased or the injector was shut off.

A duplex cab gauge is shown in the diagram. On this model of injector, one needle shows the pressure of the steam being supplied to the injector, indicating whether the injector is operating on live or exhaust steam, and the other shows the vacuum created as a result of the injector working, causing the automatic overflow valve to close.

As time progressed, more features were consequently added to the exhaust-steam injectors. One of the improved systems, introduced in the late steam era, is illustrated below. It utilized a steam-turbine-driven centrifugal water pump (described later in the section on feedwater heaters) between the tank and injector, which not only boosted the water pressure and velocity, but also allowed the injector itself to be raised to a position above the low-water mark in the tank. (However, the centrifugal pump still had to be mounted below the low-water level in order to work properly.) Union Pacific's famous Big Boy locomotives, as well as their late-model Challenger locomotives, utilized this system.



Piping diagram of Elesco model TP exhaust steam injector system.
Courtesy of Simmons-Boardman Publishing Corporation.

As can be seen from the diagrams, exhaust steam injector controls are a mix of manual and automatic. Therefore, the basic controls proposed for live-steam injectors can also be applied to exhaust injectors, the control scheme used being determined by the number of controls that are to be player-operated. Additional cab view gauge and display tokens can potentially include:

- **ORTS_INJx_STEAM_PR**
- **ORTS_INJx_WATER_PR**
- **ORTS_INJx_OVERFLOW_PR**
- **ORTS_INJx_OVERFLOW_IND (As a multi-state display, see the Elesco TP Diagram above)**

x = 1 or 2, depending on which system the control is part of.

For the automatic changeover between live and exhaust steam operation on systems so equipped, the following parameters can potentially be used:

ORTSSteamExhaustInjectorHasLiveSteamStartOption (x)

ORTSSteamExhaustInjectorHasAutomaticExhaustChangeover (x)
ORTSSteamExhaustInjectorMinimumExhaustPressureForExhaustOperation (x)
ORTSSteamExhaustInjectorExhaustCutsOutAtPressure (x)

Modern Water Supply—Feedwater Heaters and Pumps

While the exhaust steam injector was a step in the right direction, it was not an ideal solution. Since most exhaust injectors still introduce some live steam into the boiler water, either for starting, priming or operation while the main locomotive throttle is reduced, the fuel savings from the heating the water by means of exhaust steam is very minute. Later, an optimal solution came in the form of the feedwater heater system. (In fact the exhaust steam injector was sometimes termed “the poor man's feedwater heater!”)

In these systems, the water is fed, by means of a steam-driven pump, to the feedwater heater, which was a form of boiler-like tank or heat exchanger. There, the water is heated solely by a portion of the exhaust steam supplied from the locomotive's main cylinders (and sometimes also from other appliances such as the air compressors, water pumps, mechanical stoker, booster engines, and the like) before being delivered to the boiler.

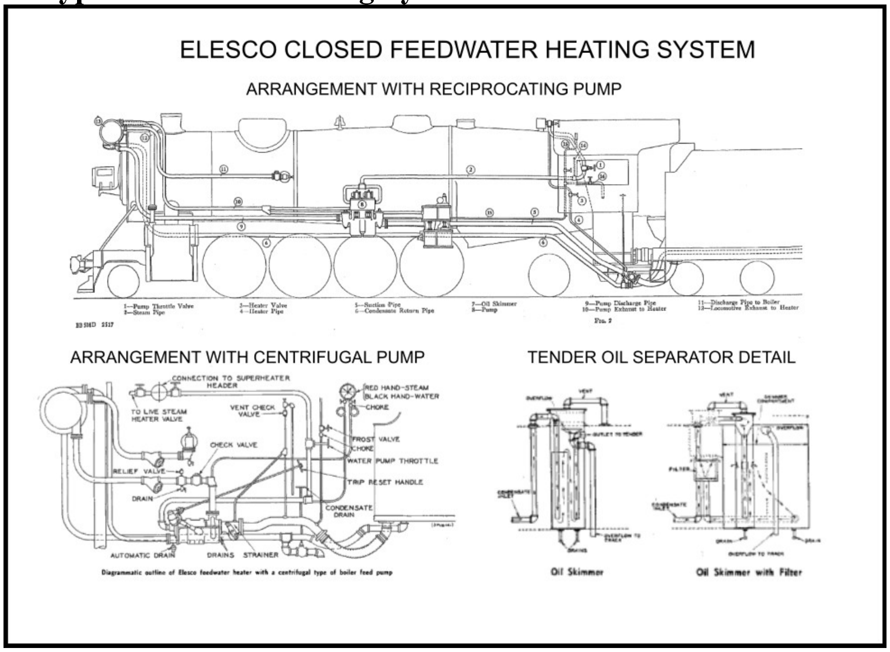
The pumps used with the heaters were live-steam-driven (remember, the main difference between a pump and an injector is that a pump has moving parts, while an injector does not), and in doing so, the live steam used to drive the pump in no way mixes with the boiler water. Thus all the heat added to the water comes from the exhaust steam being fed into the heater.

The heaters themselves came in two general varieties: closed and open. In a closed heater, the exhaust steam doesn't actually mix with the incoming water, but rather, the water is routed through a series pipes, arranged in a serpentine or coiled configuration, which are surrounded by the exhaust steam. Any exhaust steam that re-condenses back in to water is recycled back into the water supply, usually into the tender water tank, but sometimes directly into the pump's intake line, passing through an oil separator along the way to prevent lubricants from entering the water supply. In a way, it's basically your run-of-the-mill “shell and tube” type heat exchanger.

In the open heater, the water and exhaust steam directly mix with each other, just like on an exhaust steam injector. However, the supply of exhaust steam had to be cleaned of lubricants before it came into contact with the water. Some systems used oil separators while others relied on gravity to eliminate the contaminants and feeding the main cylinders only the minimum amount of lubricant required.

Systems varied widely from region to region, but the basic components are all similar. In the United States, the three most common makers of feedwater heating systems were Elesco, The JS Coffin Jr Company, and the Worthington Pump and Machinery Corporation. The following analysis of the three makers' systems will demonstrate how the components of the systems can be defined by generic terms.

The Elesco Closed-Type Feedwater Heating System



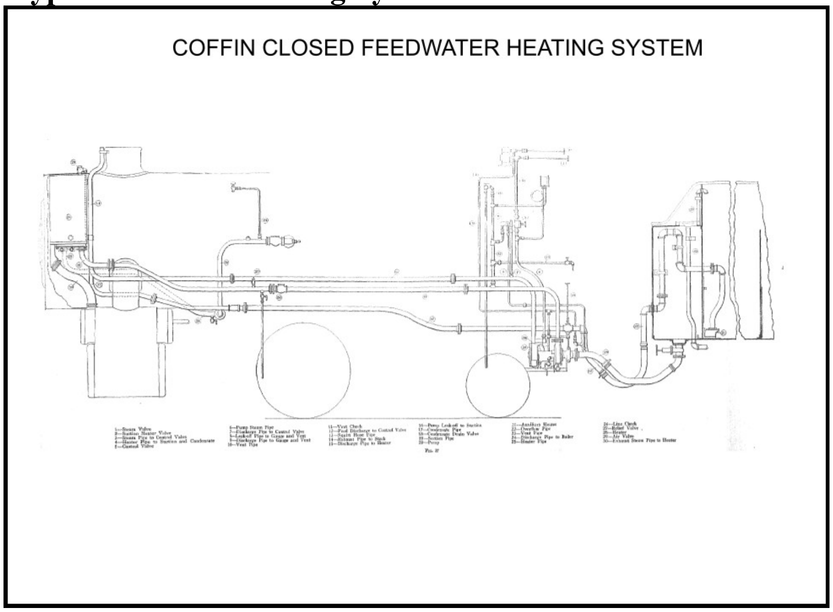
Typical installation and diagrams of Elesco Feedwater Heater and associated equipment. Courtesy of International Correspondence Schools (top) and Simmons-Boardman Publishing Corporation (bottom left and bottom right).

The Elesco system was one of the earliest feedwater heating systems introduced, about 1920. These systems used a pump (at first a double-acting single-cylinder reciprocating pump not unlike a Westinghouse 9½-inch single-cylinder air compressor, then in later years a duplex reciprocating pump or even a centrifugal pump) to pump water through the closed-type heater near the stack, and then to the boiler check valve. Exhaust steam condensation in the heater was usually diverted back to the tender, where a skimming chamber removed the cylinder lubricants, before depositing the now-purified condensate back into the tender water tank, although some arrangements have the condensate recirculated back into the pump's suction (intake) line, with an oil separator mounted on the locomotive.

The heater itself was usually the “bundle” style—resembling a laterally-oriented cylinder in a front view of the locomotive on which it was installed, which was either mounted on a shelf-like bracket in front of the smokebox, or partially embedded into the top of the smokebox. (One exception is the Santa Fe Railroad, who preferred to mount their Elesco bundle-type heaters on the pilot deck.) In later years, the “Coil” style heater—which is shaped like a box or rectangle in front and side views (often mistaken for a Worthington S or SA) and like a peanut in overhead views—was introduced, where the zigzag tubing was replaced with six coils of copper tubing.

This system, as with most if not all feedwater heating systems, has only one control in the cab—a simple valve for throttling the speed of the pump. A cab water pressure gauge was also provided to give a confirmation that the water pressure was exceeding boiler pressure to ensure it was entering the boiler.

The Coffin Closed-Type Feedwater Heating System



Typical arrangement of Coffin Feedwater Heater and associated equipment. Courtesy of International Correspondence Schools.

The Coffin system, about 1927, is similar in operation to the Elesco, except for the specifications and locations of some of the parts. A centrifugal pump mounted underneath the locomotive cab delivered water to the closed-type feedwater heater. This heater is shaped like a horseshoe or an inverted U, and was usually mounted inside the smokebox, flush with the top of edge of the smokebox ceiling. Thus the pipes entering the front of the smokebox were the only visually apparent evidence of the system's installation. In a relatively small handful of installations, the heater was mounted externally, overhanging the smokebox in a manner that resembled the visor on a baseball cap.

The design of the heater was such that the water entered the heater on the fireman's side of the locomotive, but exited from the engineer's side. Because of this, the delivery pipe and check valve had to be arranged one of 3 ways: A) have the delivery pipe duck laterally under the boiler, past a drain cock, to the check valve on the fireman's side of the locomotive; B) use a second engineer's-side check valve; or C) use a boiler-top-mounted dual check valve.

As with the Elesco system, any condensed exhaust steam is recirculated back to the tender after being skimmed of contaminants, and is operated by only one pump throttle valve. This throttle valve actually has a built-in regulator that reduces the flow of steam to the pump in the event of any interruption to the water supply, such as low water in the tank, a plugged strainer or closed tank valve.

Here's a table of Coffin heater models and their capacities, reproduced from the 1938 *Locomotive Cyclopedia of American Practice*:

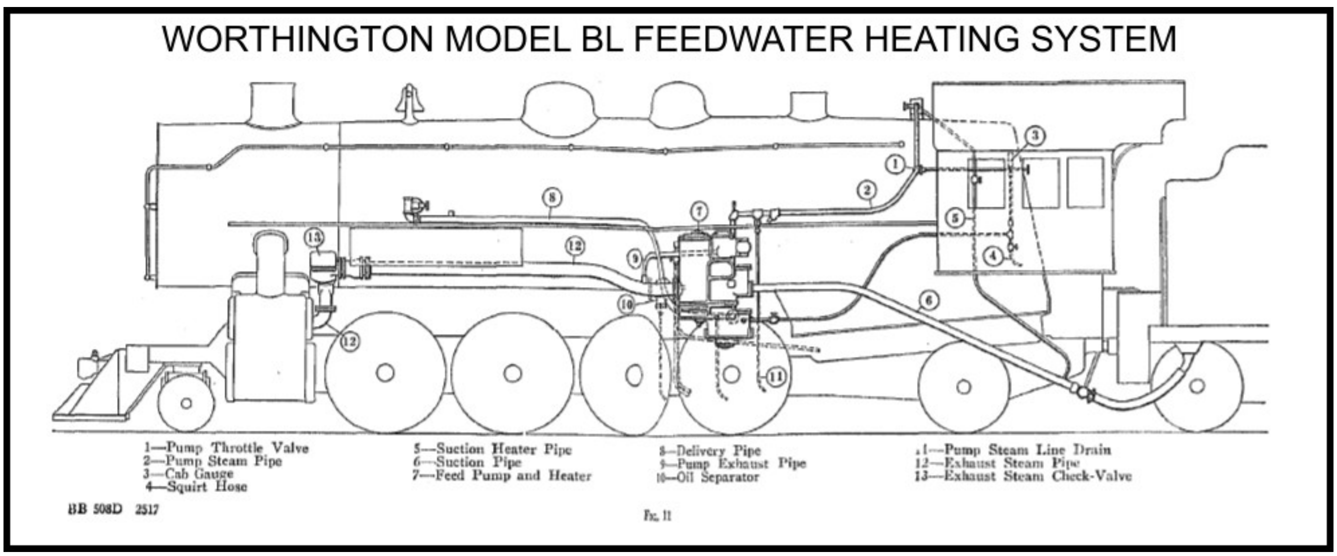
Model	Capacity (lb/h*1000)
A	Up to 50
B	40-60
C	60-80

D	80-100
BB	100-120

Worthington Feedwater Heater Systems

The Worthington systems are all open-type feedwater heaters, with the exhaust steam mixing directly with the incoming water. While many railroads found closed systems like Elesco and Coffin to be preferable to prevent contamination of the incoming boiler water, Worthington proved their systems did not contaminate the water despite using open-type heaters. Consequently, by the late steam era, the Worthington system became the most commonly-installed system.

Worthington offered 3 different models of heaters. The type later known as the model BL was introduced around 1920, and has the pump and heater combined into a single, large rectangular assembly. This assembly is mounted on the side of the boiler and is often mistaken for a cross-compound air compressor.



Typical arrangement of Worthington Model BL feedwater heater and associated equipment. Courtesy of International Correspondence Schools.

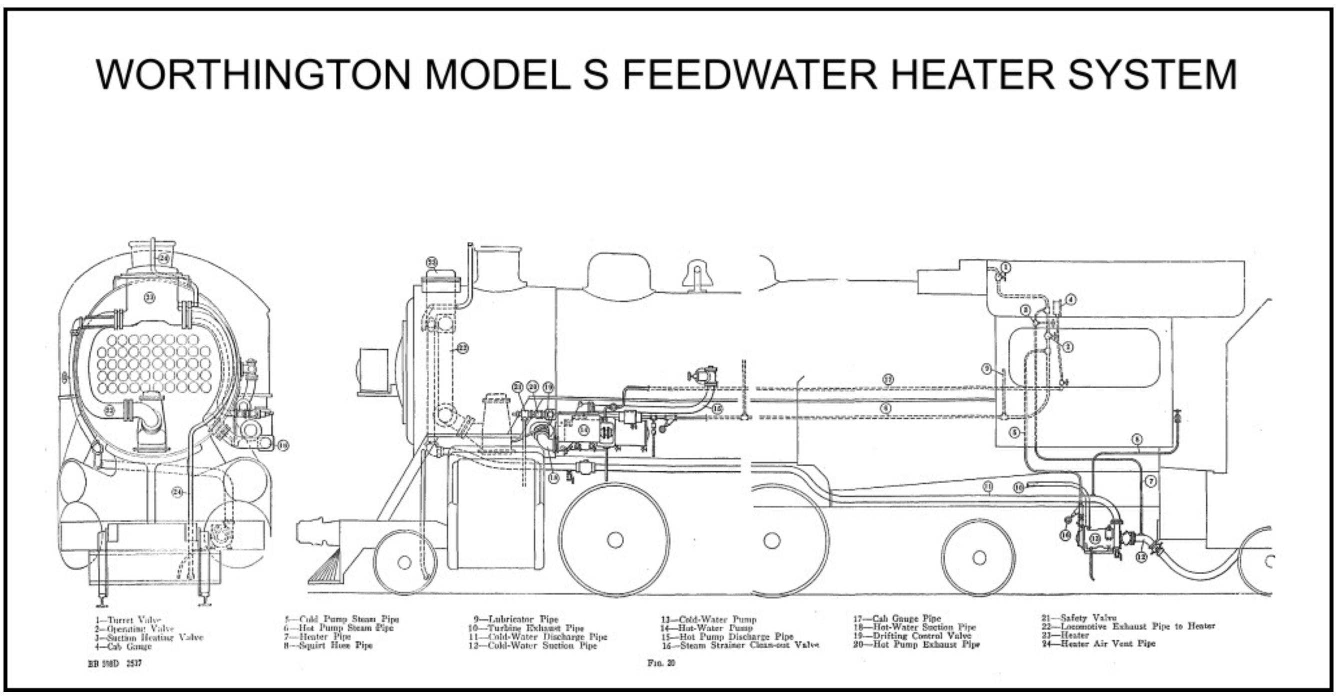
This system, like the Elesco and Coffin, has only one throttle valve to regulate the speed of the pump. The pump, which is of the reciprocating type, is actually two double-acting pumps sharing a common piston rod and a single steam cylinder. The first pump, known as the cold-water pump, draws water from the tank into the heater chamber, while the second, called the hot water pump, forces the heated water into the boiler.

In the heating chamber, the cold water is atomized and sprayed into a body of exhaust steam, condensing part of it in the process. Because of the accumulation of condensation, water accumulates in the heating chamber faster than the hot-water pump cylinder can get rid of it, and as a result, there is an inherent accumulation of water in the heater chamber in addition to the water being sprayed into the heater from the cold water pump cylinder. The heater chamber is prevented from being overfilled by an automatic float valve that, when the heating chamber is already filled to capacity, takes the water being discharged from the cold water cylinder and recirculates it back to the cold cylinder intake line. At the same time, the flow of water from the tender is either reduced or stopped until the water level in the heating chamber once again dropped. Normal flow resumes when the water level in the heater has dropped.

The heating chamber is supplied with exhaust steam from the main cylinders by means of a long pipe between the main cylinder saddle and the heating chamber, passing through an oil separator along the way.

Here's a table of sizes of BL heaters and their rated water capacities, reproduced from *ICS Textbook 508D: Locomotive Boiler-Feeding Devices*:

Size	Normal Speed, Strokes Per Minute	10% Above Normal Speed	Feedwater Capacities		
			Gallons (US) per Hour * 1000	Gallons (US) per Minute	Pounds per Hour * 1000
1	78	86	2.4	40	20
2	70	77	3.9	65	32.5
3	65	72	5.4	90	45
4	54	60	7.2	120	60
4¼	63	70	8.4	140	70
4½	54	60	10	166	83



Typical arrangement of Worthington Model S Feedwater Heater and associated equipment. Courtesy of International Correspondence Schools.

Around 1930, Worthington introduced the Model S system. Instead of the heating chamber and pumps being combined into a single unit, they were separated into 3 individual components. The cold water pump was now a steam-turbine-driven centrifugal pump mounted underneath the locomotive cab, the heater was now a box-like assembly partially embedded into the top of the smokebox ahead of (or sometimes behind) the stack, and the hot water pump was now a reciprocating pump mounted just aft of the smokebox.

Exhaust steam for the heater was conveyed from the cylinder saddle by means of two vertical pipes along the interior sides of the smokebox. No oil separator was needed as the vertical nature of the piping caused any lubricant particles to fall back toward the cylinders by gravity. Additionally, the locomotive cylinders were fed only a minimum amount of lubricant.

In this system, overfilling of the heater due to condensation was prevented by a float valve which, when the water level rose, automatically reduced the pressure of the water being discharged from the cold-water pump to no more than 60 PSI, so that the cold-water pump operated at an “idle speed” that was not significant enough to raise or force the water, but simply churn the water until the water level in the heater dropped, after which normal water flow resumed.

Another refinement was the addition of a drifting control valve. This valve, placed in the exhaust pipe of the hot water pump, used the steam chest pressure of the main cylinders to automatically reduce the flow of steam through the system when the steam chest pressure is anything less than 50 PSI. The intention was to limit the speed of the pumps when the locomotive was drifting or sitting idle, when there was limited or no exhaust steam available.

WORTHINGTON MODEL SA FEEDWATER HEATER SYSTEM (DIAGRAMMATIC VIEW)

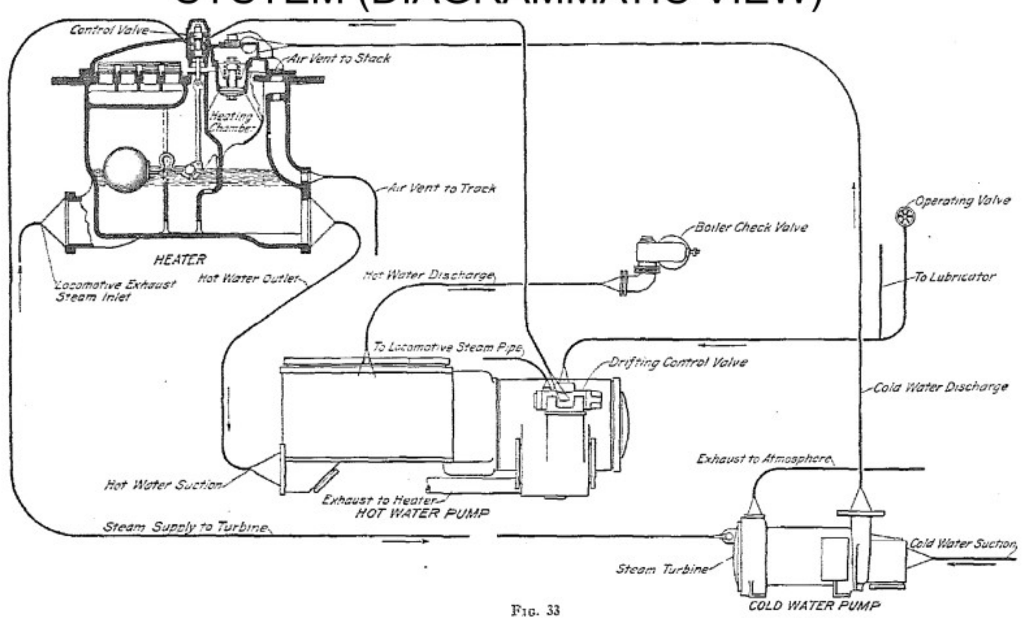


Fig. 33

General diagram of Worthington Model SA Feedwater Heater and associated equipment. Courtesy of International Correspondence Schools.

In the mid-to-late 1930s, Worthington introduced an improved version of the Model S, known as the Model SA. The main differences between the models S and SA are in both the cold-water pump and the float valve control in the heater. The cold-water pump's steam turbine is now a variable-speed rather than a single-speed turbine, and instead of merely an on/off valve to control water flow from the cold pump, the float valve on the SA was a piston-type valve that actually throttled the flow of steam to the cold-water pump. In a way, the new float valve simply regulated the cold-water pump speed so water entered the heater only as fast as the hot-water pump could get rid of it and pump it into the boiler. This eventually became the most common feedwater heater system installed on new locomotives in the late steam era.

Here's a reproduction of a table of Worthington Model SA System Sizes and their Capacities, reproduced from the 1938 *Locomotive Cyclopedia of American Practice*:

Size	Feedwater Capacities		
	Gallons (US) per Minute	Gallons (US) per Hour * 1000	Pounds per Hour * 1000
3 SA	80	4.8	40
4 SA	110	6.6	55
4½ SA	130	7.8	65
5 SA	150	9.0	75
5½ SA	170	10.2	85
6 SA	200	12.0	100
6½ SA	240	14.4	120
7 SA	270	16.2	135

Feedwater Heater System Controls and Parameters

As previously mentioned, most feedwater systems have only one control—merely a simple valve to throttle the pumps—and usually only one gauge—usually a water-pressure gauge for the pump (or one of them, while some systems also show the steam pressure of the pump as well). Other then that, these systems are, for the most part, totally automatic. So, in terms of control schemes in ORTS, then appropriating the existing injector water-flow keyboard commands are more than appropriate—either **K/SHIFT+K** (if the system is defined as water system #1) or **L/SHIFT+L** (if defined as water system #2).

Appropriate Cab View Control Tags could include:

- **ORTS_FEEDWATER_PUMP_x_THROTTLE**
- **ORTS_COLDWATER_PUMP_x_WATER_PR**
- **ORTS_HOTWATER_PUMP_x_WATER_PR**
- **ORTS_COLDWATER_PUMP_x_STEAM_PR**

x = 1 or 2, depending on which system the control is part of.

In the engine controllers section of the ***.eng** file, if one of the water systems is defined as having a feedwater heater, then instead of coding the controls as:

```
InjectorXSteam ( 0 1 0 )
InjectorXWater ( 0 1 0.1 0
  NumNotches ( 0 )
)
```

...we code them as:

```
ORTSFeedwaterPumpXThrottle ( 0 1 0.1 0
```

NumNotches (0)
)

The maximum heat added to the feedwater by the exhaust steam can be specified by the following parameter:

ORTSSteamFeedwaterHeaterYMaxWaterHeatMultiplier (x)

Where **(x)** is a decimal value that the temperature of the water when it enters the heater (assumed to be at ambient temperature) will be multiplied by when it leaves the heater and enters the boiler. For example, if the water's temperature at the moment it enters the heater is 72ºF, and the water's temperature upon entering the boiler is 206ºF, then the value would be 2.861. This value is dependent on a number of factors, including the path the water must travel within the heater, the specifications of elements inside the heater, etc. **Y** represents the number of the water system that the heater is part of (1 or 2)

To specify the flow rates and other specifications for the pumps, the following parameters can be used:

Parameter	Pump Type	Description
ORTSSteamColdWaterPumpMaxPistonRate ORTSSteamHotWaterPumpMaxPistonRate ORTSSteamCombinedColdAndHotWaterPumpMaxPistonRate	Reciprocating	Maximum speed of pump in strokes per minute.
ORTSSteamColdWaterPumpMaxRPM ORTSSteamHotWaterPumpMaxRPM ORTSSteamCombinedColdandHotWaterPumpMax RPM	Centrifugal	Maximum speed of pump turbine and impeller in RPM.
ORTSSteamColdWaterPumpFlowAtMaxSpeed ORTSSteamHotWaterPumpFlowAtMaxSpeed ORTSSteamCombinedWaterPumpFlowAtMaxSpeed	All	Water flow rate of pump at maximum speed
ORTSSteamColdWaterPumpPressureAtMaxSpeed ORTSSteamHotWaterPumpPressureAtMaxSpeed ORTSSteamCombinedWaterPumpPressureAtMaxSpeed	All	The output pressure of the pump at maximum speed
ORTSSteamColdWaterPumpHasDriftControl ORTSSteamHotWaterPumpHasDriftControl ORTSSteamCombinedWaterPumpHasDriftControl	All	Specifies whether the pump has a drift control to limit the speed of the pump when throttle is closed. (This is a binary parameter.)
ORTSSteamPumpDriftControlMinSteamChestPressureForMaxSpeed	All	Specifies the minimum steam chest pressure the drift control valve will allow the pump to operate at full speed.
ORTSSteamPumpDriftControlIdleSpeedMaxSteamPressure	All	Specifies the maximum steam pressure that the drift control will deliver to the pump when in the “idle” state (when steam chest pressure is too low).
ORTSSteamColdWaterPumpHasFloatFlowControl	Cold Water Only	Specified whether the cold water pump, when used in conjunction with an open-type heater, is subject to automatic water flow

		control by means of a float valve in the heater. (This is a binary parameter).
ORTSSteamPumpFlowControlHeaterWaterLevelThreshold	Cold Water Only	Specifies the water level in the heater that the flow control will trigger at.
ORTSSteamPumpFlowControlIdleWaterPressure	Cold Water Only	Specifies the maximum water pressure that the flow control valve will let the pump operate at.
ORTSSteamColdWaterPumpHasFloatThrottle	Cold Water Only	Specifies whether the cold water pump, when used in conjunction with an open-type heater, has a variable throttle valve controlled by a float valve in the heater (This is a binary parameter).
ORTSSteamColdWaterPumpHasWaterFlowControlledThrottle	Cold Water Only	Specifies whether the steam throttle valve to the pump has a regulator actuated by the water discharge pressure, so as to reduce the steam supply to the pump if there is any anomaly in water flow from the pump. (This is a binary parameter.)
ORTSSteamPumpFloatThrottleFullyClosesAtHeaterWaterLevel	Cold Water Only	Specifies the water level at which the cold water pump will completely shut off at.
ORTSSteamCombinedColdandHotWaterPumpHasFloatRecirculatingAndReducingValve	Combined Cold & Hot Only	Specifies whether the pump, when used in conjunction with an open-type heater has a recirculating valve that is actuated by a float valve in the heater and recirculates incoming water back through the cold pump if the heater is full. At the same time, water flow from the tender is reduced. (This is a binary parameter.)
ORTSSteamPumpRecirculatingAndReducingValveHeaterWaterLevelThreshold	Combined Cold & Hot Only	Specifies the water level that the recirculating valve will trip at.

As mentioned earlier, the main source of exhaust steam for the feedwater heater was the main locomotive steam cylinders. However, some locomotives had provisions to allow the exhaust of some steam-using appliances and auxiliaries, such as the air compressor, mechanical stoker or booster engine, to enter the heater so that some exhaust was being used to heat the heater, even when the main throttle was closed. In ORTS, this can potentially be simulated with the following binary parameters:

ORTSSteamFeedwaterHeaterYReceivesExhaustFromAirCompressor (x)
ORTSSteamFeedwaterHeaterYReceivesExhaustFromMechanicalStoker (x)
ORTSSteamFeedwaterHeaterYReceivesExhaustFromBoosterEngine (x)
ORTSSteamFeedwaterHeaterYReceivesExhaustFromElectricGenerator (x)
ORTSSteamFeedwaterHeaterYReceivesExhaustFromColdWaterPump (x)
ORTSSteamFeedwaterHeaterYReceivesExhaustFromHotWaterPump (x)
ORTSSteamFeedwaterHeaterYReceivesExhaustFromCombinedColdAndHotWaterPump (x)

Where **(x)** equals either **0** = No, or **1** = Yes. **Y** represents the number of the water system that the heater is part of (1 or 2).

With the exhaust steam being used to heat the heater, you're probably wondering how the smokebox draft for the combustion of fuel would be accomplished. Well, not all of the exhaust is used for feedwater heating, as most of the exhaust is still being used to provide the draft. The percentage of the exhaust steam being used to heat the heater can be defined with:

ORTSSteamFeedwaterHeaterYPercentageOfTotalCylinderExhaust (x)

Where (x) is a number, usually less than 1, that corresponds to the total percentage of exhaust steam drawn by the feedwater heater. This also causes a consequential reduction in cylinder back pressure, proportional to the value in the parameter, at all times. **Y** represents the number of the water system that the heater is part of (1 or 2).

Specifying Preferences for Boiler-Feeding Devices Used by the AI Fireman

The way the ORTS AI fireman currently adds water to the boiler is very simple. When the boiler water level drops below 81%, the AI fireman starts adding water with injector #1 (which is assumed, by default, to be a live-steam injector). He then slowly increases the injector 1 water flow, with the goal being to keep the water level in the boiler constant. However, if the water level continues to drop, even with injector #1 working at near-maximum capacity, he will start injector #2 (which is assumed to be an exhaust steam injector) when the water level drops below 69%. If the water level begins to increase, he will back off the flow of the injectors in a reverse manner, shutting off injector #2 when the water level increases above 69%, and then shutting off injector #1 when the water level increases above 90%.

While without a doubt, this method of adding water to the boiler is quite effective, there needs to be some preference as to which device the AI fireman operates under certain conditions. This is especially true now that these new water system parameters present a seemingly endless variation in the types of water systems available on any given locomotive. In particular, the feedwater heater or exhaust injector (if the locomotive has one) is only effective when the locomotive is moving and the throttle is open. However, live-steam injectors and inspirators are effective under all conditions, regardless of whether the locomotive is standing or moving. One rule of thumb is that the live-steam injector should be operated for the first 4-5 miles, or 7 minutes, after starting from a stop, to give the feedwater heater (if the locomotive has one) time to heat up thoroughly. Then, the live-steam injector can be shut off, and the feedwater pump/heater started.

These various conditions can be potentially modeled by including an optional **Conditions** parameter, not unlike those currently used for lighting, in the water system grouping. A few of the condition parameters can potentially include, but are certainly not limited to:

Condition Parameter	Number Format	Description
Standing	Binary	Water system operates when the locomotive is standing/idling.
Moving	Binary	Water system operates when the locomotive is in motion.
ThrottleOpen	Binary	Water system operates when the locomotive throttle is open.
ThrottleClosed	Binary	Water system operates when the locomotive throttle is closed.
ThrottleMinimumOpening	Decimal	Minimum throttle opening for system to operate
ThrottleOpenTimeDelayBeforeStarting	Decimal	The amount of time after the throttle is opened before the system will start.
ThrottleOpenTimeDelayBeforeStopping	Decimal	The amount of time after the throttle is opened before the system will stop.
ThrottleCloseTimeDelayBeforeStopping	Decimal	The amount of time after the throttle is

		opened before the system will stop.
ThrottleOpenTimeDelayBeforeStopping	Decimal	The amount of time after the throttle is opened before the system will stop.
MovingTimeDelayBeforeStarting	Decimal	The amount of time after the locomotive starts moving before the system will start.
MovingDistanceDelayBeforeStarting	Decimal	The amount of distance the locomotive must move before the system will start.
MutuallyExclusive	Binary	Indicates that if this water system starts, the other is automatically stopped, unless the boiler water level is very low.

Prototype Example Codes

Here's a sampling of the potential example codes using the new water system parameters, using real-world prototypes (in the US) as the basis:

```
Comment ( ***Example 1 --- Two Lifting Live Steam Injectors***)
Comment ( ***Nathan Number 10 Simplex Lifting Injectors*** )
ORTSSteamWaterSystem1EquipmentType ( “Lifting_live_steam_injector” )
ORTSSteamInjector1FeedRatePerUnitOfBoilerPressure ( 19.0g-us/h/psi )
ORTSSteamLiftingInjector1MustBePrimedToOperate ( 1 )
ORTSSteamLiftingInjector1ToTenderHighWaterLevel ( 3.0ft )
ORTSSteamLiftingInjector1ToTenderLowWaterLevel ( 8.0ft )

ORTSSteamWaterSystem2EquipmentType ( “Lifting_live_steam_injector” )
ORTSSteamInjector2FeedRatePerUnitOfBoilerPressure ( 19.0g-us/h/psi )
ORTSSteamLiftingInjector2MustBePrimedToOperate ( 1 )
ORTSSteamLiftingInjector2ToTenderHighWaterLevel ( 3.0ft )
ORTSSteamLiftingInjector2ToTenderLowWaterLevel ( 8.0ft )

Comment ( ***Example 2 --- Open Feedwater Heater and Non-Lifting Injector***)
Comment ( *** Worthington SA Feedwater Heating System *** )
ORTSSteamWaterSystem1EquipmentType ( “Centrifugal_cold_water_pump,
Open_type_feedwater_heater, Reciprocating_hot_water_pump” )
Conditions (
        Standing ( 0 )
        Moving ( 1 )
        ThrottleOpen ( 1 )
        ThrottleClosed ( 0 )
        MutuallyExclusive ( 1 )
        ThrottleOpenTimeDelayBeforeStarting ( 420s )
        ThrottleCloseTimeDelayBeforeStopping ( 300s )
        MovingTimeDelayBeforeStarting ( 420s )
        MovingDistanceDelayBeforeStarting ( 4.5mi )
        )
ORTSSteamFeedwaterHeater1MaxWaterHeatMultiplier ( 2.45 )
ORTSSteamFeedwaterHeater1PercentageOfTotalCylinderExhaust ( 0.125 )
ORTSSteamFeedwaterHeater1ReceivesExhaustFromAirCompressor ( 1 )
ORTSSteamFeedwaterHeater1ReceivesExhaustFromBoosterEngine ( 1 )
ORTSSteamColdWaterPump1MaxRPM ( 4500.0 )
```

```
ORTSSteamColdWaterPump1FlowAtMaxSpeed ( 14400.0g-us/h )
ORTSSteamColdWaterPump1HasFloatThrottle ( 1 )
ORTSSteamColdWaterPump1FloatThrottleFullyClosesAtHeaterWaterLevel ( 0.375 )
ORTSSteamHotWaterPump1MaxPistonRate ( 100.0strokes/min )
ORTSSteamHotWaterPump1FlowAtMaxSpeed ( 14400.0g-us/h )
ORTSSteamHotWaterPump1HasDriftControl ( 1 )
ORTSSteamHotWaterPump1DriftControlMinSteamChestPressureForMaxSpeed ( 50.0psi )
ORTSSteamHotWaterPump1DriftControlIdleSpeedMaxSteamPressure ( 90psi )

Comment ( ***Nathan 4000C Non-Lifting Injector*** )
ORTSSteamWaterSystem2EquipmentType ( Nonlifting_live_steam_injector )
Conditions (
        Standing ( 1 )
        Moving ( 1 )
        ThrottleOpen ( 1 )
        ThrottleClosed ( 1 )
        MutuallyExclusive ( 1 )
        ThrottleOpenTimeDelayBeforeStopping ( 420s )
        ThrottleCloseTimeDelayBeforeStarting ( 300s )
        )
ORTSSteamInjector2FeedRatePerUnitOfBoilerPressure ( 36.25g-us/h/psi )
ORTSSteamNonLiftingInjector2OverFlowOperation ( Automatic )
ORTSSteamNonLiftingInjector2DoesSteamAndWaterShareOneControl ( 1 )

Comment ( ***Example 3 --- Centrifugal Pump and Exhaust Injector in Series***)
Comment ( ***Elesco Type TP Exhaust Injector System*** )
ORTSSteamWaterSystem1EquipmentType ( “Centrifugal_cold_water_pump,
Exhaust_steam_injector” )
Conditions (
        Standing ( 0 )
        Moving ( 1 )
        ThrottleOpen ( 1 )
        ThrottleClosed ( 0 )
        MutuallyExclusive ( 1 )
        ThrottleOpenTimeDelayBeforeStarting ( 420s )
        ThrottleCloseTimeDelayBeforeStopping ( 300s )
        MovingTimeDelayBeforeStarting ( 420s )
        MovingDistanceDelayBeforeStarting ( 4.5mi )
        )
ORTSSteamColdWaterPump1MaxRPM ( 4500.0 )
ORTSSteamColdWaterPump1FlowAtMaxSpeed ( 14400.0g-us/h )
ORTSSteamExhaustInjector1PercentageOfTotalCylinderExhaust ( 0.25 )
ORTSSteamExhaustInjector1HasLiveSteamStartOption ( 1 )
ORTSSteamExhaustInjector1HasAutomaticChangeover ( 1 )
ORTSSteamExhaustInjector1MinimumExhaustPressureForExhaustOperation ( 5.0psi )
ORTSSteamExhaustInjector1ExhaustCutsOutAtPressure ( 1.0psi )
ORTSSteamExhaustInjector1FeedRatePerUnitOfExhaustPressure ( 500.0g-us/h/psi )

Comment ( ***Example 4 --- Closed Feedwater Heater with Duplex Reciprocating Pump***)
```

```
Comment ( ***Elesco Feedwater Heater with CF-1 Duplex Reciprocating Pump*** )
ORTSSteamWaterSystem1EquipmentType ( “Duplex_reciprocating_cold_water_pump,
Closed_type_feedwater_heater, Condensate_drain_to_tender” )
Conditions (
	Standing ( 0 )
	Moving ( 1 )
	ThrottleOpen ( 1 )
	ThrottleClosed ( 0 )
	MutuallyExclusive ( 1 )
	ThrottleOpenTimeDelayBeforeStarting ( 420s )
	ThrottleCloseTimeDelayBeforeStopping ( 300s )
	MovingTimeDelayBeforeStarting ( 420s )
	MovingDistanceDelayBeforeStarting ( 4.5mi )
	)
ORTSSteamFeedwaterHeater1MaxWaterHeatMultiplier ( 2.1 )
ORTSSteamFeedwaterHeater1PercentageOfTotalCylinderExhaust ( 0.14 )
ORTSSteamFeedwaterHeater1ReceivesExhaustFromAirCompressor ( 1 )
ORTSSteamFeedwaterHeater1ReceivesExhaustFromBoosterEngine ( 1 )
ORTSSteamColdWaterPump1MaxPistonRate ( 80.0strokes/min )
ORTSSteamColdWaterPump1FlowAtMaxSpeed ( 13000.0g-us/h )

Comment ( ***Example 4 --- Closed Feedwater Heater with Centrifugal Pump***)
Comment ( ***Coffin Feedwater Heater*** )
ORTSSteamWaterSystem1EquipmentType ( “Centrifugal_cold_water_pump,
Closed_type_feedwater_heater, Condensate_drain_to_tender” )
Conditions (
	Standing ( 0 )
	Moving ( 1 )
	ThrottleOpen ( 1 )
	ThrottleClosed ( 0 )
	MutuallyExclusive ( 1 )
	ThrottleOpenTimeDelayBeforeStarting ( 420s )
	ThrottleCloseTimeDelayBeforeStopping ( 300s )
	MovingTimeDelayBeforeStarting ( 420s )
	MovingDistanceDelayBeforeStarting ( 4.5mi )
	)
ORTSSteamFeedwaterHeater1MaxWaterHeatMultiplier ( 2.1 )
ORTSSteamFeedwaterHeater1PercentageOfTotalCylinderExhaust ( 0.14 )
ORTSSteamFeedwaterHeater1ReceivesExhaustFromAirCompressor ( 1 )
ORTSSteamFeedwaterHeater1ReceivesExhaustFromBoosterEngine ( 1 )
ORTSSteamColdWaterPump1MaxRPM ( 5000 )
ORTSSteamColdWaterPump1FlowAtMaxSpeed ( 21000.0g-us/h )

Comment ( ***Example 5 --- Motion Pumps***)
Comment ( ***Motion Pumps*** )
ORTSSteamWaterSystem1EquipmentType ( “Motion_pump” )
ORTSSteamMotionPump1MaxWaterFeedRateAtMaxDrivingWheelRPM ( 10000.0g-us/h )

ORTSSteamWaterSystem2EquipmentType ( “Motion_pump” )
```

ORTSSteamMotionPump2MaxWaterFeedRateAtMaxDrivingWheelRPM (10000.0g-us/h)

Comment (***Example 5 --- Two Non-Lifting Inspirators***)
Comment (***Hancock Model MNL Non-Lifting Inspirators***)
ORTSSteamWaterSystem1EquipmentType (Nonlifting_inspirator)
ORTSSteamInspirator1FeedRatePerUnitOfBoilerPressure (70.0g-us/h/psi)
ORTSSteamNonLiftingInspirator1OverFlowOperation (Manual)

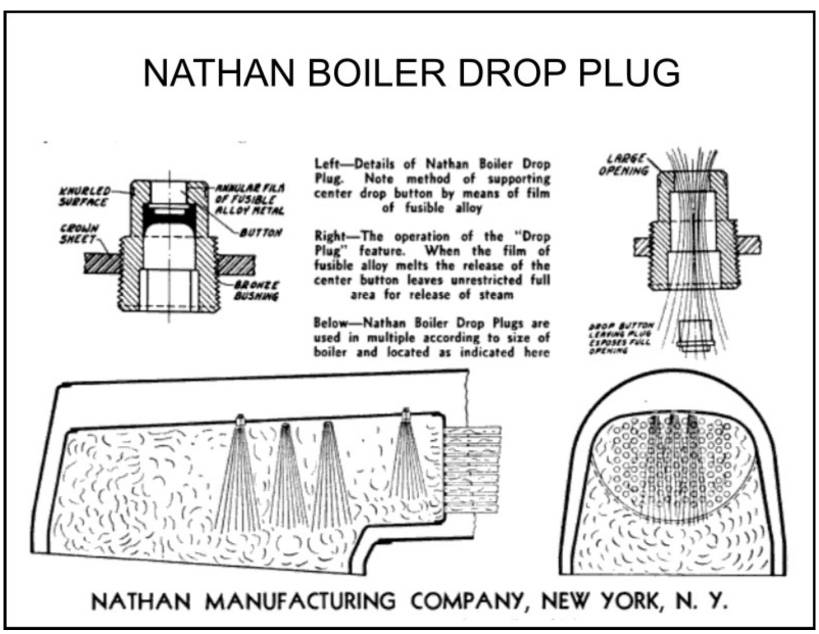
ORTSSteamWaterSystem2EquipmentType (Nonlifting_inspirator)
ORTSSteamInspirator2FeedRatePerUnitOfBoilerPressure (70.0g-us/h/psi)
ORTSSteamNonLiftingInspirator2OverFlowOperation (Manual)

Low-Water Alarms and Fusible Plugs

The three most essential questions a steam locomotive crew must ask themselves when operating a locomotive are:

1. Where is the water level in your boiler?
2. Where is the water level in your boiler?, and
3. Where is the water level in your boiler?

It is very important that the boiler water cover the top of the boiler crown sheet at all times, so it will not overheat, rupture and cause a potentially fatal boiler explosion. Both ORTS and MSTS have modeled devices called ***fusible plugs***, also known as "soft plugs" or "drop plugs", which are devices that have a brass pipe-shaped body with a brass button held in place by a fusible, solder-like metal that melts at temperatures above 500-575ºF or thereabouts, releasing steam into the firebox, thus relieving the pressure and extinguishing the fire. In MSTS, letting the boiler water level get too low resulted in the activity being terminated with a "game-over"-type message, while in ORTS, a low water level resulted in a sudden drop in both boiler pressure and fire temperature, actually modeling the melting of the fusible plugs.



Typical fusible plug installation. Courtesy of Simmons-Boardman Publishing Corporation.

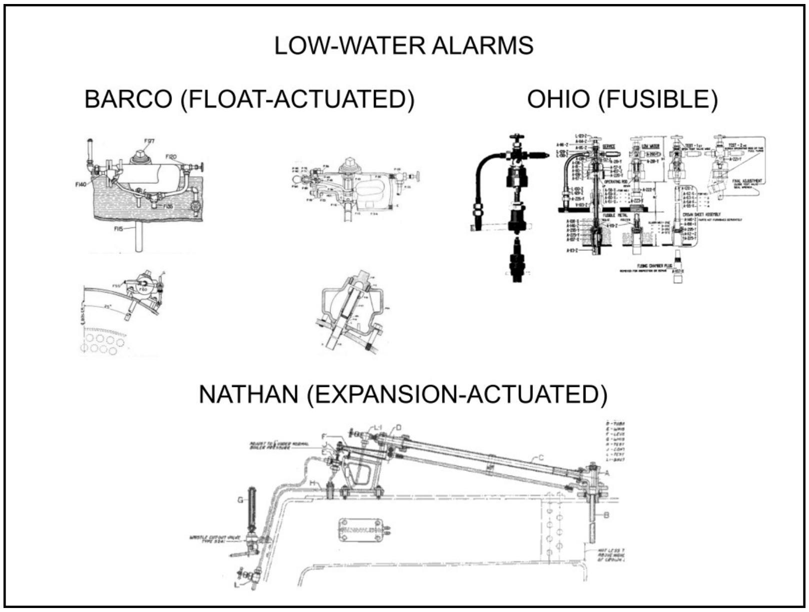
However, ORTS and MSTS currently assume that all steam locomotives have fusible plugs, but in reality that is not the case. According to The US' **Title 49 CFR Part 230**, the use of fusible plugs was (and still is) not required, but if they are used, they must be periodically removed and cleaned of scale and other residue. Furthermore, a study of the NTSB's investigative report of the Gettysburg Railroad's boiler accident of 1995 stated that the locomotive involved in the incident, Canadian Pacific 1278, did not have any fusible plugs at all.

Therefore, fusible plugs should be made optional by utilizing the following parameter:

ORTSSteamBoilerHasFusiblePlugs (x)

Where **(x)** equals either:
0 = Boiler does not have fusible plugs. If not equipped with fusible plugs, ORTS terminates the activity automatically if the boiler water level is allowed to drop too low, or
1 = The boiler is equipped with fusible plugs, and when the boiler water level gets too low, the fire temperature and boiler pressure are relieved suddenly as ORTS currently does.

Locomotives may have low-water alarms in addition to (or in lieu of) fusible plugs. These devices detected when the boiler water level was getting too low for safe operation, either by means of a float, or by detecting abnormal expansion and/or temperature. Once activated, the alarms would blow a whistle to get the attention of the locomotive crew before either the boiler exploded, the crown sheet burned, or (if so equipped) the fusible plugs melted. The whistle would continue to blow until either the water level rose, or the fire was dumped or extinguished.



A few examples of low-water alarms. Courtesy of Simmons-Boardman Publishing Corporation.

For the purposes of ORTS, a low-water alarm can potentially be modeled as a monitoring device not unlike those used for AWS, Vigilance or Overspeed on modern locomotives:

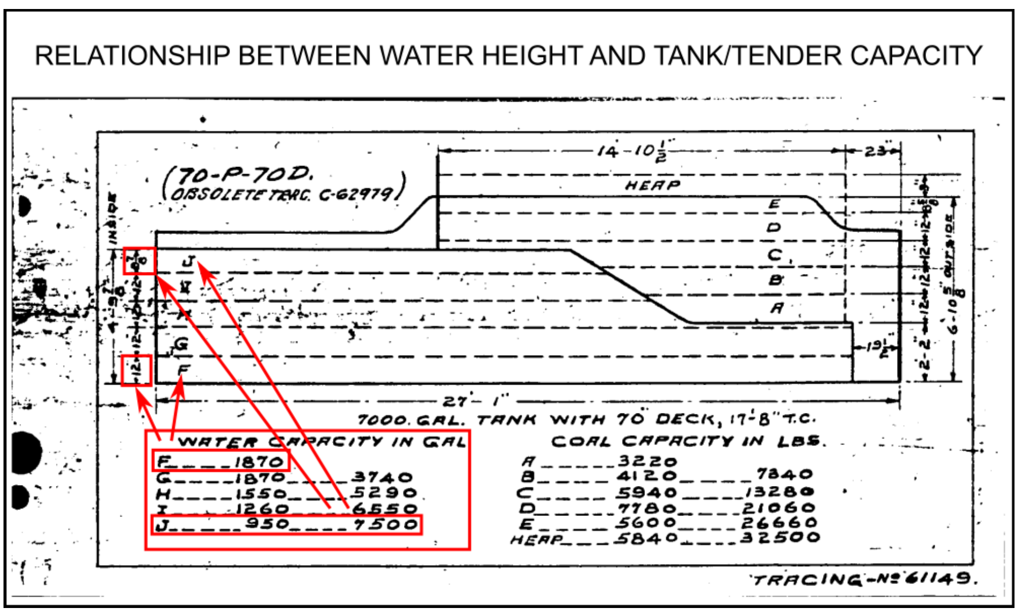
```
ORTSLowWaterMonitor (
        MonitoringDeviceAlarmTriggerWaterLevel ( 0.2 )
```

MonitoringDeviceAlarmDelayTimeBeforeSounding (40s)
MonitoringDeviceResetWaterLevel (0.35)
)

How this code works should be fairly obvious, but if it isn't, here's how it works: When the water level in the boiler drops below the **MonitoringDeviceAlarmTriggerWaterLevel** value, the alarm begins to sound (using a brand new discrete ***.sms** file trigger). If the parameter **MonitoringDeviceAlarmDelayTimeBeforeSounding** is specified, the alarm will wait for the time specified in the parameter before it begins to sound. This simulates any lag in reaction time caused by the mechanical idiosyncrasies of the alarm system. Once the water level rises above the **MonitoringDeviceResetWaterLevel** value, the alarm gets silenced. If, on the other hand, the water level continues to drop even further than **MonitoringDeviceAlarmTriggerWaterLevel**, the alarm will continue to sound until either **a)** the activity ends (if the loco doesn't have any fusible plugs) or **b)** the boiler pressure drops to a very low value (if the loco is equipped with fusible plugs), perhaps 50 PSI.

Tender/Tank Capacity—Water Height vs Tank Volume

Currently, ORTS models the depletion and replenishment of the water supply in the locomotive's tender or tank(s) just like MSTS did—in a linear fashion. However, this assumes that the tanks are a perfect cube, cylinder or rectangular prism in cross-section. In reality, the tender water tank is often an irregular shape—particularly in the United States, where the "water-bottom" tender, as well as "slope-back" tenders used on yard switching locomotives, were commonplace. With these tank designs, the irregular shape meant that the water supply did not deplete in a linear fashion relative to the height of the water in the tank.



Pennsylvania Railroad tender body diagram showing the relationship of water and coal supply height relative to volumetric capacity. Courtesy of prr.railfan.net.

This drawing of the body of a Pennsylvania Railroad locomotive tender demonstrates that because of the "water-bottom" arrangement of the tank, and the fact that the coal bunker "slope sheet" forms part of the tank, the rated water capacity for each 12-inch (1-foot) interval of water height is not consistent from interval to interval, but gradually decreases as the water height increases. Thus in the case of the

7500-gallon tender shown in the drawing, the height of the water at the top of marker “F”, at 1870 gallons, represents 25% of the tank volume, even though the height of this marker constitutes 21% of the total height of the water tank. Likewise, when the water level reaches the top of marker “H”, at 5290 gallons, it reflects a tank capacity of 71%, despite the height of the water being at 62% of the height of the tank interior.

Thus it was a common practice to calibrate tender-water gauges in distance units (inches or feet) rather than either volumetric units (gallons) or percentages. This can potentially be simulated with curve parameters not unlike those which we already have for brake friction, diesel tractive effort, and prime mover RPM. However, it is also necessary for ORTS to know the maximum height of the water above the tank bottom by specifying the overall interior height of the tank. Here's what such a curve would look like using the above diagram as an example:

```
ORTSWaterTankInteriorHeight ( 57.875in )
ORTSWaterCapacityCurve (
	Comment ( ***Height in meters vs Volume in liters*** )
	0		0
	0.3048		7078.72
	0.6096		14157.44
	0.9144		20024.83
	1.2192		24794.45
	1.470025	28390.59
)
```

Just like **MaxTenderWaterMass** and **ORTSTenderWagonWaterMass**, these water capacity curves either can be located in the locomotive ***.eng** file or the tender ***.wag** file, and if located in the latter, those values override those in the former.

Further Reading

Harding, JW and Williamson, GV *International Correspondence Schools (ICS) Textbook 508D: Locomotive Boiler Feeding Devices*
Scranton, PA, International Textbook Company, 1937

Westcott, Linn H. *Model Railroader's Cyclopedia Vol 1: Steam Locomotives*
Waukesha, WI, Kalmbach Books, 1960.
Contains piping diagrams for various injector and feedwater systems.

Locomotive Cyclopedia of American Practice, 1938 Edition, Simmons-Boardman Publishing Corporation
Further information about various boiler-water devices described in this document can be found on the following pages:

Device	Page(s)
Nathan Boiler Drop (Fusible) Plug	285
Wilson Water Conditioner	381-383
Feedwater Heaters, Elesco	385-387

Feedwater Heaters, Coffin	388-389
Feedwater Heaters, Worthington	390-393
Injectors, Live Steam	397, 400-403
Injectors, Exhaust Steam, Elesco	398-399
Sellers Exhaust Feedwater Heater	402
Injector Starting and Steam Valves	404
Inspirators, Hancock	418
Low-Water Alarms	490-493

Locomotive Cyclopedia of American Practice, 1950-52 Edition, Simmons-Boardman Publishing Corporation
Further information about various boiler-water devices described in this document can be found on the following pages:

Device	Page(s)
Nathan Boiler Drop (Fusible) Plug	555
Feedwater Heaters, Elesco	608
Feedwater Heaters, Worthington	609
Feedwater Heaters, Hancock Turbo	610-11
Injectors, Live Steam	613-617
Inspirators, Hancock	618-619
Injector Starting and Steam Valves	620
Injectors, Exhaust Steam, Elesco	622-623

Locomotive Cyclopedia of American Practice, 1922 Edition, Simmons-Boardman Publishing Corporation
Further information about various boiler-water devices described in this document can be found on the following pages:

Device	Page(s)
Feedwater Heaters, Elesco	314-316
Feedwater Heaters, Worthington (BL)	317-319
Injectors, Live Steam	323-327, 330-331
Inspirators, Hancock	323
Injectors, Exhaust Steam, Elesco	328-329
Injector Starting and Steam Valves	335
Low-Water Alarms	559

Locomotive Dictionary, 1909 Edition, Railroad Age Gazette

Further information about various boiler-water devices described in this document can be found on the following pages:

Device	Page(s)
Inspirators, Hancock	288-290
Injectors, Live Steam	291-296

Suggested Unit Course in Locomotive Firing, Education Department of the Sate of New York, 1944. Includes descriptions and operating practices for various types of locomotive water systems.

SIR-96/05: Special Investigative Report Steam Locomotive Firebox Explosion On the Gettysburg Railroad Near Gardners, PA, 6/16/95, National Transportation Safety Board (NTSB), 1996.

1999 CFR Title 49, Volume 8, Part 230—Steam Locomotive Inspection and Maintenance Standards.