

Steam School Notes

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Preface

Steam School is presented by members of the Steam Association of Manitoba (SAM) in conjunction with the Manitoba Agricultural Museum.

The mission of SAM is to support the preservation and safe operation of historical boilers in Manitoba. To further these goals, SAM operates a Steam School and administers a registered quality assurance program.

SAM serves as an umbrella organization for boiler owners, steam operators, and associated museums. It also acts to communicate the interests of the steam community to Inspection and Technical Services Manitoba.

The Steam School program was developed to provide a practical understanding of steam equipment, boiler construction, safe operation, inspection requirements, and the principles that govern pressure-retaining structures. The course combines classroom instruction with the operation of real equipment.

These scripted notes grew out of that program. Their purpose is to collect in one place the information, explanations, examples, and calculations used throughout Steam School. While various codes, standards, and reference texts provide the detailed requirements for boiler construction and inspection, students often benefit from a simpler explanation of the underlying principles.

The emphasis throughout is on understanding rather than memorization. Whenever possible, the notes begin with physical observations and practical examples before developing the associated calculations. The intent is not merely to show what a formula is, but to explain why it works.

The material is intended for steam enthusiasts, boiler owners, operators, inspectors, restorers, and museum volunteers. No formal engineering background is assumed, although those with technical training may recognize many of the principles from strength of materials, thermodynamics, and pressure-vessel design.

Steam power combines history, craftsmanship, engineering, and public safety. The continued operation of historical steam equipment depends on understanding all four. It is my hope that these notes contribute, in a small way, to the preservation and safe operation of steam in Manitoba and beyond.

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Power Engineer's Certificate
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Vulcan Locomotive Operator's Card
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Acknowledgements

Steam School at the Manitoba Agricultural Museum was established in the mid-1980s by Bill McCreery and Garth Christison. Building on that foundation, SAM later developed a formal curriculum that allowed the course to meet evolving regulatory and licensing requirements.

The curriculum on which the current program is based was developed in 2012 by Jim Nowell and Gerald Dueck. Jim brought extensive steam-school instructional experience from Rollag, Minnesota, and from the Wisconsin Steam School, helping to incorporate proven teaching methods and course structure into the Manitoba program.

The continued success of Steam School depends on the dedicated volunteers of SAM, who donate their time, expertise, and privately owned engines to ensure that students receive both classroom instruction and hands-on practical experience.

We are grateful to the Manitoba Agricultural Museum, which has provided facilities and steam engines for the presentation of this course.

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- Flexmark
- Myron Algebra
 - Math Expression Language
- MarkdownMath workbench (MDML)
 - Flexmark/MEL formatting extensions
 - Markdown Preprocessor (MP)
 - Preprocessor Scripting Language (PSL)
 - Temml
 - Katex
 - Chrome Developer Tools

Details are available from the author.

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Chapter 1

Introduction

Steam power combines history, mechanics, metallurgy, thermodynamics, boiler construction, inspection, and safe operating practice. The challenge for most students is that these subjects are often presented separately, even though they all meet in the same machine.

The purpose of these notes is to bring those subjects together in a practical and accessible form. The material originated as supporting notes for Steam School, presented by the Steam Association of Manitoba in conjunction with the Manitoba Agricultural Museum. Over time, the notes grew beyond the classroom and evolved into a reference for owners, operators, inspectors, museum volunteers, and anyone interested in historical steam equipment.

The book begins where most Steam School students begin: standing beside a boiler and asking, "What am I looking at?"

The early chapters identify the principal parts of a boiler and steam traction engine, explain their functions, and introduce the safety devices and operating systems found on steam equipment. Later chapters examine how pressure acts within a boiler and how pressure-retaining structures are designed to resist it. Topics include shell strength, safety factors, riveted joints, and stayed surfaces.

Additional chapters discuss water and steam, water treatment, injectors, piping systems, valves, fittings, and the documentation required for the inspection and operation of historical boilers.

The emphasis throughout is on understanding rather than memorization. Wherever possible, the text begins with observation and practical experience before introducing mathematics and formulas. Many of the calculations used in boiler construction are easier to understand when the physical behaviour is understood first.

Several recurring ideas appear throughout the book:

- Pressure acts in all directions.
- Boilers do not fly.
- Round surfaces want to be round.
- Flat surfaces want to be round.
- The weakest element governs.

These simple observations explain much of boiler construction and operation. The formulas that follow are often nothing more than a mathematical expression of these ideas.

The reader is not expected to have an engineering degree. Familiarity with basic arithmetic is sufficient for most of the calculations presented. More important than mathematics is a willingness to examine how a boiler is constructed, how it behaves under pressure, and why particular safety rules exist.

Steam engineering occupies a unique place between history and modern engineering practice. The preservation of historical steam equipment requires an understanding not only of how these machines were built, but also of why they were built that way and how they can be operated safely today.

It is hoped that these notes help the reader develop that understanding.

Chapter 2

Boiler Construction

Boiler construction is the study of how the pressure-retaining parts of a boiler are shaped, supported, joined, and protected against failure. A boiler is not merely a tank for holding water and steam. It is a pressure vessel made from curved shells, flat sheets, openings, seams, tubes, stays, fittings, and reinforcement.

Some parts of a boiler are naturally strong because of their shape. Other parts are weak unless they are stayed or otherwise supported. Much of boiler construction analysis consists of deciding which surfaces

are self-supporting, which surfaces require stays, and how the strength of each region is calculated.

This chapter begins with the main historical boiler types, then identifies the important parts of a firetube boiler. The remainder of the chapter develops the construction analysis used for shells, riveted joints, and stayed surfaces.

2.1 Boiler Types

Historic steam equipment used several boiler arrangements. The differences are not merely visual. Each type places the fire, water, steam space, tubes, flues, and pressure-retaining surfaces in a different relationship.

2.1.1 Vertical Boiler

A vertical boiler places the shell upright. This makes the boiler compact and useful where floor space is limited or where moderate steam output is sufficient.

The vertical shell is a cylindrical pressure vessel. Because the shell is round, it is relatively strong under internal pressure. The firebox and heating surface may be arranged in several ways, depending on the design. Some vertical boilers use tubes, some use cross tubes, and some use other internal heating surfaces.

A vertical boiler is simple and compact, but steam space, water level, and heating surface must all fit within a short vertical vessel. This can make water-level management especially important.

2.1.1.1 Diagram

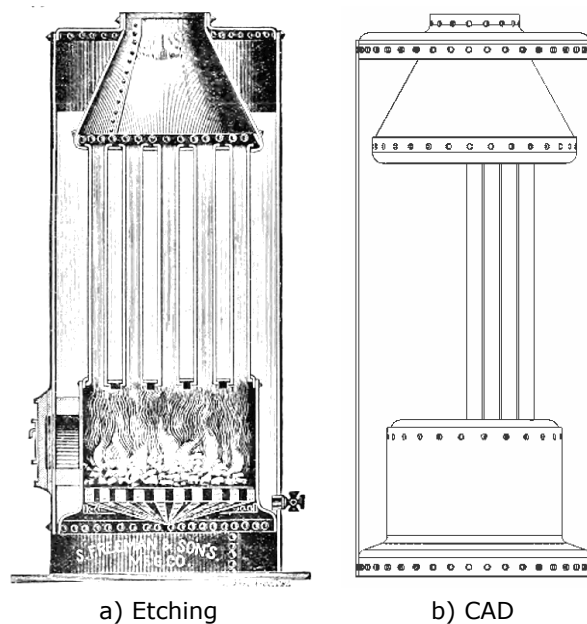


Fig. 1 Vertical boiler.

2.1.2 Water-tube vertical Boiler

In a water-tube boiler, water flows inside tubes while hot gases pass around the outside of the tubes. This is the reverse of a firetube boiler.

The important construction advantage is that the pressure-retaining tubes are small in diameter. A small-diameter pressure part is much easier to make strong than a large-diameter shell at the same pressure. For that reason, water-tube boilers are well suited to higher pressures.

Water-tube boilers can also provide large heating surface in a compact arrangement. However, they are more complex than simple firetube boilers and involve more individual pressure parts.

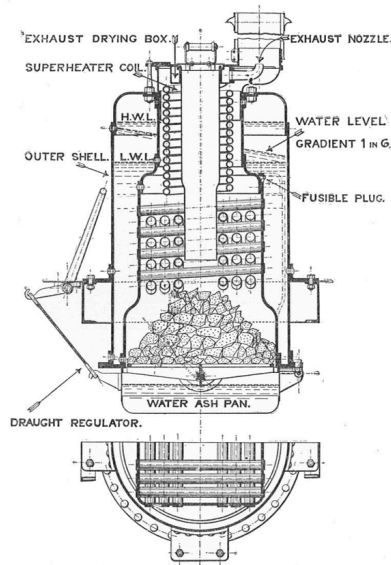


Fig. 2 Water-tube boiler.

2.1.3 Return Flue Boiler

A return flue boiler uses a gas path that returns through the boiler before discharge. The arrangement increases the effective heating path within a relatively compact shell.

The return flue boiler is a firetube-family design in the broad sense that hot gases pass through flues surrounded by water. Like other shell boilers, the cylindrical shell is largely self-supporting, while flat ends, tube sheets, and openings require construction details that provide adequate strength.



Fig. 3 Return flue boiler.

2.1.4 Locomotive-style Firetube Boiler

The locomotive-style firetube boiler is the familiar arrangement used on locomotives, traction engines, and many portable engines. The firebox is located at the rear. Hot gases pass from the firebox through tubes or flues toward the front smokebox. Water surrounds the firebox and tubes, and steam collects above the water line.

This type combines several construction problems in one vessel:

An internal steam pipe that usually runs from the dome toward the throttle or steam outlet. Its purpose is to collect steam from a higher, drier part of the steam space.

Mud ring

The lower ring or frame around the firebox water legs. It closes the bottom of the water space and ties together the lower firebox structure.

Manholes and handholes

Openings used for inspection, cleaning, and maintenance.

Boiler jacket

Outer covering, usually over insulation, used to reduce heat loss and improve appearance.

Ash pit

The space below the grate where ash collects and where combustion air enters.

Grate surface

The area that supports the fire.

Heating surface

Wetted metal surface exposed to fire or hot gases. This includes firebox sheets, tube surfaces, and other surfaces that transfer heat to the water.

Steam space

The space above the water line where steam collects.

Water space

The space occupied by water around the firebox, tubes, shell, and other internal parts.

Staybolts

Short stays used to support flat firebox sheets.

Through stays

Longer stays that extend through the boiler to support larger flat areas.

Diagonal stays

Stays installed at an angle, often used where direct staying is not practical.

Double plating

Reinforcing plate added at regions requiring extra strength, such as around openings or fittings.

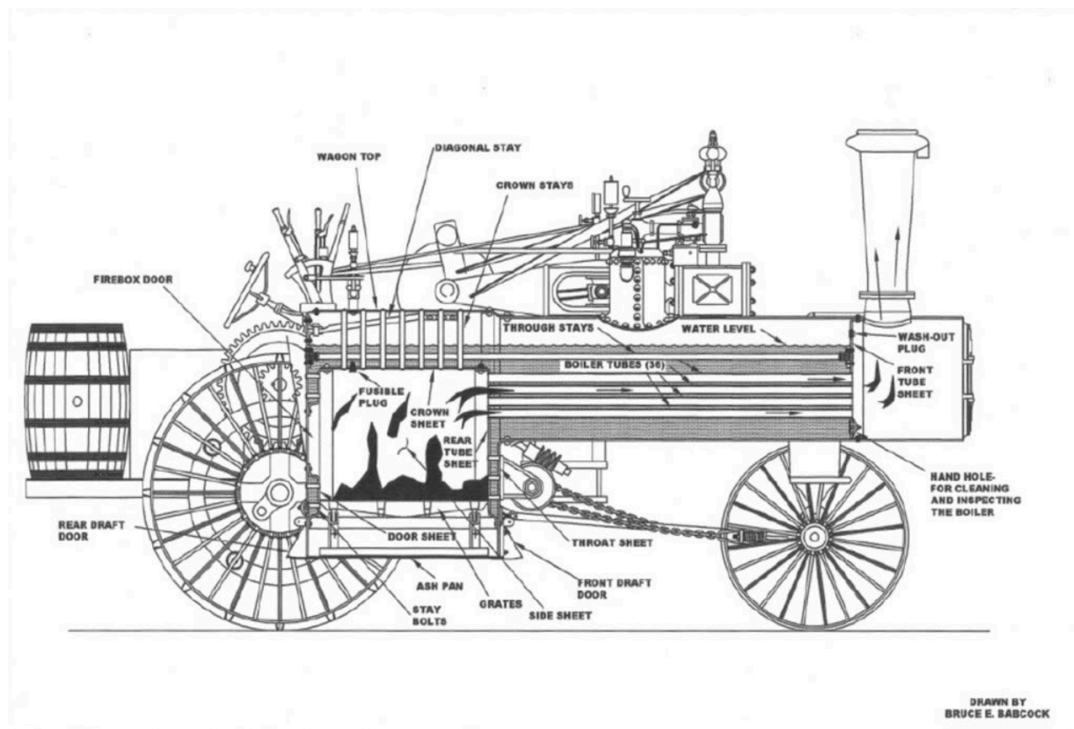


Fig. 5 Principal parts of a locomotive-style firetube boiler.

2.3 Flue Sheets and Internal Features

The flue sheets are more than simple plates with holes in them. They locate and support the tubes or flues, form part of the pressure boundary, and often show evidence of other internal boiler features.

2.3.1 Rear Flue Sheet

The rear flue sheet is at the firebox end of the tube bank. It receives intense heat from the firebox and supports the rear ends of the tubes or flues.

Because it is pierced by many tube holes, the rear flue sheet is not a plain solid plate. Its strength depends on plate thickness, tube spacing, ligament width between holes, staying, and the condition of the tube-to-sheet joints.



Fig. 6 Rear flue sheet.

2.3.2 Front Flue Sheet

The front flue sheet is visible from the smokebox. It contains the front tube ends and may also reveal other important internal construction features.

In [Fig. 7](#), the front flue sheet area shows several features worth identifying:

- tube or flue ends
- through stays
- an internal butt cover
- water inlet details
- a dry pipe emerging from beneath the steam dome
- a dry-pipe hanger
- double plating around the water inlet

The dry pipe is especially important. It is part of the steam collection path and is normally located within the steam space. Its position, support, and connection to the dome or throttle arrangement affect how steam is taken from the boiler.

The water inlet area is also important because feedwater entering the boiler may be colder than the surrounding boiler water. Reinforcement or double plating may be found where fittings enter the pressure shell.



Fig. 7 Front flue sheet showing tube ends and internal features.

2.4 Boiler Analysis: Construction Factors

The construction analysis of a boiler begins by separating the boiler into regions that behave differently under pressure.

The main regions include:

- barrel and dome
- curved shell surfaces
- longitudinal shell seams
- firebox sheets
- flat stayed surfaces
- semi-curved stayed surfaces
- crown sheet and wagon-top areas
- backhead
- front flue sheet
- rear flue sheet
- stayed firebox surfaces

Each region has its own controlling factors. For example, the shell barrel is a curved surface. Its strength depends on diameter, thickness, material strength, joint efficiency, and safety factor. A flat firebox sheet, by contrast, is not self-supporting and depends on plate thickness, staybolt size, staybolt pitch, and stay attachment method.

For stayed surfaces, the important construction factors include:

- plate thickness
- staybolt diameter
- staybolt pitch
- stay engagement
- stay attachment type
- construction factor
- condition of the plate and stays

The central idea is simple: pressure acts everywhere, but not every shape resists pressure in the same way.

2.5 What's Next?

A boiler is more than a pressure vessel. It is also a complete operating system with fittings, valves, safety devices, lubrication points, water-management equipment, and many other components that must work together safely.

Understanding the names, locations, and functions of these parts is the first step toward understanding steam operation and boiler inspection.

The next chapters examine the safety features and attached components found on steam boilers and traction engines. Later chapters return to the pressure-retaining structure itself and show how shell strength, riveted joints, stayed surfaces, and allowable working pressure are analyzed.

Chapter 3

Boiler Safety Features

There are five required safety features on every boiler

Safety valve

Prevents overpressure by automatically releasing steam if boiler pressure exceeds the set limit.

Pressure gauge

Indicates internal pressure so the operator can keep the boiler within its safe working range.

Fusible plug

Last-ditch low-water protection—the core melts if the crown sheet is uncovered, dumping steam into the firebox and giving a dramatic warning.

Try cocks

Independent check on water level—a set of test cocks at different heights to confirm gauge glass readings and detect false readings or glass failure.

Water gauge glass

Shows actual water level in the boiler so low-water conditions can be detected before they become dangerous.

Sixth, common but not mandatory

Water column

A remote water-level assembly that often combines a gauge glass and try cocks in one fitting, mounted off the boiler shell for better visibility and maintenance—but not strictly required by code in all cases.

3.1 Safety valve

A safety valve is an automatic, spring-loaded device fitted to the boiler shell that prevents the boiler from exceeding its maximum allowable working pressure. Steam pressure acts on a valve disc held shut by an adjustable spring. When boiler pressure reaches the valve's set pressure, the steam force overcomes the spring tension and lifts the valve, releasing steam rapidly to atmosphere. This prevents further pressure rise.

Once pressure drops slightly below the set point (the blowdown), the spring reseats the valve and normal operation resumes.

Key characteristics:

- Spring-loaded (modern traction and portable boilers)
- Set pressure is sealed so the operator cannot adjust it
- Opens fully and quickly to prevent dangerous pressure rise
- Reseats automatically when pressure falls to safe level
- Must be sized to discharge steam faster than the boiler can generate it

3.1.1 Why a Boiler Safety Valve "Pops" Instead of Just Lifting

A boiler safety valve is designed with two effective areas, not one:

The primary seat area — the small circular area of the valve disc that steam pushes on while the valve is closed.

The secondary (huddling) chamber area — a larger annular area that becomes exposed only after the valve cracks open.

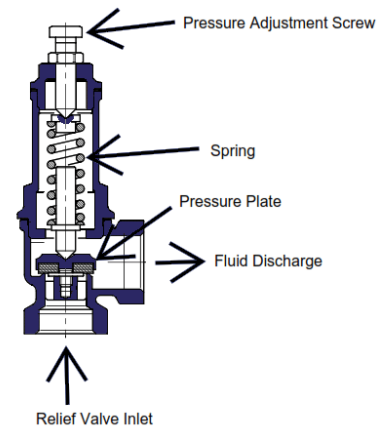


Fig. 8 Safety valve

When the valve first begins to lift at the set pressure, only the small seat area is exposed to steam pressure. But the moment the disc lifts even a tiny amount, steam rushes into the huddling chamber, where it acts on a much larger surface area.

Because force = pressure × area:

Before lift: $F = P \times A_1$

After lift: $F = P \times (A_1 + A_2)$

where A_2 is the larger huddling-chamber area

This sudden increase in effective area produces a rapid, positive, self-reinforcing lift — the “pop.”

The spring cannot resist this larger force, so the valve snaps fully open, releasing steam at a very high rate.

This is intentional and required by code.

3.1.2 Getting the right size

The MAWP determines the safety-valve set pressure, and the heating-surface area determines the required relieving capacity; together these specify the orifice size needed so the valve can discharge steam faster than the boiler can generate it.

A practical rule of thumb is to size the safety valve capacity at about 7–11 lb/h per square foot of heating surface. This gives a conservative capacity range for historic, hand-fired boilers. In practice, actual safety valves must be sized using the applicable boiler code and manufacturer capacity charts for the chosen set pressure.

Heating surface is the sum of all wetted boiler surfaces exposed to fire or hot gases — firebox sheets, crown sheet, tubes, and flues.

Using the capacity and the set pressure, look up the orifice in a table like the one in [Table 1](#).

Table 1. Capacity by Oriface and Set Pressure

KUNKLE SAFETY VALVE PRODUCTS
SERIES 6000

Capacities

ASME Section I Steam (U.S., lb/h)						
Flow Coefficient = 0.878						
Set Pressure (psig)	Orifice Area, in ²					
	D (0.121)	E (0.216)	F (0.336)	G (0.554)	H (0.863)	J (1.414)
15	173	310	482	794	1237	2027
20	201	358	558	919	1432	2346
25	228	407	634	1045	1627	2666
30	256	456	710	1170	1822	2986
35	283	505	785	1295	2017	3306
40	310	554	861	1420	2213	3625
45	338	603	937	1546	2408	3945
50	365	651	1013	1671	2603	4265
55	392	700	1089	1796	2798	4584
60	420	749	1165	1921	2993	4904
65	447	798	1241	2047	3188	5224
70	475	848	1319	2174	3387	5550
75	503	898	1397	2303	3588	5879
80	531	948	1475	2432	3789	6208
85	559	999	1553	2561	3990	6538
90	588	1049	1632	2690	4191	6867
95	616	1099	1710	2819	4392	7196
100	644	1150	1788	2948	4593	7525
105	672	1200	1866	3077	4794	7855
110	700	1250	1945	3206	4995	8184
115	728	1300	2023	3335	5196	8513
120	757	1351	2101	3464	5397	8842
125	785	1401	2179	3593	5598	9172
130	813	1451	2258	3722	5799	9501
135	841	1502	2336	3851	6000	9830
140	869	1552	2414	3980	6201	10160
145	898	1602	2492	4109	6402	10489
150	926	1653	2571	4238	6603	10818
160	982	1753	2727	4497	7004	11477
170	1038	1854	2884	4755	7406	12135
180	1095	1954	3040	5013	7808	12794
190	1151	2055	3197	5271	8210	13452
200	1208	2156	3353	5529	8612	14111
210	1264	2256	3510	5787	9014	14769
220	1320	2357	3666	6045	9416	15428
230	1377	2457	3823	6303	9818	16087
240	1433	2558	3979	6561	10220	16745
250	1489	2659	4136	6819	10622	17404
260	1546	2759	4292	7077	11024	18062
270	1602	2860	4448	7335	11426	18721
280	1658	2960	4605	7593	11828	19379
290	1715	3061	4761	7851	12230	20038
300	1771	3162	4918	8109	12632	20696

- select the row corresponding to the set point
- select the column corresponding to the capacity
- obtain the orifice from the column heading

Then construct a model number using the orifice and inlet sizes.

Model Number/Order Guide																
Model Number Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Example	6	0	1	0	H	G	M	0	1	—	A	M	0	1	5	0
Model																
6010	6130	6230														
6021	6186	6933														
6030	6283	6934														
6182	6221	6935														
6121																
Orifice																
D	G															
E	H															
F	J															
Inlet Size																
C - 1/2"	[12.7]	G - 1 1/2"		[38.1]												
D - 3/4"	[19.0]	H - 2"		[50.8]												
E - 1"	[25.4]	J - 2 1/2"		[63.5]												
F - 1 1/4"	[31.8]															
Seat Material																
M - Metal	T - Teflon® [Models 6021,															
E - EPR	6121, 6221, 6934 only]															
V - Viton®																
Variation [01 to 99]																
01 - Plain lever																
02 - Plain lever with vibration dampener																
03 - Plain lever with gag																
60 - BSP Threads																
Design Revision																
Indicates non-interchangeable revision.																
Dash [-] if original design.																
Valve Service																
A - Steam ASME Section I																
K - Air/Gas ASME Section VIII																
L - Steam ASME Section VIII																
G - Steam ASME Section IV [Models 6933, 6934, 6935 only]																
P - Steam, Non-code																
N - Air, Non-code																
Spring Material																
M - SS																
Set Pressure																
0015 - 15 psig [1.0 barg] only for Models 6933, 6934, 6935																

3.2 Pressure Gauge

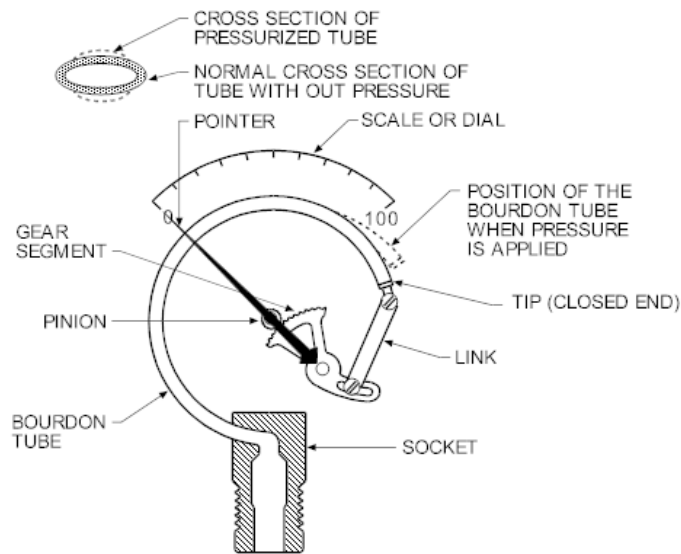


Fig. 9 Bourdon-tube gauge

Steam pressure enters a curved Bourdon tube and makes it try to straighten; this tiny motion is transmitted through a linkage and gears to rotate the needle, giving a direct reading of boiler pressure.

A siphon or pigtail forms a water seal between the boiler and the gauge; the water absorbs the steam's heat so the Bourdon tube only sees pressure, not live steam temperature, which greatly extends gauge life.

The gauge siphon is mounted above an isolation valve, typically quarter-turn style.

3.3 Fusible Plug

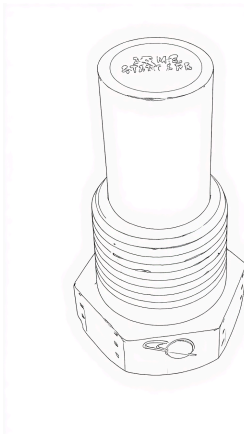


Fig. 10 Fusible Plug

A fusible plug contains a low-melting-point alloy on the water side of the crown sheet.

If the water level drops and the crown sheet overheats, the alloy melts out, creating an opening.

When it melts, it vents steam and some water into the firebox, producing a violent roar and a blast of white steam.

The discharge does not quench the fire — the amount of water/steam is far too small, and the draft usually overwhelms it.

What it does do is provide an immediate, unmistakable warning of dangerously low water and forces the operator to react.

Its real purpose is to prevent crown-sheet failure by giving a warning before the plate reaches a critical temperature.

3.4 Try cocks

Try cocks are installed on the boiler head at the normal waterline, with one above and one below it to verify the true water level. Mounting try cocks on a water column keeps them in the same vertical plane as the gauge glass, giving a cleaner, more stable indication and making it easier to verify the true water level without opening fittings directly on the boiler shell.

A try cock is cracked open briefly to check whether it blows steam or water, confirming the true boiler water level independently of the gauge glass.

3.4.1 Operating a Try Cock — Key Points

Open the top try cock first

A steady stream of steam indicates the water level is below that cock.

Open the bottom try cock next

A steady stream of water indicates the water level is above that cock.

The correct water level lies between the two

If the top blows water and the bottom blows steam, the gauge glass is lying — shut down and investigate.

Crack the valve open slowly

Try cocks discharge forcefully; opening gently prevents water hammer and avoids scalding spray.

Stand to the side

Never directly in front of the discharge. Hot water or wet steam can eject violently.

Use short, controlled bursts

Long openings waste water and can drop the level unnecessarily.

Try cocks are an independent check

They confirm the gauge glass reading and detect a plugged, broken, or false-reading glass.

Two are required, three are common

The term “tricock” is traditional, but only two are required to bracket the safe operating level.

3.5 Gauge Glass

A gauge glass is the vertical sight tube mounted on the boiler that shows the true water level inside. It connects to the boiler through a top steam connection and a bottom water connection, so the water in the glass rises and falls to the same height as the water inside the boiler. Because the glass is open to boiler pressure at both ends, it acts as a simple, pressure-balanced column of water that gives the operator a direct, continuous indication of water level while the boiler is steaming.

3.5.1 Proving a gauge glass

A gauge glass is proved by momentarily opening each cock to confirm that steam can reach the top fitting, water can reach the bottom fitting, and the drain passage is clear.

If any passage is blocked, the glass cannot be trusted.

1. Ensure the steam cock, water cock, and drain cock move freely before applying pressure.
 - Stand to the side of the gauge glass
 - Confirm handles operate smoothly
 - Ensure the drain pipe is directed to a safe discharge point
2. Blow down the gauge using the drain cock
 - This confirms the drain passage is clear and resets the water level.

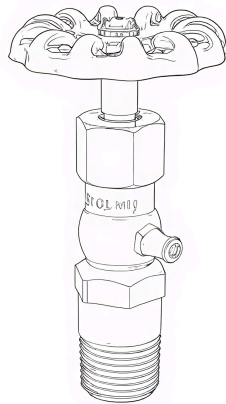


Fig. 11 Try Cock [1]

Fusible Plug — Myth vs. Reality

Myth: A fusible plug melts and dumps water onto the fire, putting the fire out.

Reality: What comes through the plug is mostly steam, not enough water to quench a fire, and the firebox draft blows it away. What it really does is produce a violent roar and a blast of white steam — an unmistakable warning of low water or crown-sheet overheat.

Bottom line: A fusible plug is a temperature-triggered warning device, not a fire extinguisher.

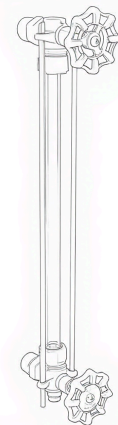


Fig. 12 Gauge Glass

- With both steam and water cocks open, open the drain cock fully
 - Observe a strong discharge of water followed by steam
 - Close the drain cock; the glass should refill to the true level
3. Prove the steam connection. Ensures the top fitting is not blocked by scale or sludge.
- Close the water cock
 - Open the drain cock briefly -The glass should blow clean steam from the top connection -Close the drain cock
4. Prove the water connection. Ensures the bottom fitting is clear and supplying water.
- Close the steam cock
 - Open the drain cock briefly
 - The glass should blow solid water from the bottom connection
 - Close the drain cock

3.5.2 Return the gauge to service

Confirm the water level stabilizes at a believable height

If both cocks are closed under pressure, open the **steam cock first** Opening the steam cock first prevents water from being forced violently up the glass.

- Crack the steam cock slightly
- Allow steam to warm and pressurize the glass
- Once stable, open the steam cock fully
- Then open the water cock slowly to admit water

Chapter 4 Isolation Valves

One of the first things to do when approaching a boiler for operation, aside from proving the glass, is to check the position of the valves. Regardless of how the engine was left, the valves have a curious way of changing position, especially in a museum setting with many inquisitive hands.

4.1 Purpose

Isolation valves are shut-off valves placed in the boiler's plumbing so that a fitting, line, or accessory can be taken out of service without dropping boiler pressure or draining the system. Their job is to let the operator isolate a component for proving, cleaning, repair, or replacement while the rest of the boiler remains fully pressurized and in water. Any line that must occasionally be serviced—steam, water, or blowdown—will have an isolation valve at its boiler end.

4.2 Valve Type

Regardless of type, an isolation valve must:

- withstand full boiler pressure
- withstand steam temperature
- seal positively when closed
- be fully open in normal operation
- be located as close to the boiler shell as practical

If a valve cannot meet those requirements, it is not suitable for isolation duty on a boiler.

4.3 Location

An isolation valve is always installed as close to the boiler shell as practical, so that closing it leaves only a short length of pipe or a single fitting exposed. On a traction engine this includes the steam and water isolation valves for the gauge glass, the turret isolation valve feeding the accessory manifold, the injector steam and water isolation valves, the blower isolation valve, and the blowdown valve at the lowest point of the boiler. Each one sits at the point where a branch line leaves the boiler, marking the boundary between "boiler proper" and "serviceable plumbing."

4.4 Position under operation:

During normal steaming, all isolation valves that serve operating equipment must be fully open so that each device sees true boiler pressure and unrestricted flow. A gauge glass with either isolation valve shut will lie; an injector with its steam or water valve partly closed will not pick up; a blower or turret line with its isolation valve shut will appear dead. Isolation valves are therefore open in service, and closed only when isolating a component for maintenance, proving, or safety.

4.5 Location

In order to check the the isolation valves, one has to know where they are, and whether they should be open or closed. The best way to find the isolation valves is to consider each plumbing section in turn. As a general rule, if there is a fixture connected to the steam or water space, there should also be an isolation valve at the closest point to the boiler.

injectors

- at the feedwater entry
- at the steam supply

main steam line

- at the dome

water column

- on the steam side
- on the water side

whistle

gauge

blower

- on some engines, the blower is fed from the injector steam supply and is isolated when the injector is isolated

Chapter 5 Lubrication Points

5.1 Types of lubricators and how to recognize them

Lubrication is one of those deceptively simple topics that becomes difficult the moment you try to find every point that needs oil on a warm engine. The fittings are small, the types vary, and many of them look like ordinary hardware unless you know what you're looking for. Before you can lubricate anything during warm-up, you need to be able to recognize the different types of lubricators and understand what each one uses for lubricant.

5.1.1 Oil cups (gravity lubricators)

These are small, upright cups with a cap or flip-lid. You fill them with light machine oil and open the needle or drip hole so oil feeds by gravity. The knurled knob controls the drip rate. The lever flips to one side to turn off oil entirely. Where found: main bearings, crank pins, valve-gear pivots, governor bearings. Recognition: small brass cup, often with a knurled cap or hinged lid.

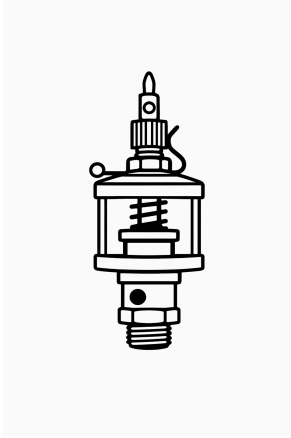


Fig. 13 Oil Cup

5.1.2 Screw-down grease cups

These are filled with hard grease. Screw the cap down a turn to force grease into the bearing. Where found: slow-moving, high-load points like steering gear, axle bearings, and some valve-gear joints. Recognition: a short, squat cup with a threaded cap that screws downward. Remove the cup to fill it with grease.

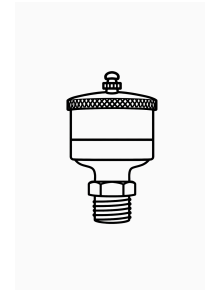


Fig. 14 Grease Cup

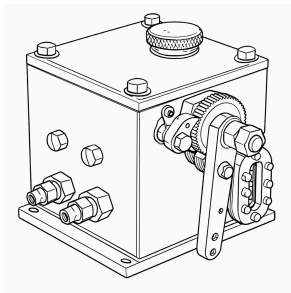


Fig. 15 Lubricator

5.1.3 Mechanical lubricators (ratchet or displacement type)

These deliver oil in measured strokes driven by engine motion. Where found: cylinder lubrication on some traction engines, governor drive, or high-load bearings. Recognition: a small box with a ratchet arm or linkage; oil lines leading away from it.

5.1.4 Hydrostatic lubricators (sight-feed lubricators)

These feed cylinder oil using steam pressure and a sight glass where you can see the drops. Where found: cylinder lubrication on many engines; water pumps. Recognition: a glass column with a needle valve and feed lines; usually mounted on the turret.

5.1.5 Alemite / Zerk fittings (modern retrofits)

Some restorations use modern grease nipples. Where found: anywhere a previous owner wanted easier greasing. Recognition: small conical or ball-type grease nipples.



Fig. 16 Zerk

5.1.6 Wick lubricators

These use a felt or cotton wick to meter oil slowly. Where found: valve rocker arm, upper and lower cannon bearings Recognition: a reservoir in the casting filled with cotton waste.

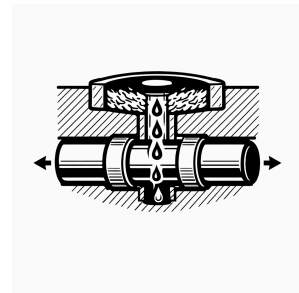


Fig. 17 Wick lubricator

5.2 Types of lubricants matched to the lubricator

5.2.1 Cylinder oil

- Very heavy, high-temperature oil
- Used only where steam enters (cylinders, valves)
- Formulated to dissolve in water
- Delivered by hydrostatic or mechanical lubricators

5.2.2 Engine oil (light machine oil)

- Medium-weight
- Used for bearings, pins, and moving joints
- Delivered by oil cups, wicks, or mechanical lubricators

5.2.3 Grease

- Used for slow, high-load bearings
- Delivered by grease cups or Zerk fittings
- Matching the wrong lubricant to the wrong lubricator is as bad as missing the point entirely.

5.3 Why extra lubrication matters during warm-up

When the engine is cold:

- oil is thick
- grease is stiff
- wicks don't draw

- mechanical lubricators may not stroke
- hydrostatic lubricators won't feed until steam is up
- there is time to perform lubrication

So every point that won't self-lubricate must be hand-oiled. That requires knowing:

- where each point is
- what type of lubricator it uses
- what lubricant belongs there
- whether it needs manual priming before the engine moves

This is why experienced operators walk the engine with an oil can during warm-up: they know exactly what they're looking at.

5.4 Why recognition matters during steam school

Because there will be a test.

Chapter 6

Water & Draft

A traction engine's ability to make steam depends on two continuous processes: managing water as it enters the boiler, and managing draft as hot gases leave it. These two systems work together from the moment feedwater is pressurized until the exhaust finally exits the stack.

Water management and draft management are two halves of the same cycle:

- Water enters the boiler through injectors or pumps, often preheated by the heater.
- Steam is generated as the fire burns hotter under the influence of the exhaust-driven draft.
- Exhaust steam not only powers the engine but also drives the draft system that keeps the fire burning.
- Spent steam from the Marsh pump and injectors may preheat feedwater, improving efficiency.
- Sediment is removed through the blowdown valve to keep the boiler clean and safe.
- Combustion gases exit through the smokebox and stack, completing the cycle.

Together, these systems allow a traction engine to maintain steady steam production under varying loads and operating conditions — the heart of reliable field work.

- injectors use steam pressure and velocity to force water into a boiler without moving parts. They rely on steam expansion, entrainment, and condensation to raise feedwater pressure.
- Ejectors are like injectors but are used to transfer water from a tank or other source into a tender.
- pumps are mechanical devices that move water into the boiler using positive displacement. There are two types:
 - direct mechanical drive
 - steam driven
- feedwater heaters warm incoming water using exhaust steam or hot gases, improving efficiency and reducing thermal shock to the boiler.
- The smokebox is the chamber at the front of the boiler where hot gases from the flues mix with the engine's exhaust steam before being drawn up the stack.
- The stack is the tall exhaust chimney on a traction engine that creates draft for the fire by discharging exhaust steam and smoke upward.
- Blower is a small steam-driven exhaust that pulls draft up the stack when the engine is not moving, improving firebed combustion.
- The exhaust nozzle is the jet orifice in the smokebox that shoots each exhaust pulse up the stack, creating the draft that makes the fire burn.
- blowdown controls the release of water from the boiler to remove sediment, scale-forming minerals, and impurities that concentrate during operation.

6.1 Injectors

These have been covered elsewhere.

6.2 Direct-Drive Feedwater Pump

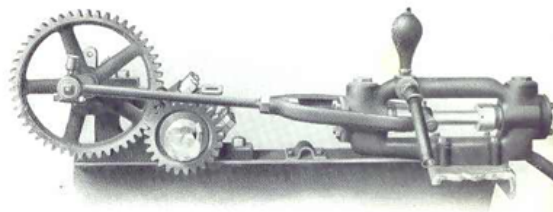


Fig. 18 Feedwater pump

6.2.1 Mechanical Fundamentals

A reciprocating plunger pump driven from the engine through a **gear reduction**, not directly from the crank throw. A small gear on the crankshaft drives a larger gear; the larger gear carries a yoke or crankpin that moves a push rod connected to the pump plunger. The **gear ratio determines the pump-stroke rate**, typically giving several engine revolutions per pump stroke. Inside the pump, inlet and outlet check valves control water flow.

6.2.2 Operating Principles

As the engine turns, the crankshaft gear drives the larger pump gear. The offset crankpin on the large gear converts rotation into reciprocating motion of the push rod and plunger. On the suction stroke, water enters through the inlet check; on the delivery stroke, the plunger forces water through the outlet check toward the boiler. A bypass valve allows excess water to return to the tank for feed-rate control. A relief valve prevents over pressurization.

6.2.3 Advantages

- Simple, durable, and mechanically efficient
- No steam consumption
- Very reliable at road speed
- Pump output naturally increases with engine workload
- Under steady load, the pump can be tuned with its inlet throttle valve to supply water at a stable rate matching boiler consumption

6.2.4 Disadvantages

- Cannot pump when the engine is stopped
- Weak delivery at very low engine speeds
- Requires tight packing and good check-valve condition
- Feed rate fixed by the gear ratio and engine RPM, limiting fine control
- The pump is always engaged with the engine

6.3 Independent pump

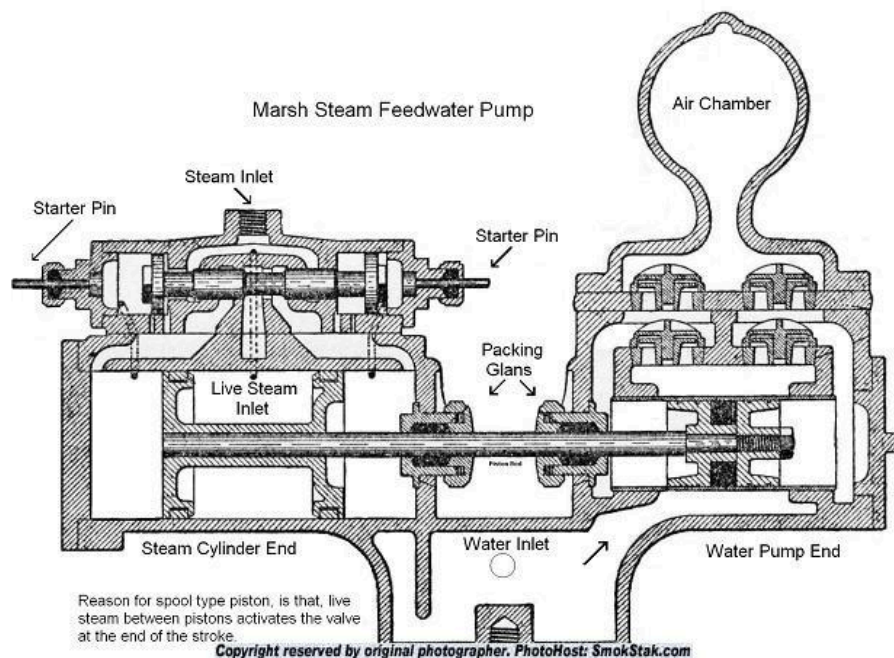


Fig. 19 Marsh pump

The Marsh Pump (specifically the Marsh Simplex) is an independent steam-driven feedwater pump commonly supplied on Case traction engines, either as standard equipment or as an option alongside the mechanical pump. Unlike the mechanical pump—which only works when the engine is turning—the Marsh pump is a self-contained steam engine dedicated to moving water.

6.3.1 Operation

The pump has two cylinders on a common piston rod:

- a steam cylinder that receives live steam from the boiler, and
- a water cylinder that forces feedwater toward the boiler.

6.3.2 Simplex Design

It is a simplex pump: one steam cylinder and one water cylinder. A distinctive internal piston-valve mechanism automatically shifts steam admission from one end of the cylinder to the other, allowing the pump to reciprocate continuously without a flywheel or external valve gear.

6.3.3 Feedwater Preheating

A key advantage of the Marsh pump is that it exhausts its spent steam directly into the incoming feedwater. This warms the water before it enters the boiler, reducing thermal shock to the flues and improving overall steaming efficiency.

6.4 Heater

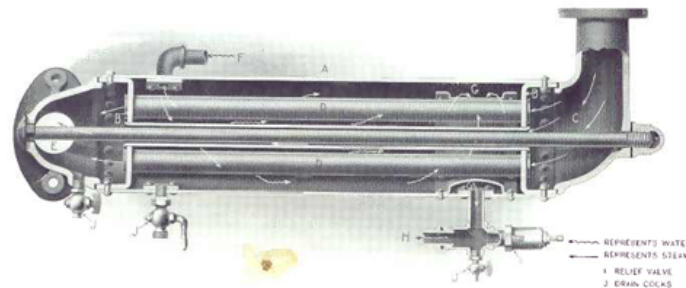


Fig. 20 Heater

The heater is essentially a small, non-pressurized feedwater heater. Exhaust steam from the engine is routed through a bank of small tubes, and the surrounding water space absorbs that heat. The water space is supplied and pressurized by the mechanical pump, and a check valve at the pump discharge prevents boiler pressure from pushing back into the heater.

On engines equipped with a pump, the heater warms the incoming feedwater before it enters the boiler, reducing thermal shock and improving steaming efficiency.

Case shipped all engines with a heater, but many engines left the factory without a pump. On those engines, the heater still receives exhaust steam, but with no pump to move water through it, the entire heater simply rises to the temperature of the exhaust steam and serves no feedwater-heating function.

6.5 Exhaust and Draft System

6.5.1 Smokebox

The smokebox is the front compartment of a locomotive-type boiler, located just behind the stack. Its job is to collect the hot gases that have passed through the boiler flues and combine them with the engine's exhaust steam. When each exhaust pulse shoots through the exhaust nozzle, it creates a vacuum in the smokebox. That vacuum pulls the fire's hot gases through the flues and sends them up the stack, completing the draft system.

Inside the smokebox you'll find the exhaust nozzle, the petticoat pipe (on engines that use one), the blower ring, and the ends of the flues. The smokebox must stay reasonably tight so the draft comes through the fire and flues—not through leaks around the door or seams. A leaky smokebox weakens draft and makes an engine sluggish to steam.

Because the smokebox handles soot, ash, and cinders, it requires regular cleaning. A buildup of soot can choke the flues, reduce heat transfer, and impair draft. Case engines often have a hinged or bolted smokebox door to make this maintenance straightforward.

The smokebox is the central meeting point of the entire draft system:

- Firebox → flues → smokebox → stack
and it works in partnership with the exhaust nozzle (draft while running) and the blower (draft while stopped).

6.5.2 Stack

On a traction engine, the stack is far more than a chimney. It is the upper end of the engine's draft system, the mechanism that pulls air through the firebed, across the grates, through the flues, and out the top of the boiler. The stack works in partnership with the exhaust nozzle in the smokebox: every time the engine exhausts steam, that jet of steam shoots upward into the stack and creates a partial vacuum in the smokebox. That vacuum draws hot gases through the flues, which in turn pulls fresh air through the fire. This is why the engine "breathes" harder when it is working under load — more exhaust pulses mean stronger draft.

The stack also provides the vertical path for smoke, ash, and cinders to leave the boiler. Its height helps keep sparks away from the operator and reduces the chance of setting fire to dry stubble or straw around the machine.

6.5.3 Spark arresters

Because traction engines burned wood, straw, or soft coal, they could throw live cinders out the stack. A spark arrester is any device fitted inside or atop the stack to prevent those cinders from escaping. Designs varied widely:

- Screen arresters used fine wire mesh to catch sparks before they left the stack.
- Deflector-cone arresters forced the exhaust stream to change direction abruptly, causing heavier cinders to fall out of the flow.
- Cyclone or centrifugal arresters spun the exhaust gases so that embers were flung outward and trapped in a chamber.
- Stack caps sometimes incorporated baffles or screens to reduce spark throw while still allowing free exhaust.

A good spark arrester has to strike a balance: it needs to stop sparks without choking the draft. Too fine a screen or too restrictive a baffle can smother the fire and ruin steaming. Too open a design can start a field fire. This is why many engines had removable or seasonal arresters — operators would install them during dry harvest conditions and remove them when working on damp ground or in the spring.

6.5.4 Blower

The blower is a simple but essential draft-making device used whenever the engine is not running fast enough to produce its own exhaust draft. It consists of a ring or series of small nozzles located inside the base of the stack. When the operator opens the blower valve, live steam is admitted to these nozzles and shoots upward into the stack. That jet of steam creates a vacuum in the smokebox, pulling hot gases through the flues and drawing fresh air through the firebed.

The blower is used for several purposes:

- Starting the fire — to get draft before the engine can run.
- Maintaining draft while stopped — such as when belted to a machine and idling.
- Controlling the fire — a quick burst of blower can brighten the fire or clear smoke.

- Safety — when the engine is drifting downhill or coasting with the throttle closed, the blower prevents the fire from “backing up” into the flues.

Because the blower uses live steam, it must be used sparingly; too much blower wastes steam and can overfire the boiler.

6.5.5 Exhaust nozzle

The exhaust nozzle is the small, precisely sized opening at the base of the stack where the engine’s spent steam is discharged into the smokebox. Every time the engine exhausts, that pulse of steam is forced through the nozzle at high velocity. As it shoots upward into the stack, it creates a partial vacuum in the smokebox. That vacuum pulls hot gases through the flues and draws fresh air up through the grates and firebed.

This is the core of the locomotive-type draft system:

- Exhaust pulse → jet through nozzle
- Jet → vacuum in smokebox
- Vacuum → strong draft through fire and flues

The harder the engine works, the more frequent and forceful the exhaust pulses become, and the stronger the draft. This is why a traction engine “fires up” under load and why the fire brightens when the engine is pulling hard.

The nozzle’s diameter and position are critical. Too small a nozzle chokes the exhaust and wastes power; too large a nozzle weakens the draft and makes the engine sluggish to steam. Case and other builders spent real engineering effort getting the nozzle size right for each boiler and cylinder combination.

The exhaust nozzle works hand-in-hand with the stack, the smokebox, and the blower. When the engine is running, the nozzle provides nearly all the draft. When the engine is stopped or drifting with the throttle closed, the blower takes over to keep the fire from backing up into the flues.

6.6 Blowdown

The blowdown valve is mounted at the very bottom of the boiler—usually on the mud ring—so it can remove the heaviest sediment that settles out of the water. As the boiler operates, minerals, rust flakes, and impurities drop out of suspension and collect in the lowest part of the shell. If this material is not removed, it can insulate the metal from the water, cause uneven heating, and contribute to scale formation or even localized overheating.

When the operator opens the blowdown valve, boiler pressure forces water and sediment out in a fast, powerful jet. This rapid discharge scours the mud ring and carries the accumulated solids out of the boiler. Blowdown is normally done briefly and regularly—often once or twice a day—rather than in long intervals, to keep sediment from building up.

Because the blowdown valve opens directly to atmosphere, it must be strong, reliable, and absolutely tight when closed. It is typically a self-cleaning Y-valve designed to withstand full boiler pressure, although straight-through, quick-opening valves are also used. Operators must stand clear of the discharge and ensure no one is in the path of the hot water and steam plume.

The blowdown valve is part of the boiler’s routine maintenance system, working alongside proper water treatment and regular washouts to keep the boiler clean, efficient, and safe.

Chapter 7

Dome to Exhaust

- The dome valve is the main shutoff valve mounted on the dome that controls the flow of steam from the boiler to the throttle.
- The throttle is the operator's control valve that regulates how much steam is admitted to the engine.
- The governor is a speed-regulating device that automatically adjusts the throttle to maintain a steady engine RPM.
- The steam chest is the chamber beside the cylinder where steam is admitted and exhausted by the valve gear.
- The motor is the engine assembly—cylinder, piston, valve gear, and connecting rod—that converts steam pressure into mechanical motion.
- Cylinder drains are small valves at the ends of the cylinder used to release water and prevent damage during startup. The exhaust is the spent steam discharged from the cylinder into the smokebox, where it creates draft up the stack.

7.1 Dome

The dome is the raised chamber mounted on top of the boiler shell, and its purpose is to provide a space where the driest, least-water-laden steam can collect before it is sent to the engine. As steam forms in the boiler, water droplets and turbulence near the waterline can carry moisture upward. By placing the steam takeoff point high above the water surface, the dome allows gravity and distance to separate water from steam, ensuring that only relatively dry steam reaches the throttle and engine.

Inside the dome is the dome valve, the main internal shutoff that isolates the boiler from the engine's steam line. The dome's height and volume are carefully chosen: too small, and the engine draws wet steam; too large, and the boiler becomes unnecessarily tall and heavy. Case and other builders designed domes to balance steam quality, boiler strength, and manufacturing practicality.

Because the dome is part of the pressure vessel, it is built from heavy plate and riveted or welded as an integral part of the boiler shell. It must withstand full boiler pressure and is inspected just like the rest of the boiler. The dome also provides a convenient location for mounting the safety valve, steam gauge line, and other fittings, since it is the highest point where steam naturally accumulates.

The dome is the boiler's steam reservoir and collection chamber, ensuring a steady supply of dry steam for smooth, efficient engine operation.

7.2 Dome valve

The dome valve is the main steam shutoff located on the boiler dome. Its job is to control the flow of steam from the boiler into the engine's steam line. When the dome valve is closed, the engine is completely isolated from boiler pressure; when it is opened, steam can reach the throttle and, from there, the motor.

Because the dome valve sits on the dome — and some cases reaches inside the dome — where the driest steam collects, it ensures that the steam entering the engine is as clean and moisture-free as the boiler can provide.

The dome valve is not a regulating valve. It is a stop valve: fully open for operation, fully closed for maintenance or safety. During normal running, the dome valve is left wide open so the throttle can do the fine control. Closing the dome valve while the engine is working would starve the steam chest and could damage the valve gear or cause the engine to stall abruptly.

Because it is the first valve in the steam path, the dome valve must be absolutely tight when closed and strong enough to withstand full boiler pressure. Inspectors pay close attention to its condition, packing, and seating, since a leaking dome valve can allow steam to reach the throttle unexpectedly.

The dome valve must be opened slowly to avoid thermal shock. Opening the dome valve is just the first step in warming up the motor.

7.3 Throttle

The throttle is the operator's primary control over the engine, regulating how much steam is admitted from the boiler into the steam chest. While the dome valve is the master shutoff, the throttle is the working control, used constantly during operation to manage power, speed, and response.

On a traction engine, the throttle is usually a balanced poppet or slide-type valve mounted in the steam line between the dome valve and the steam chest. The operator controls it with a lever on the platform. Moving the lever opens or closes the valve, allowing more or less steam to reach the engine. Because the throttle is downstream of the dome valve, it never sees raw boiler turbulence—only the dry steam collected in the dome.

A good throttle must do three things well:

- Open smoothly so the engine can start without a violent lurch.
- Hold any intermediate position so the operator can meter steam precisely.
- Close tightly to prevent the engine from creeping when the lever is shut.

When the throttle is opened, steam flows into the steam chest, where the valve gear admits it to the cylinder. The more the throttle is opened, the higher the pressure in the steam chest and the more power the engine develops. Under heavy load, the operator may run with the throttle wide open and let the governor regulate speed. Under light load, the throttle may be partially closed to conserve steam.

The throttle is also a safety-critical component. A worn or leaking throttle can allow steam to reach the engine even when "closed," causing the engine to creep or turn unexpectedly. For this reason, operators test throttle tightness before belting to machinery and during inspections.

In short, the throttle is the engine's power valve, giving the operator direct, fine-grained control over how much steam the motor receives and how hard the engine works.

7.4 Governor

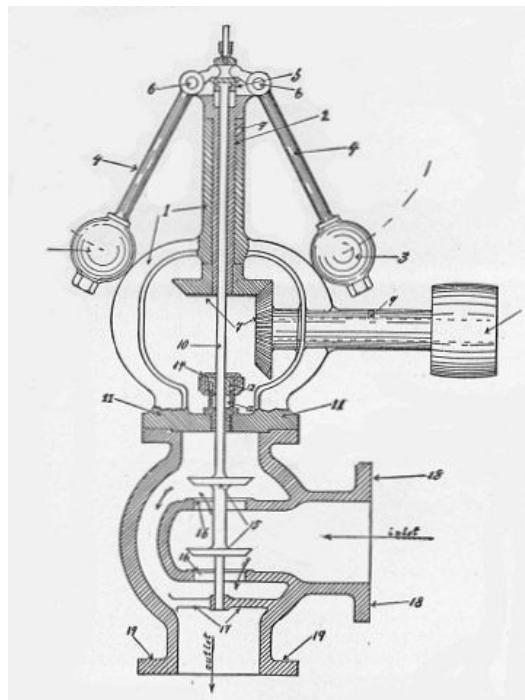


Fig. 21 Flyball Governor

The governor is the automatic speed-regulating device that keeps a traction engine running at a steady RPM regardless of load changes. While the throttle gives the operator manual control of steam flow, the

governor provides continuous, hands-off adjustment, preventing the engine from racing when the load lightens or slowing excessively when the load increases.

Most traction engines use a flyball (centrifugal) governor mounted on the engine's crankshaft or driven by a belt. As the engine speeds up, the spinning flyballs move outward under centrifugal force. This motion lifts a collar connected to a linkage that partially closes the throttle. When the engine slows down, the balls fall inward, the collar drops, and the linkage opens the throttle wider. The result is a self-correcting system that constantly meters steam to match the work being done.

The governor does not replace the operator's throttle control; instead, the operator sets the throttle to the desired working position, and the governor trims the steam flow around that setting. Under heavy load, the governor may run nearly wide open; under light load, it may nearly close the throttle. This is why a traction engine can run a threshing machine at a steady speed even as the feed rate varies.

A properly adjusted governor prevents overspeeding, reduces fuel waste, and protects the machinery being driven. A worn or sticky governor can cause hunting (oscillating speed), sluggish response, or dangerous overspeed conditions. For this reason, governors are kept clean, lubricated, and inspected regularly.

The governor is the engine's automatic speed manager, constantly balancing steam supply against load to keep the machine running smoothly and safely.

7.5 Steam Chest

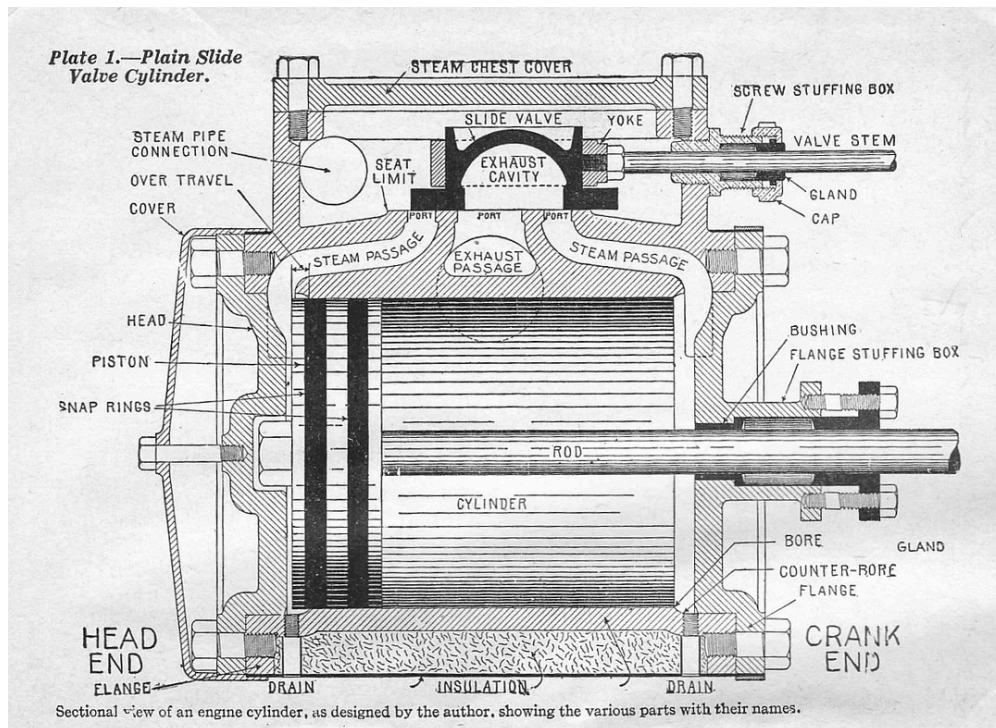


Fig. 22 Motor and steam chest (top view)

The steam chest is the chamber mounted alongside or above the cylinder where steam is distributed to the engine by the valve gear. It serves as the buffer and control space between the throttle and the cylinder itself. When the throttle is opened, steam flows into the steam chest and fills it to whatever pressure the operator has selected. From there, the valve gear admits steam alternately to each end of the cylinder and releases spent steam on the opposite stroke.

Inside the steam chest is the valve—usually a slide valve or piston valve on traction engines. This valve moves back and forth in time with the crankshaft, uncovering and covering ports that lead to the cylinder.

The steam chest must be large enough to supply steam freely without starving the cylinder, but not so large that it wastes steam or causes sluggish response.

The pressure inside the steam chest is the engine's working pressure—the pressure the piston actually sees. It is almost always lower than boiler pressure because the throttle and governor regulate flow. Under heavy load, the governor opens the throttle wider, raising steam-chest pressure; under light load, it closes the throttle, reducing pressure.

A tight, well-fitted valve in the steam chest is essential for efficient operation. Leaks past the valve waste steam, reduce power, and can cause the engine to "creep" when the throttle is closed. For this reason, the steam chest is a critical inspection point, and its cover is often removed during maintenance to check valve condition, lubrication, and port cleanliness.

In short, the steam chest is the control chamber where steam is metered, timed, and delivered to the cylinder—making it the heart of the engine's power cycle.

7.6 Motor

On a traction engine, the motor is the complete steam-engine assembly that converts boiler pressure into mechanical work. It includes the cylinder, piston, crosshead, connecting rod, crankshaft, valve gear, and steam chest. Steam admitted through the valve gear pushes the piston back and forth, and the motor turns this reciprocating motion into rotary motion to drive the flywheel, gearing, and rear wheels. Although the motor is covered in depth in its own dedicated section, it is referenced here because the throttle, governor, steam chest, and cylinder drains all interact directly with it and form the control system that determines how the motor receives, uses, and exhausts steam.

7.7 Drains

7.7.1 Cylinder Drains

The cylinder drains (also called cylinder cocks) are small valves located at the lowest points of the cylinder ends. Their purpose is simple but absolutely critical: to remove water from the cylinder before it can cause damage. Because steam condenses in any cold space, a stopped or cooling engine will accumulate water in the cylinder. Water is incompressible, and if the piston tries to compress a slug of it, something else must give—usually a head gasket, a piston, or even the cylinder head itself.

When the operator opens the cylinder drains, any water present is blown out by steam pressure as soon as the engine begins to move. This produces the familiar jets of water and white steam from the cylinder ends during startup. Once the cylinder warms and the drains run clear, the operator closes them so the engine can develop full power.

Cylinder drains also serve a second purpose: preventing vacuum lock when the engine is drifting with the throttle closed. Opening the drains allows air to enter or steam to escape freely, preventing the piston from being pulled hard against one end of the cylinder.

The drains must be easy to operate, reliable, and tight when closed. A leaking drain wastes steam and reduces power; a stuck-closed drain risks catastrophic damage. For this reason, operators test the drains before moving the engine and keep them clean and lubricated.

In short, cylinder drains are the engine's safety valves for water, protecting the motor from hydraulic damage and ensuring a smooth, safe warm-up.

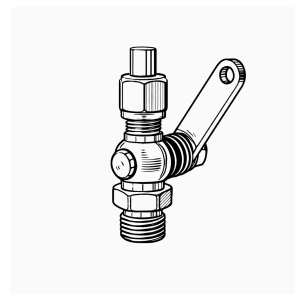


Fig. 23 Drain cock

7.7.2 The Steam-Chest Drain

Many traction engines also include a steam-chest drain, a small valve located at the bottom of the steam chest. Its purpose is similar to the cylinder drains: to remove condensate that forms in the steam chest when the engine is cold or has been sitting. Because the steam chest is the first space to receive steam when the throttle is cracked open, it tends to accumulate water quickly during warm-up.

Opening the steam-chest drain allows this water to escape before it can be carried into the cylinder. In practice, operators open the steam-chest drain together with the cylinder drains during startup. As the engine warms, the steam-chest drain is closed first—once it blows clear—followed by the cylinder drains once the cylinders themselves are hot and dry.

The steam-chest drain is smaller and less dramatic than the cylinder drains, but it plays an important role in preventing slugs of water from being swept into the valve passages and then into the cylinder on the first few strokes.

7.8 Exhaust

The exhaust is the spent steam released from the cylinder after it has done its work on the piston. Each time the valve gear uncovers the exhaust port, the used steam escapes into the exhaust passage and is directed into the smokebox. There, it is discharged through the exhaust nozzle as a high-velocity jet.

Although the full draft-system explanation appears elsewhere, the key point here is that the exhaust serves two roles at once:

- It clears the cylinder so fresh steam can enter on the next stroke.
- It powers the draft, creating the vacuum in the smokebox that pulls air through the fire and flues.

The exhaust is therefore both the end of the engine's power cycle and the beginning of the boiler's combustion cycle. Even in this brief section, it's worth noting that the crisp, rhythmic exhaust beat you hear from a traction engine is not just sound—it is the engine actively pulling its own fire.

Chapter 8

Crank Pin to Hitch

The cylinder produces force, but it is the drive train that turns that force into useful motion. Beginning at the crankdisk, this chapter traces the path of power through the clutch, gearing, differential, and rear wheels, and concludes with the structural members that carry the resulting drawbar loads.

- The crankdisk converts the piston's back-and-forth motion into rotary motion, turning the engine's main output shaft.
- The pulley wheel is mounted on the crankshaft and provides a belt drive for stationary work, transmitting power to threshers, saws, or other machinery.
- The clutch connects or disconnects the crankshaft from the traction gearing, allowing the operator to start, stop, or idle the engine without moving the wheels.
- The first-motion pinion is the small gear on the crankshaft that drives the intermediate gear, beginning the power train to the rear axle.
- The intermediate gear transfers motion from the crankshaft pinion to the differential shaft, changing direction and reducing speed for traction work.
- The differential permits the rear wheels to rotate at different speeds while maintaining power transmission.
- The upper (cross) shaft carries the differential and serves as the main transverse drive shaft between the gearing and the rear axle.
- The final-drive pinion is the small gear on the cross shaft that meshes with the bull gear on each rear wheel. The bull gear is the large gear bolted to the rear wheel hub; it receives power from the final-drive pinion and turns the wheel.
- The rear wheels and axle convert the rotary motion of the bull gears into traction, propelling the engine forward or backward.

8.1 Crankdisk

On a single-cylinder traction engine, the crankdisk is the large, circular plate mounted on the main shaft that converts the piston's back-and-forth motion into rotary motion. The crankpin is set off-center in the disk, and the connecting rod attaches to this pin. As the piston moves, the crankdisk turns the main shaft, providing the rotary power that drives the flywheel, pulley wheel, and traction gearing. The disk also acts as a counterweight, balancing the reciprocating mass of the piston and rod to reduce vibration and smooth the engine's running.

The crankdisk is one of the defining features of many single-cylinder traction engines. It is simple, strong, and easy to manufacture, and it provides a broad, rigid structure for mounting the crankpin. Because the disk is large and heavy, it contributes to the engine's rotational inertia, helping the engine carry through the dead centers and maintain steady motion under load.

8.2 Twin-Cylinder Engines: A Different Arrangement

Twin-cylinder traction engines use a completely different configuration. Instead of a single crankdisk, they employ a crankshaft with two crank throws, much like an automotive engine. Each cylinder has its own crankpin, set at an angle (often 90°) to ensure smooth, even torque and eliminate dead centers. This arrangement allows the engine to start from any position and provides more uniform power delivery.

In these engines, the crankshaft is a multi-throw forging or built-up assembly with webs and journals rather than a single disk. The mechanical principles are the same—converting reciprocating motion to rotary motion—but the geometry and construction more closely resemble later internal-combustion practice.

Summary Whether through a single crankdisk or a multi-throw crankshaft, this component is the mechanical heart of the power train, turning the piston's linear force into the rotary motion that ultimately drives the wheels.

8.3 Pulley Wheel

The pulley wheel is mounted on the crankshaft (or crankdisk shaft) and provides the engine's belt-power output for stationary work. Before tractors and electric motors took over, this was one of the most important features of a traction engine: it allowed the engine to serve as a portable power plant for threshers, sawmills, feed grinders, pumps, and countless other machines.

The pulley is usually a wide, flat, cast-iron wheel with a smooth rim designed to grip a heavy canvas or leather belt. When the engine is belted to a machine, the pulley becomes the primary power takeoff, and the traction gearing is typically disengaged so the engine can run at a steady speed without moving the wheels. The governor maintains constant RPM, and the pulley delivers smooth, continuous rotary power to whatever machine is being driven.

Because the pulley is mounted directly on the crankshaft, it turns at full engine speed. This makes it ideal for machinery designed to run at several hundred revolutions per minute. The pulley's diameter is chosen to give the correct belt speed for common farm equipment, and many engines offer optional pulley sizes to match specific applications.

The pulley wheel also plays a role in balancing the crankshaft assembly. Its mass contributes to the rotational inertia of the engine, helping smooth out the power pulses from the single cylinder. When not in use, the pulley simply freewheels with the crankshaft, but when belted up, it becomes the engine's external power output, turning the traction engine into a stationary engine on wheels.

8.4 Clutch

The clutch on a traction engine is a sliding-hub friction clutch built directly onto the crankshaft. Its purpose is to connect or disconnect the engine from the traction gearing, but unlike automotive clutches, it is not required for starting the machine from rest. A traction engine can start smoothly from zero RPM with the clutch fully engaged; the clutch is only needed when the operator wants to let the engine run without moving the wheels, or when backing into a belt.

8.4.1 Sliding Hub and Actuating Fork

The clutch consists of a hub that slides on the crankshaft, guided by a keyway so it can move axially but must rotate with the shaft. A lever arrangement on the operator's platform ends in a fork that fits into grooves machined around the hub. Pulling the lever moves the fork, which in turn slides the hub along the crankshaft to engage or disengage the clutch.

8.4.2 Spokes, Shoes, and Expanding Action

The hub carries a set of spokes, each ending in a friction shoe. These shoes face outward toward the inner surface of the pulley wheel, which acts as the clutch drum.

In the disengaged position, the spokes sit at an angle, pulling the shoes inward so their effective circumference is smaller than the inside of the pulley. The pulley spins freely around the crankshaft.

When the operator engages the clutch, the fork pushes the hub forward. This action straightens the spokes, forcing the shoes outward. As the spokes approach a straight line, the shoe circle expands until it grips the inside of the pulley wheel.

This expanding-shoe geometry gives the clutch a strong, positive friction fit while remaining simple and robust.

8.4.3 Over-Center Locking

A key feature of this design is the over-center action. As the spokes are pushed past their straight-line position, the geometry "locks" the shoes outward. This prevents the clutch from slipping out of engagement under load. The operator feels this as a distinct snap or firm detent when the clutch lever goes over center.

8.4.4 Retention Systems: Pawls and Pins

Different manufacturers used different methods to keep the clutch from popping out of engagement:

Some engines use a ratchet and pawl on the clutch lever quadrant. Once the lever is pulled over center, the pawl drops into a tooth and holds it there.

Others use a locking pin or latch that the operator drops into place after engaging the clutch.

A few rely solely on the over-center geometry, though this requires careful adjustment to prevent accidental disengagement.

8.5 When the Clutch Is Actually Needed

Unlike automotive practice, the clutch is not used to ease the engine into motion. Traction engines produce enormous low-speed torque and are perfectly happy to start from rest with the clutch fully engaged.

The clutch is only required when:

- Running the belt pulley while keeping the engine stationary
- Backing into a belt, where the pulley must already be turning
- Stopping the machine without stopping the engine
- Idling the engine while adjusting gearing or preparing to move
- In normal forward operation, the clutch is simply engaged and left there.

8.5.1 Backing Into a Belt

When a traction engine is backed into a belt, the pulley wheel must already be turning before the belt can be taken up. Because the clutch is what connects the crankshaft to the traction gearing, the clutch must be engaged for the wheels to turn the engine backward.

As the engine rolls backward, the pulley wheel turns with it. The belt—already looped over the pulley—initially slips freely on the rim. As the engine continues backing, the belt becomes taut. The increasing tension creates enough friction for the belt to begin turning with the pulley. Once the belt is fully stretched and friction is established, the belt and pulley rotate together, and the machine being belted begins to turn.

This is the only situation in normal operation where the clutch is required to engage a moving engine. In all forward work, a traction engine can start from rest with the clutch fully engaged; its immense low-speed torque makes slipping the clutch unnecessary. But when backing into a belt, the engine must already be rotating—driven by the wheels—so the clutch must be engaged to transmit that motion to the pulley.

Summary The traction-engine clutch is a sliding-hub, expanding-shoe friction clutch with an over-center locking action. It is simple, strong, and perfectly suited to the slow-speed, high-torque work of a steam traction engine. Its purpose is not to modulate power during starts, but to give the operator control over when the engine's rotation is delivered to the traction gearing or the belt pulley.

8.6 Pinion, Intermediate, and Differential

8.6.1 First-Motion Pinion

The first-motion pinion is the small gear mounted directly on the crankshaft (or crankdisk shaft). Once the clutch is engaged, this pinion becomes the engine's first point of contact with the traction gearing. Because it turns at full engine speed, it must be small, strong, and precisely fitted.

Its job is straightforward: to transmit the crankshaft's rotation into the gear train and begin the necessary speed reduction.

Since the crankshaft, intermediate shaft, and rear axle are all parallel on virtually all traction engines, the first-motion pinion meshes directly with the intermediate gear without changing the direction of rotation. Only a few unusual machines—such as certain road rollers and the Shay locomotive—depart from this parallel-shaft arrangement.

8.6.2 Intermediate Gear

The intermediate gear is the large gear that meshes with the first-motion pinion. It provides the second stage of speed reduction and carries the full torque of the engine after the clutch.

Its functions are:

- **Speed Reduction:**
The intermediate gear is significantly larger than the first-motion pinion, reducing engine RPM to the slow, powerful rotation needed for traction work.
- **Torque Transmission:**
It passes the engine's torque to the differential gear on the upper (cross) shaft.

The intermediate gear is mounted on its own short shaft with bearings, usually supported by a heavy bracket cast into the frame. In some engines, the intermediate gear can be slid out of mesh to provide a neutral position, allowing the engine to run without turning the differential or wheels. This is separate from the clutch and is part of the traction gearing arrangement.

Because the shafts are parallel, the intermediate gear simply passes rotation along the line of gears without redirecting it.

8.6.3 Differential

The differential sits in the same plane as the intermediate gear. Many traction engines use a flat sun-and-planet differential arrangement. Instead of bevel gears, many traction engines use a crown gear cast into a platter that forms the rotating carrier.

The differential consists of:

- A pinion gear, which turns with the ring gear and rotates the differential platter
- Two or more planet gears, mounted on pins between the crown gear (in the platter) and the sun gear
- A sun gear, splined or keyed to the cross shaft, which drives the final-drive pinions

How the mechanism actually works

- The intermediate gear drives the ring gear, which is fixed to the platter.
- The platter carries the crown gear cast into its face.
- The planet gears run between the crown gear and the sun gear on the cross shaft.
- As the platter rotates, it carries the planet gears around, which in turn drive the sun gear.

Differential action

When both wheels turn at the same speed, the planet gears simply orbit without spinning on their pins.

When the wheels need to turn at different speeds (as in a corner): the planet gears rotate on their pins, allowing the sun gear to turn faster or slower than the platter, which lets each wheel rotate at the speed it needs.

Why this design was used

- It is compact and flat, fitting neatly between the frame rails
- It is extremely rugged and tolerant of dirt and misalignment
- It handles high torque at low speed
- It integrates cleanly with the cross shaft and final-drive pinions

Some engines include a differential lock, which slides a collar to tie both sun gears together for plowing or heavy pulling, where wheel slip is more likely than turning.

8.6.4 Final-Drive Pinions

Once torque leaves the differential's sun gear and enters the cross shaft, it reaches the final-drive pinions—one on each end of the shaft. These pinions are small, hardened gears of equal size, keyed or splined to the cross shaft so they rotate with it.

Their job is simple and crucial:

to deliver the differential's output directly to the bull gears on the rear wheels.

Because the pinions are small and the bull gears are very large, this stage provides the largest single speed reduction in the entire traction-drive system. This reduction is what allows a traction engine to move slowly, steadily, and with enormous pulling power.

The pinions must be:

- precisely aligned
- well-lubricated
- extremely robust

They carry the full torque of the engine after all previous reductions.

8.6.5 Bull Gears

The bull gears are the large, heavy gears bolted directly to the hubs of the rear wheels. They are often the largest gears on the entire machine, sometimes several feet in diameter, and they form the final mechanical link between the engine and the ground.

When the final-drive pinions turn, they mesh with the bull gears and rotate the wheels. Because the bull gears are so large relative to the pinions, they multiply torque dramatically while reducing speed to the slow, controlled pace needed for field work, hauling, or road travel.

Bull gears are typically:

- cast iron or steel
- bolted to the wheel hub or wheel spokes
- open to the air (not enclosed), requiring regular lubrication
- designed with wide, deep teeth to handle dirt, misalignment, and shock loads

Their exposed nature is intentional: traction engines operate in dusty, muddy, and uneven environments, and enclosed gearboxes would trap grit and moisture. Open gearing can be cleaned, inspected, and lubricated easily.

8.6.6 Traction Wheels

The traction wheels are the final stage of the power train. They convert the rotary motion of the bull gears into forward or backward movement of the engine.

Traction wheels on steam engines are:

- large in diameter to provide leverage and smooth travel over rough ground
- wide to distribute weight and prevent sinking
- fitted with cleats or lugs for grip in soil, gravel, or loose material
- built with massive hubs to carry the bull gears and axle loads

The wheels are mounted on a fixed rear axle, but the differential allows each wheel to rotate at its own speed when cornering. Under heavy pulling, one wheel may slip; under turning, one wheel may rotate faster. The gearing accommodates all of this while delivering steady torque.

The combination of:

- high torque from the gearing
- large wheel diameter
- and positive traction from the lugs

gives the traction engine its characteristic slow, powerful, unstoppable movement.

8.7 Hitch and Drawbar Loads

Once the engine can generate tractive effort, the next question is how that force reaches the implement being pulled.

Plowing engines are designed to pull extremely heavy, continuous loads, often under shock conditions as the plow enters and leaves the soil. Because of this, the drawbar and hitch arrangement must transmit all draft forces through the engine's structural members — the hornplates, cannon bearings, and rear axle — without placing any load on the boiler shell.

This requirement is not optional or stylistic. It comes directly from boiler-design principles that were already well understood in the traction-engine era and are explicitly stated in modern historical-boiler regulations: a boiler is a pressure vessel, not a structural frame, and must not be subjected to bending, twisting, or external mechanical loads.

Any such load can distort seams, stays, or firebox sheets and reduce the boiler's safe working pressure.

8.7.1 Hitch

On a plowing engine, the lower cannon bearing carries the rear axle and already absorbs:

- wheel thrust
- bull-gear reaction forces
- torque from the cross shaft
- side loads from uneven ground
- shock loads from traction work

It is the strongest structural point on the rear of the machine and is designed to carry mechanical loads. For this reason, the hitch or drawbar bracket is tied directly into the cannon-bearing structure, not the boiler.

This ensures that:

- all draft forces pass through the axle and hornplates,
- no bending moment is applied to the boiler barrel,
- the firebox and stays remain undistorted,
- and the boiler's maximum allowable working pressure (MAWP) is not compromised.

8.7.2 Why the Boiler Cannot Carry Hitch Load

Boilers are strong in internal pressure tension, but weak in:

- bending
- twisting
- external point loads
- frame-type stresses

Riveted shells and stayed fireboxes are especially vulnerable to distortion. Even small deflections can:

- misalign the crankshaft and gearing
- distort the firebox sheets
- overstress stays

- reduce MAWP
- or cause leaks at seams and rivet lines

For these reasons, both historical practice and modern boiler codes agree: the boiler must not be used as a structural member.

8.7.3 Hitch Load

On a plowing engine, the load path is:

Plow → Hitch → Drawbar Bracket

Drawbar Bracket → Lower Cannon Bearing / Axle Structure

Axle Structure → Hornplates

Hornplates → Engine Frame

The boiler is not part of this chain.

This arrangement keeps the pressure vessel isolated from mechanical strain while allowing the engine to deliver enormous draft forces safely.

8.7.4 Why This Matters for Plowing Engines Specifically

Plowing engines experience:

- continuous high drawbar load
- shock loads from soil engagement
- long periods of sustained torque
- uneven ground and side loads

These loads are far greater than those seen in road haulage. If transmitted into the boiler, they could distort the pressure vessel enough to reduce its safe operating pressure or cause structural damage.

By routing the load through the cannon bearing and hornplates, the engine can pull safely at full power without risking the boiler.

Chapter 9 Steering Wheel to Front Axle

Unlike an automobile, where individual front wheels pivot on steering knuckles, a traction engine steers by swinging the entire front axle assembly. The steering gear provides enough mechanical advantage for the operator to control this heavy axle smoothly and accurately.

9.1 Steering Linkage

9.1.1 Steering Wheel

The steering wheel is large to give the operator leverage. Because the steering system is heavily geared down, the wheel must be turned many revolutions to swing the front axle from lock to lock.

9.1.2 Steering Shaft

The wheel turns a steering shaft that runs diagonally down toward the front of the engine. This shaft is supported in bearings and ends in the worm gear.

9.1.3 Worm Gear

At the bottom of the steering shaft is the worm, which engages a worm wheel or worm segment. This provides:

- very high mechanical advantage

- slow, controlled steering
- self-locking action (the front wheels cannot kick back)

The worm turns the chain roll.

9.1.4 Chain Roll (Steering Drum)

The chain roll is a horizontal drum with grooves or flanges to guide the steering chain. As it rotates:

- one side of the chain is wound in
- the other side is paid out

This converts the worm's rotation into a controlled pull on the steering chains.

9.1.5 Steering Chains

The steering chains run from the chain roll down to the front axle. They pull **directly on the axle** (through the steering springs). Winding in the left chain and paying out the right turns the axle left; reversing the drum turns it right.

9.1.6 Steering Springs

Between the chain and the axle are steering springs. These springs:

- keep the chain tensioned
- absorb shocks from rough ground
- prevent sudden jerks from reaching the worm gear
- allow the axle to rock without slackening the chain

They ensure smooth, quiet steering and protect the gearing.

9.2 Front-end Structure

9.2.1 Front Axle

The front axle assembly allows two distinct motions:

1. **Horizontally**, for steering — the entire axle swings left or right as a unit.
2. **Vertically**, to follow uneven terrain — the axle rocks up and down around its central pivot pin.

This dual-pivot action allows the engine to steer while also keeping both front wheels on the ground over bumps and ruts.

9.2.2 Pedestal (Front Axle Pivot)

The pedestal is the heavy casting at the front of the engine that carries the axle pivot pin. It supports:

- the weight of the front of the engine
- the side loads from steering
- the rocking motion of the axle over uneven ground

It is the structural anchor for the entire steering system.

9.2.3 Reach

The reach is the long structural member connecting the pedestal to the boiler and hornplates. It:

- keeps the pedestal aligned with the engine frame
- carries fore-and-aft loads from steering and road shocks
- prevents the pedestal from twisting or shifting
- maintains correct geometry between the front and rear axles

Without the reach, the pedestal would have no structural reference to the rest of the engine.

Summary

The steering system is a worm-and-chain mechanism that gives slow, powerful, shock-free control. The load path is:

Steering Wheel → Steering Shaft → Worm Gear → Chain Roll → Steering Chains → Steering Springs → Front Axle (horizontal + vertical pivot) → Pedestal → Reach → Hornplates

This arrangement is simple, durable, and perfectly suited to the heavy, low-speed work of a steam traction engine.

Chapter 10 Ash Pan, Grates and Damper

Just as steam follows a path through the engine, combustion air follows a path through the boiler. Understanding that airflow path is the key to understanding firing and steam production.

The production of steam requires more than fuel and water. It also requires a continuous supply of air to support combustion.

Three components work together to control this process:

- The ash pan
- The grates
- The damper

Although these parts are simple in appearance, they have a major influence on firing efficiency, steaming capacity, fuel consumption, and boiler performance.

Understanding how they work together helps the operator maintain a clean fire, good draft, and reliable steam production.

10.1 Airflow Through the Firebox

Combustion requires three elements:

- Fuel
- Heat
- Oxygen

The oxygen is supplied by air passing through the combustion system.

A simplified airflow path is:

Damper
↓
Ash Pan
↓
Grates
↓
Fuel Bed
↓
Firebox
↓
Flues
↓
Smokestack

The fire does not burn because fuel is present. It burns because air flows through the fuel bed and supplies oxygen to the combustion process.

Anything that restricts airflow will reduce combustion efficiency.

10.2 The Ash Pan

The ash pan is located beneath the grates.

Its primary functions are:

- Collecting ash and debris falling through the grates.
- Providing an air chamber beneath the fuel bed.
- Directing incoming air toward the fire.

Although operators often think of the ash pan as merely a place where ashes accumulate, it is also an important part of the draft system.

10.2.1 Ash Accumulation

As fuel burns, non-combustible material accumulates as ash.

If ash is allowed to build up excessively:

- Airflow is restricted.
- Draft decreases.
- Fire temperature falls.
- Smoke production increases.
- Steam production suffers.

Regular removal of ash is therefore an important part of boiler maintenance.

10.3 Grates

The grates form the floor of the firebox.

They support the fuel bed while allowing combustion air to pass upward through the fire.

An effective grate must satisfy two competing requirements:

- It must support the burning fuel.
- It must allow adequate airflow.

10.3.1 Fixed Grates

Fixed grates remain stationary during operation.

They are simple and durable but require periodic cleaning to remove accumulated ash and clinker.

10.3.2 Rocking Grates

Many traction engines use rocking grates.

Rocking grates can be moved by the operator to shake ash and clinker loose while the fire remains in place.

Advantages include:

- Improved airflow.
- Easier ash removal.
- Better fire maintenance during operation.

Excessive grate shaking, however, may disturb the firebed and result in the loss of unburned fuel.

10.3.3 The Firebed

A good firebed is:

- Evenly distributed.
- Free of large holes.
- Thick enough to maintain combustion.
- Thin enough to allow airflow.

An uneven firebed often creates hot spots, cold spots, and poor combustion.

10.4 Clinker

Not everything in fuel burns completely.

Minerals, dirt, and ash can fuse together under high temperatures to form a hard mass known as clinker.

Coal + Ash + Heat
↓
Clinker

Large clinker deposits can:

- Block airflow through the grates.
- Disturb the firebed.
- Reduce steaming capacity.
- Make firing more difficult.

Clinker should be removed whenever it begins to interfere with airflow or grate operation.

10.4.1 Why Clinker Matters

A boiler may contain plenty of fuel and still steam poorly if airflow is restricted by clinker.

Experienced operators often judge the condition of a fire not by the amount of fuel present but by the quality of airflow through the grate area.

10.5 Draft

Draft is the movement of air through the boiler's combustion system.

The firebox operates at a slight vacuum created by the exhaust steam nozzle and smokestack.

This vacuum draws air:

1. Through the damper.
2. Through the ash pan.
3. Through the grates.
4. Through the fuel bed.
5. Through the flues.
6. Up the stack.

Good draft promotes:

- Clean combustion.
- Efficient fuel use.
- Strong steam production.

Poor draft results in:

- Smoke.
- Reduced power.
- Incomplete combustion.
- Difficulty maintaining pressure.

10.6 The Damper

The damper controls the volume of air entering the ash pan.

By regulating airflow, the damper controls the intensity of combustion.

10.6.1 Damper Open

When the damper is opened:

- More air reaches the fire.
- Combustion increases.
- Fire temperature rises.
- Steam production increases.

10.6.2 Damper Closed

When the damper is closed:

- Airflow is reduced.
- Combustion slows.
- Fire temperature falls.
- Steam production decreases.

The damper is one of the operator's primary tools for controlling the fire.

10.6.3 Front and Rear Dampers

Some traction-engine boilers are equipped with both front and rear dampers.

Although both openings provide access to the ash pan area, they do not serve the same purpose.

The rear damper is the normal combustion-air inlet and should be used to regulate airflow through the fire.

The front damper is typically used only for:

- Ash removal
- Cleaning
- Inspection

During operation, combustion air should enter primarily through the rear damper.

10.6.4 Why Air Direction Matters

The direction of airflow through the ash pan affects how air is distributed beneath the grates and through the fuel bed.

Air entering from the rear follows the intended path through the firebox and promotes more uniform combustion.

Air entering from the front can create undesirable airflow patterns beneath the fire and may allow relatively cool air to impinge on the rear tube sheet.

Repeated exposure to uneven heating and cooling can contribute to thermal stresses and may increase the risk of distortion or warping of the rear tube sheet.

For this reason, experienced operators generally keep the front damper closed during normal operation and use the rear damper as the primary means of air control.

10.7 Damper and Fire Door

New operators often assume that opening the fire door is an effective way to increase the fire.

In normal operation, combustion air should enter through the grates, not through the fire door.

Air entering through the fire door tends to:

- Bypass portions of the fuel bed.
- Disturb the draft pattern.
- Cool portions of the firebox.

The preferred method of increasing combustion is typically to adjust the damper and maintain a proper fuel bed.

10.8 Firebox Design Considerations

The ash pan, grates, and damper are all part of the combustion-air system.

Good firebox design seeks to:

- Distribute air evenly beneath the fuel bed.
- Maintain consistent draft.
- Provide convenient ash removal.
- Minimize maintenance requirements.

Although individual traction engines differ in construction, these principles remain the same.

10.9 Preparation for Service

Before lighting a fire or preparing an engine for operation, operators should inspect:

- Ash pan condition.
- Grate condition.
- Clinker accumulation.
- Damper operation.
- Air passages.

Ashes and clinker should be removed as required and the damper should move freely through its full range of travel.

A clean combustion system promotes easier firing, stronger draft, and more reliable steam production.

10.10 Key Takeaway

Efficient steaming depends as much on airflow as on fuel. The ash pan, grates, and damper form the boiler's air-control system, and keeping that system clean and unobstructed is essential for maintaining combustion, draft, and steam production.

Chapter 11

Strength of the Boiler Shell

Water and steam under pressure exert force in all directions. Pressure does not care whether the boiler surface is horizontal, vertical, curved, or flat. At every point, the pressure acts perpendicular to the surface.

The pressure-retaining parts of a boiler are subjected to enormous forces. Understanding how those forces are carried through the structure is the key to understanding boiler strength.

11.1 Curved and Flat Surfaces

Pressure acts equally in all directions, but not all shapes respond to pressure in the same way.

A round surface wants to remain round. A cylindrical shell under pressure expands slightly, but the load is carried efficiently as tension around the shell.

A flat surface behaves differently. Pressure causes the plate to bend and bulge outward. As the plate becomes larger, the bending stresses increase rapidly. For this reason, flat surfaces usually require stays or reinforcement.

Because a cylindrical shell carries pressure so efficiently, it forms the main body of most boilers. The shell, barrel, steam dome, and many other pressure-retaining parts are based on curved shapes.

11.2 Why boilers don't fly

To understand why the cylindrical shell is such an efficient structure, it is useful to consider how the shell would fail if the internal pressure became excessive.

The simplest way to understand shell strength is to ask how a cylindrical shell would fail if the pressure became too high.

Imagine a cylindrical shell divided into two halves by a longitudinal plane. The pressure inside the boiler pushes upward on one half and downward on the other. The total separating force is the pressure multiplied by the projected area.

Consider the areas of the lower and upper portions of the boiler cylinder along a horizontal plane dividing the boiler in half. In [Fig. 24](#), the cross section of the cylinder is shown in three stages. In the first stage, the cross section is circular. In the second stage, the lower portion of the cylinder has been partially flattened. In the third stage, the lower portion has been completely flattened, resulting in the figure shown in [Fig. 25](#).

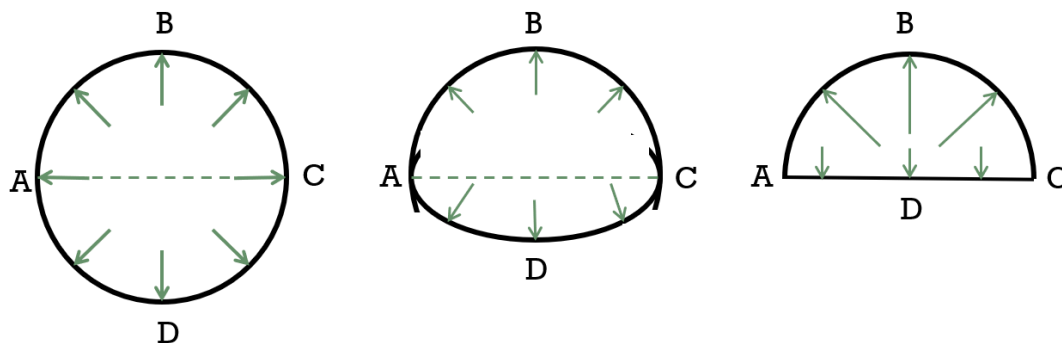


Fig. 24 Cylinder shapes

The cross-section projected along the shell looks like the upper half of a horizontal cylinder.

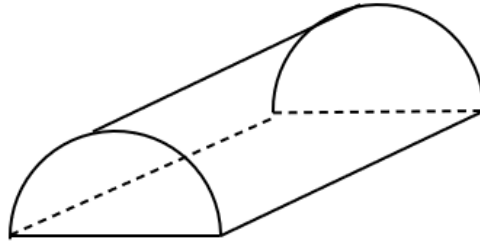


Fig. 25 Upper half of cylinder

The arrows in [Fig. 24](#) show internal pressure as being normal to the inner shell. In the first stage, the sum of the pressure along the projection of semicircle ABC is the same as the sum of the pressure along the projection of ADC. The pressures are balanced.

In the second stage, the lower shape ADC also experiences all the pressure below the horizontal line AC. This is true in the third stage as well.

It is clear that the length of the arc ADC in stage two is less than the arc ADC in stage one, and it is easy to see that the volume of the shape ADC in stage two is also less than the shape in stage one.

In stage three, the lower shape has been collapsed to a line, which has a volume of zero.

The question is now this: what is the combined force due to pressure along line ADC in each of the three stages, in comparison to the pressure along ABC.

Consider what must happen if the the lower force was less. The sum of the vertical components would have to be less on the lower shell than the upper shell. If this were the case, the boiler would rise due to the differential. Either we have invented a new form of air travel, or this cannot be the case.

In fact the upper and lower forces must match. This means the force on the flat lower surface in [Fig. 25](#) must match that on the curved upper surface.

Now consider what must happen along the line where the two surfaces meet. The material along this line experiences two equal forces in opposite directions. As we will see later, when metal is pulled in two opposite directions, the force required to tear the metal is determined by the tensile strength of the material. The resisting area is the area of metal crossing the imaginary dividing plane. This area equals the shell thickness multiplied by the cylinder length at each side, giving a total resisting area of $2LT$.

For a cylinder with diameter $D = 30$ in and length $L = 96$ in with internal pressure $P = 100 \frac{\text{lb}}{\text{in}^2}$, the total upward (or downward) force is

$$\begin{aligned} P_D &= (D \cdot L \cdot P) \\ &= (30 \text{ in} \cdot 96 \text{ in} \cdot 100 \frac{\text{lb}}{\text{in}^2}) \\ &= 288000 \text{ lb} \end{aligned}$$

If the cylinder has a thickness of $T = 0.250$ in, the area of a tear along the complete seam is

$$\begin{aligned} A_s &= (2LT) \\ &= (2 \cdot 96 \text{ in} \cdot 0.250 \text{ in}) \\ &= 48 \text{ in}^2 \end{aligned}$$

So the force on the seam is

$$\begin{aligned} \frac{P_D}{A_s} &= \frac{P_D}{A_s} \\ &= 6000 \end{aligned}$$

The shell will burst when the force on the seam equals the tensile strength of the material. If the tensile strength is $\sigma_t = 60000 \frac{\text{lb}}{\text{in}^2}$

$$\frac{D \cdot L \cdot P_b}{2LT} = \sigma_t$$

Solving for P_b ,

$$\begin{aligned} P_b &= \frac{2LT\sigma_t}{D \cdot L} \\ &= \frac{296 \text{ in} \cdot 0.250 \text{ in} \cdot \sigma_t}{30 \text{ in} \cdot 96 \text{ in}} \\ &= 1000 \end{aligned}$$

That is, a cylinder 30 inches wide, 96 inches long and a quarter inch thick with a tensile strength of 60000 will burst at 1000 PSI internal pressure.

One more thing. Looking at the equation $P_b = \frac{2LT\sigma_t}{D \cdot L}$, note that length appears both in the numerator and the denominator of the pressure-area ratio. The equation can be reduced to $P_b = \frac{2T\sigma_t}{D}$. The reduced form shows that bursting pressure is a function of thickness and diameter. The cylinder could be an inch long or a mile long, and the bursting pressure will still be the same.

11.3 Safety Factor and MAWP

The previous section showed that a cylindrical boiler shell fails in tension when the hoop stress reaches the tensile strength of the material. The calculations showed the relatively thin shell would burst at 1000 psi.

A shell that bursts at 1000 psi should obviously not be operated at 1000 psi. To determine a safe maximum operating pressure, a **factor of safety** is applied.

This section shows how a factor of safety relates to the physical characteristics of metal.

11.3.1 Tensile Failure of a Bolt

Before looking at the formal definitions of stress, strain and elasticity, consider the bolt in [Fig. 26](#) that has been pulled in tension until failure.

As the tensile force increased, the bolt first stretched elastically. During this stage the bolt lengthened slightly, but would have returned to its original shape if the load had been removed.

At a higher load, the material reached its yield strength and began to deform permanently. The deformation became concentrated in one region of the bolt, producing the narrowed section known as a *neck*.

As the neck became smaller, the remaining metal had to carry the entire load across a progressively smaller cross-sectional area. The stress in the neck therefore increased rapidly until the material could no longer support the load.

The bolt finally fractured at its ultimate tensile strength.

The necked shape seen on the failed specimen is characteristic of a *ductile* material. Before breaking, the material gave a visible warning by deforming significantly. A more brittle material would show little or no necking before fracture.

Boiler shells behave in a similar way. Internal pressure creates tensile forces in the shell. If these forces become large enough, the metal first yields and deforms, and only at a higher stress does it tear apart. For this reason boiler design is based not only on preventing rupture, but also on keeping working stresses well below the yield point.



Fig. 26 Tensile test of AlMgSi alloy

11.3.2 Stress, Strain, and Elasticity

A force acting on a material creates **stress**.

Stress causes the material to deform, producing **strain**.

At low stresses, most metals behave elastically. The deformation is completely recoverable when the load is removed.

As the load increases, the material reaches its **yield strength**. Beyond this point, permanent deformation occurs.

If the load continues to increase, the material eventually reaches its **ultimate tensile strength**, and finally fractures.

For most boiler materials, the yield strength is approximately one-half of the tensile strength.

A typical stress-strain curve therefore contains three important regions:

1. Elastic region
2. Yield point
3. Plastic deformation leading to fracture

Safe operation should remain well within the elastic region.

11.3.3 Why a Safety Factor is Needed

The tensile strength represents the point at which the material tears apart.

In practice, boilers are never operated anywhere near this limit.

A **factor of safety** provides a margin between the working stress and the failure stress.

The Maximum Allowable Working Pressure (MAWP) is therefore

$$P_{MAWP} = \frac{P_B}{F} \text{ where } F \text{ is the factor of safety.}$$

Substituting the bursting-pressure equation gives

$$P_{MAWP} = \frac{2T\sigma_t}{F \cdot D}$$

11.3.4 Using a Factor of Safety of Four

For the example boiler,

$$F = 4$$

so

$$P_{MAWP} = \frac{2 \times 0.25 \times 60,000}{4 \times 30} = 250 \text{ psi}$$

Thus a boiler that theoretically bursts at 1000 psi is limited to a working pressure of 250 psi.

11.3.5 Relationship to Yield Strength

The reason a factor of safety of four works well can be understood from the stress-strain curve.

For typical boiler steels,

$$\sigma_y = \frac{\sigma_t}{2}$$

where σ_y is the yield strength.

A factor of safety of four limits the working stress to

$$\frac{\sigma_t}{4}$$

which is approximately

$$\frac{\sigma_t}{2}$$

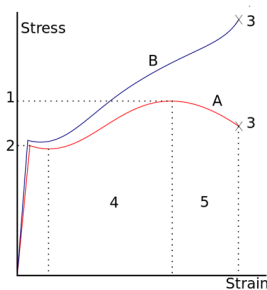
In other words, the working stress lies in the lower half of the elastic range and well below the onset of permanent deformation.

This provides a practical margin for:

- pressure fluctuations,
- material variations,
- corrosion and wear,
- manufacturing tolerances,
- minor stress concentrations,
- uncertainties in operation.

The boiler therefore operates comfortably within the region where the metal will return to its original shape when the load is removed.

11.3.6 True Stress and Engineering Stress



[Fig. 27](#) Stress-Strain Curve

1. Ultimate strength
2. Yield strength
3. Fracture
4. Strain hardening region
5. Necking

- A. Engineering stress
- B. True stress

When a tensile test is performed, the engineering stress is calculated using the original cross-sectional area of the specimen.

$$s = \frac{F}{A_0}$$

As the specimen stretches, its width and thickness decrease.

The actual stress in the material at any instant is therefore greater than the engineering stress. This is called **true stress**.

$$\sigma = s \cdot (1 + e)$$

where e is the engineering strain.

Similarly,

$$\varepsilon = \ln(1 + e)$$

where ε is the true strain.

Engineering stress is convenient because it requires only the original dimensions of the specimen. True stress better represents the actual state of the material during deformation.

For boiler design, however, the important point is that the allowable working stress is intentionally kept far below both ultimate tensile strength and fracture. A factor of safety of four places operation safely within the elastic region of the material.

11.3.7 Design Implications

The MAWP equation shows that

$$P_{MAWP} = \frac{2T\sigma_t}{F \cdot D}$$

A larger diameter requires either:

- a thicker shell,
- a stronger material,
- a lower working pressure,
- or a smaller factor of safety approved by code.

Conversely, increasing shell thickness increases the safe working pressure in direct proportion.

This simple relationship is one of the fundamental principles of boiler and pressure-vessel design.

Chapter 12

Riveted Joints

12.1 Classification

Riveted joints are commonly classified as

- **Strong joints**, used in structures such as bridges, beams and trusses.
- **Tight joints**, used in tanks and containers where leakage must be prevented.
- **Strong and tight joints**, used in boilers and pressure vessels where the joint must both resist load and remain steam- and water-tight.

12.2 Installation

A rivet consists of a cylindrical shank with a factory head formed at one end. Before installation, the rivet length is chosen so that enough material projects beyond the plates to form the second, or field, head after upsetting.

The rivet is heated and inserted into the prepared hole. The factory head is supported by a bucking bar while the projecting end is upset using a hammer and rivet set. The displaced metal forms the field head and clamps the plates together.

As the hot rivet cools it contracts. Because the rivet heads prevent shortening, the rivet is placed in tension while the plates are compressed together.

This produces a clamping force that helps prevent leakage and causes part of the load to be transferred by friction between the plates.

12.3 Caulking

Even a well-made riveted joint may contain minute gaps between adjoining plates. To make the joint steam- and water-tight, the exposed plate edge can be caulked.

A blunt caulking tool is driven along the edge of the plate at an angle of approximately 15° to 18° . The metal at the edge is displaced slightly, forcing it tightly against the adjoining plate and closing any leakage path.

Caulking improves the tightness of the seam but contributes little to its strength. A seam may therefore contain more rivets than required for strength alone in order to achieve satisfactory tightness.

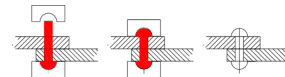


Fig. 28 Installation

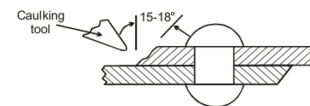


Fig. 29 Single Rivet

12.4 Riveted joint types

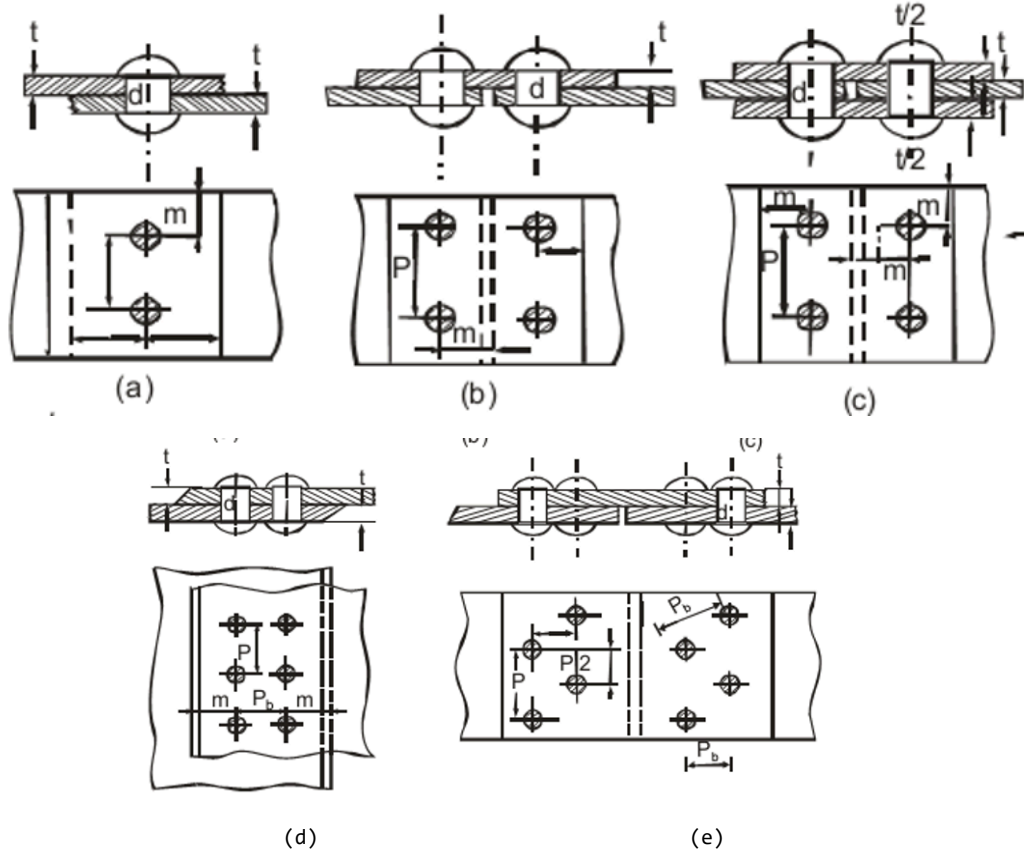


Fig. 30 Riveted joint types

The most common forms of riveted joints used in boilers and pressure vessels are shown in [Fig. 30](#).

The simplest joint is the **lap joint**, in which one plate overlaps another. The rivets pass through both plates and transfer load by shear. Lap joints require fewer parts and are easy to manufacture, but the load path is offset, which tends to bend the plates when the joint is loaded.

A **butt joint** places the edges of the plates together and joins them using one or more cover plates, called **straps**. Because the plates remain in the same plane, butt joints provide a more direct load path than lap joints and are commonly used for important boiler seams.

The illustrated joints are:

a. Lap joint

The plates overlap and are connected by a single row of rivets.

b. Single-cover butt joint

The plate edges meet and are joined by a single cover strap on one side.

c. Double-cover butt joint

The plate edges meet and are joined by cover straps on both sides. The load is transmitted symmetrically through the joint, making this arrangement stronger and more efficient than the single-cover butt joint.

d. Double-riveted lap joint

A lap joint using two rows of rivets. The additional rivets increase the strength and tightness of the seam.

e. Double-riveted butt joint

A butt joint using two rows of rivets arranged in a staggered pattern. Staggering improves the efficiency of the joint by reducing the weakening effect of the rivet holes.

The dimensions shown in the figures are commonly used in riveted-joint calculations:

Symbol	Meaning
p	rivet pitch, the distance between adjacent rivets in the same row
m	margin, the distance from the centre of a rivet to the edge of the plate
d	rivet diameter
p_b	back pitch, the distance between adjacent rows of rivets
p_d	diagonal pitch, the centre-to-centre spacing of staggered rivets measured diagonally

The selection of rivet diameter, pitch, and row spacing is a compromise between strength, tightness, manufacturing cost, and ease of inspection. Additional rows of rivets generally increase the strength of a joint, but they also require more holes to be drilled, which removes metal from the plates and increases construction time.

12.5 Analysis of Riveted Joints

Riveted joints can fail in several different ways. These are known as **failure modes**.

The principal failure modes are:

- Tearing of the plate along a section weakened by rivet holes
- Shearing of the rivets
- Crushing of the rivets
- Crushing of the plate at the rivet holes or margin

Each failure mode can be analysed separately to determine the load required to produce failure.

The strength of the joint is governed by the weakest failure mode. In other words, the maximum load that can be carried safely is limited by the failure mode requiring the smallest load to produce failure.

Good riveted-joint design aims to proportion the rivets, pitch, and plate thickness so that no single failure mode is excessively weaker than the others.

12.5.1 Tearing of plate

A line of rivet holes weakens a plate in much the same way that perforations weaken a sheet of paper.

A familiar example is a spiral-bound notebook. When the paper is pulled, it usually tears between adjacent holes because only a narrow strip of material remains to resist the load.

The same effect occurs in riveted joints. In Fig. 5, the pulling force acts across a section containing rivet holes. The holes remove part of the metal, leaving only the material between the holes to resist tearing.

The width of metal available to resist tearing is

$$(p - d)$$

where

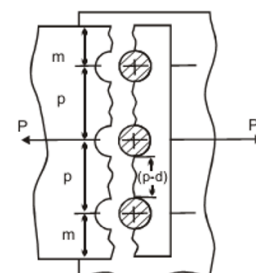


Fig.

31 Tearing

p = rivet pitch
 d = rivet-hole diameter

Multiplying by the plate thickness gives the net tearing area:

$$A_{t(d,p,t)} \rightarrow (p - d) \cdot t$$

The force required to tear the plate is therefore

$$P = \sigma_t \cdot A_t(d, p, t)$$

where

P = tearing force
 A_t = net area resisting tearing
 σ_t = tensile strength of the plate material

For example,

$$P_t = \sigma_t \cdot A_t(d, p, t) \text{ where } \begin{cases} \sigma_t \rightarrow 60000 \\ p \rightarrow 3.500 \\ d \rightarrow 0.750 \\ t \rightarrow 0.375 \end{cases}$$

$$= 61875$$

Notice that the rivet hole removes part of the plate section.

For comparison, the tearing force of an identical plate with no hole is

$$P = \sigma_t \cdot A_t(d, p, t) \text{ where } \begin{cases} \sigma_t \rightarrow 60000 \\ p \rightarrow 3.500 \\ d \rightarrow 0 \\ t \rightarrow 0.375 \end{cases}$$

$$= 78750$$

The reduction in strength is due entirely to the metal removed to make the rivet hole.

A larger rivet is not always stronger. Increasing rivet diameter increases the rivet's shear strength, but it also removes more metal from the plate and reduces the tearing strength.

12.5.2 Shearing of Rivet

A rivet transfers load from one plate to another. If the load becomes large enough, the rivet may fail by shearing across its cross-sectional area.

In a lap joint or single-cover butt joint, the rivet is usually in single shear, as shown on the left side of [Fig. 32](#). The load attempts to cut the rivet along one shear plane.

The area resisting shear is the cross-sectional area of the rivet:

$$A_{s(d)} \rightarrow \pi \left(\frac{d}{2} \right)^2$$

where

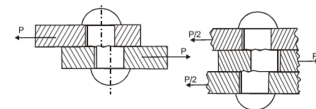


Fig. 32 Shearing

A_s = area resisting shear

d = rivet diameter

The load-carrying capacity in single shear is

Shearing stress in single shear is thus:

$$P_s = \sigma_r \cdot \pi \cdot \left(\frac{d}{2}\right)^2$$

where σ_r is the allowable shear stress of the rivet material.

For example,

$$P_s = \sigma_r \cdot \pi \cdot \left(\frac{d}{2}\right)^2 \text{ where } \begin{cases} \sigma_r \rightarrow 44000 \\ d \rightarrow 0.750 \end{cases}$$

$$= 19438.605$$

In **double shear**, as shown on the right side of [Fig. 32](#), two shear planes must fail before the rivet is severed.

The load-carrying capacity in double shear is therefore approximately twice that of single shear:

$$P_d \approx 2P_s$$

Some authorities use a factor of 1.75 rather than 2.0 to account for unequal loading of the two shear planes. The NBIC uses a factor of 2 when evaluating riveted joints.

12.5.3 Crushing of Rivet

As load is applied to a riveted joint, the rivet bears against the wall of the hole. If the bearing pressure becomes excessive, the rivet material may be crushed.

This failure mode differs from shearing. In shearing, the rivet is cut across its cross-section. In crushing, the rivet is compressed where it bears against the plate.

The area resisting crushing is the projected contact area of the rivet:

$$A_{c(d,t)} \rightarrow d \cdot t$$

where

A_c = area resisting crushing

d = rivet diameter

t = plate thickness

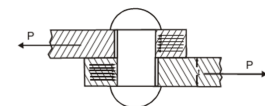
The crushing strength is therefore

$$P_c = \sigma_c \cdot d \cdot t$$

where

P_c = crushing load

σ_c = allowable crushing stress of the rivet material



33 Crushing

Fig.

For example,

$$P_c = \sigma_c \cdot d \cdot t \text{ where } \begin{cases} \sigma_c \rightarrow 95000 \\ d \rightarrow 0.750 \\ t \rightarrow 0.375 \end{cases}$$
$$= 26718.750$$

Increasing either the rivet diameter or plate thickness increases the resistance to crushing.

12.5.4 Tearing of Plate Margin

A rivet placed too close to the edge of a plate may tear out the material between the hole and the edge.

The resisting area consists of two sections of metal, one on each side of the rivet hole. The total area resisting failure is

$$A_{ms} = 2mt$$

where

m = margin

t = plate thickness

The load required to tear out the plate margin is

$$P_{ms} = 2mt\sigma_t$$

where σ_t is the tensile strength of the plate material.

For example,

$$P_{ms} = 2mt\sigma_t \text{ where } \begin{cases} m \rightarrow 2 \\ t \rightarrow 0.375 \\ \sigma_t \rightarrow 60000 \end{cases}$$
$$= 90000$$

To prevent this type of failure, rivets must be located sufficiently far from the edge of the plate.

12.5.5 Summary of Failures

A riveted joint may fail in several different ways:

Tearing of plate:	P_t	61875
Shearing of rivet:	P_s	19438.605
Crushing of rivet:	P_c	26718.750
Crushing of plate margin:	P_{ms}	90000

The strength of a riveted joint is determined by calculating the load required for each failure mode.

The safe load of the joint is governed by the weakest failure mode; that is, the failure mode requiring the smallest load to produce failure.

A well-designed joint proportions the rivets, pitch, margin, and plate thickness so that no single failure mode is excessively weaker than the others.

In practice, however, the theoretically optimum design cannot always be achieved. Plate thicknesses and rivet diameters are available only in standard sizes, traditionally in increments of one sixteenth of an inch.

Rivet spacing is likewise limited by practical measurement and manufacturing considerations.

The designer must therefore select dimensions from available materials and proportions, then verify that the resulting joint is safe and suitable for service. Riveted-joint design is consequently a compromise between theoretical efficiency, manufacturing practicality, and economy.

12.5.6 Assumptions Used in Riveted-Joint Analysis

The equations developed in this chapter are based on several simplifying assumptions. Real riveted joints do not satisfy all of these assumptions exactly.

In practice, loads are not perfectly distributed, rivets may bend slightly, stress concentrations exist around holes, and friction between plates may carry part of the load. Nevertheless, the assumptions provide calculations that are sufficiently accurate for practical boiler design and form the basis of most traditional riveted-joint analysis.

12.6 Efficiency of Riveted Joints

The load carrying capacity of a solid plate is $P_t = p \cdot t \cdot \sigma_t$ where

p = pitch

t = thickness

σ_t = tensile strength

A solid plate is stronger than a riveted plate because rivet holes remove material.

The ratio of the strength of a riveted joint to the strength of the unperforated plate is called the joint efficiency.

Ideally, the strength of all modes will be equal.

In practice, equal strengths cannot usually be achieved because rivet diameters, plate thicknesses, and pitches are limited to standard sizes.

$$E = \frac{\min(P_t, P_s, P_c, P_{ms})}{P_t}$$

Joint efficiency is the ratio of the strength of the joint to the strength of the corresponding unperforated plate.

Since the joint can only carry the load associated with its weakest failure mode, the minimum of the calculated strengths is used.

Joint efficiencies are usually stated on boiler blue prints.

When detailed calculations or original drawings are unavailable, the following typical efficiencies may be used.

12.6.1 Typical Riveted Joint Efficiencies

Type of Joint	Efficiency (%)
Lap Seam, Single Riveted	58
Lap Seam, Double Riveted	74
Lap Seam, Triple Riveted	78
Butt Strap, Double Riveted	82
Butt Strap, Triple Riveted	88
Butt Strap, Quadruple Riveted	94

Source: NBIC 2007

The shell plate between seams has full strength. The seams do not. Joint efficiency is therefore used when determining the strength and maximum allowable working pressure of riveted boilers.

Chapter 13 Stayed Surfaces

13.1 Stayed Surfaces

Round surfaces want to be round. Flat surfaces want to be round.

A cylindrical boiler shell naturally resists internal pressure because its curved shape allows the load to be carried as tension in the shell. The pressure tries to make the shell larger, but not flatter.

A flat plate behaves differently. Internal pressure causes a flat surface to bulge outward, attempting to transform it into a curved surface. Unless the plate is made very thick, the resulting bending stresses quickly become excessive.

Boiler designers therefore support flat surfaces with stays. The stays transfer the pressure load into tension members and prevent the plate from deflecting excessively.

Analysis of stayed surfaces therefore requires three separate calculations:

1. The load applied to the plate by pressure.
2. The strength of the connection between the stay and the plate.
3. The strength of the stay itself.

The allowable load is governed by the weakest of these three conditions.

The construction of the stay attachment significantly affects strength. For this reason the ASME Code assigns different construction factors to different stay arrangements.

Riveted-joint analysis showed that the strength of a structure is often governed by its connection details rather than by the strength of the metal itself.

The same principle applies to stayed surfaces. A stay may be made from excellent material, but the allowable pressure is often determined by the manner in which the stay is attached to the plate.

13.1.1 Through Stays

The equations used for stayed surfaces vary between references because different codes incorporate the factor of safety in different ways.

Older ASME boiler formulas often express the allowable pressure using the ultimate tensile strength and an explicit factor of safety. Modern NBIC calculations typically use an allowable stress value that already includes the required safety factor.

Although the equations may appear different, they generally produce equivalent results when the same assumptions are used.

Before looking at the formula, consider what must happen.

- A thicker plate should resist pressure better than a thinner plate.
- Stays placed closer together should support the plate better than stays placed farther apart.

The ASME equation reflects both of these observations.

$$P_{\text{through}} = \frac{t^2 \cdot S \cdot C}{p^2}$$

where

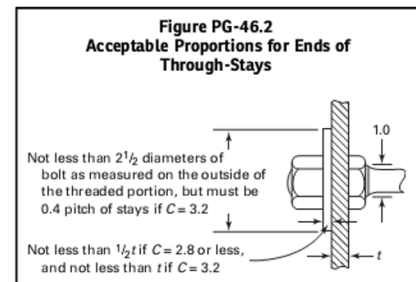


Fig. 35 Through-stay attachment details

Symbol Meaning

t	Thickness of the stayed surface
p	Stay spacing (centre-to-centre distance between stays)
S	Allowable stress for the stayed surface. In NBIC this value already includes the required factor of safety.
C	Construction factor based on stay attachment details: 2.1 for welded stays or stays screwed through plates not over 7/16 in. thick and riveted over 2.2 for welded stays or stays screwed through plates over 7/16 in. thick and riveted over 2.5 for stays fitted with nuts but without washers 2.8 for headed or taper-fit stays having true bearing on the plate 3.2 for stays fitted with inside and outside nuts and outside washers meeting Code requirements

For example,

$$P_{through} = \frac{t^2 \cdot S \cdot C}{p^2} \text{ where } \begin{cases} t \rightarrow 2 \cdot 0.375 \\ S \rightarrow \frac{55000}{4} \\ C \rightarrow 3.200 \\ p \rightarrow 6.500 \end{cases}$$

$$= 585.799$$

The values chosen reflect a boiler having widely spaced through stays connecting double-plated heads fitted with nuts and washers.

13.1.2 Regular Staybolt Patterns.

Where flat surfaces are supported by staybolts, the stays are often arranged in a regular square pattern.

Each staybolt supports the pressure acting on the surrounding area of plate, often called the tributary area of the stay. For uniformly spaced staybolts, the area supported by one stay is approximately the square of the stay pitch.

The ASME Code treats regularly spaced staybolts threaded into plate less than 1/2 inch thick and riveted over in the same manner as through stays. The allowable working pressure is given by

$$P_{regular} = \frac{t^2 \cdot S \cdot C}{p^2}$$

For example,

$$P_{regular} = \frac{t^2 \cdot S \cdot C}{p^2} \text{ where } \begin{cases} t \rightarrow 0.300 \\ S \rightarrow \frac{55000}{4} \\ C \rightarrow 3.200 \\ p \rightarrow 4.500 \end{cases}$$

$$= 195.556$$

Notice that stay spacing appears in the denominator as the square of the pitch.

If the spacing is increased, each stay must support a larger area of plate and the allowable pressure decreases rapidly.

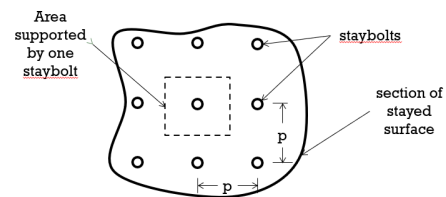


Fig. 35 Area supported by a staybolt

As a boiler deteriorates through corrosion, the stay spacing and construction factor remain unchanged. The principal change is a reduction in plate thickness.

Because plate thickness appears squared in the equation, small losses of material can result in a surprisingly large reduction in allowable working pressure.

- A useful rule of thumb is that pressure falls approximately with the square of the remaining thickness.
- A plate thinned to 90% of its original thickness has only about 81% of its original pressure-carrying capacity.

This equation evaluates the strength of the stayed surface.

The staybolt itself must also be capable of carrying the load imposed by the supported area. The strength of the staybolt is considered separately.

13.1.3 Maximum Allowable Load for Staybolts

The previous section considered the strength of the stayed plate.

A stayed surface can fail either because the plate is too weak for the spacing of the stays, or because the staybolts themselves are too weak to carry the imposed load.

The strength of the staybolt must therefore be evaluated separately.

Each staybolt supports the pressure acting on its tributary area. For a regular pattern of staybolts, the tributary area is approximately equal to the square of the stay pitch.

$$P_{load} = \frac{\pi \left(\frac{d}{2}\right)^2 S}{1.100p^2}$$

where

Symbol	Meaning
P	Maximum allowable working pressure
d	Diameter of the staybolt
p	Staybolt pitch (centre-to-centre spacing)
S	Maximum allowable stress value (11,300 psi in NBIC)

Notice that staybolt strength varies with the square of the diameter.

A small increase in staybolt diameter produces a significant increase in load-carrying capacity.

Conversely, staybolt spacing also appears squared in the equation. Increasing the spacing between staybolts increases the area supported by each stay and reduces the allowable pressure.

For a stayed surface, both the plate-strength equation and the staybolt-strength equation must be evaluated.

The allowable working pressure of a stayed surface is therefore determined by the weakest element in the load path. The plate between the stays, the attachment of the stay to the plate, and the stay itself must all be capable of resisting the imposed load. The allowable pressure is the smallest value produced by the applicable calculations.

Chapter 14

Properties of Water and Steam

It takes about 800,000 kJ of energy to get a steam engine from cold start to working pressure. This amount of energy would power a house for 7 days, run a 1.5 kW electric heater for 150 hours, run a 100 horsepower engine for 3 hours, drive a car for 150 to 200 miles or lift a 1000 kg mass against gravity to a height of 80 km. And that's just getting the engine ready to roll. A working traction boiler is already a large energy reservoir before it does a single stroke of useful work.

An energy input of 800,000 kJ (≈ 222 kWh) is comparable to the total stored energy in three to four large modern electric-vehicle battery packs. Most contemporary passenger EVs carry batteries in the 60–80 kWh range, while even large long-range vehicles rarely exceed 100 kWh of usable capacity. It is also roughly equivalent to the energy stored in nearly half a million wooden matches — counting only the wood, not the match heads.

Modern lithium-ion battery packs achieve pack-level volumetric energy densities on the order of 300–400 Wh/L once structure, cooling, and protection systems are included. 222 kWh corresponds to roughly 550–740 litres of battery volume. For comparison, a modern Toyota Camry has a 428L trunk capacity. On a typical home Level-2 charger (7–11 kW), charging 222 kWh would take 20–30 hours of continuous charging.

The sections that follow provide a guided progression from the familiar to the slightly more technical. Starting with the basic terms used in steam work, they build a simple picture of how water turns into steam, and then put it all to work in a few concrete examples. By the end, the energy required to warm-up a boiler won't feel mysterious—it'll just be a sequence of sensible steps with sensible numbers attached.

14.1 Core Quantities Used in Steam Work

Steam and boiler calculations rely on a small set of physical quantities. Students will see these repeatedly in warm-up problems, firing-rate estimates, and steam-table work.

- Mass — amount of water or steam
- Volume — water space, steam space, tender, wagon
- Temperature — sensible heat, saturation temperature
- Pressure — boiler pressure, steam-table lookup
- Energy — heat added or removed
- Power — rate of heat transfer
- Specific heat & latent heat — how water stores energy
- Specific volume — why small steam masses fill large spaces

These eight quantities form the backbone of all boiler physics.

14.2 Units Used in SI and Imperial Systems

The machines discussed here were conceived in a world of inches and pounds, long before the widespread adoption of SI units. The physics that governs their behaviour, however, is most clearly expressed in kilograms, metres, and seconds. As a result, this document necessarily lives in both worlds: historical dimensions are presented as originally specified, while analytical discussions convert those quantities into SI form. Any apparent mixing of unit systems reflects this historical reality rather than inconsistency.

Historical boiler pressures were measured and reported using gauge instruments, and are therefore understood as gauge pressures (PSIG), referenced to local atmospheric pressure. In this document, pressures derived from historical sources are treated in the same way. When required for thermodynamic analysis, gauge pressures are converted to absolute pressure by adding atmospheric pressure; when analysing forces, flow, and momentum, gauge pressure is used directly, as only pressure differences are physically relevant. This distinction is made explicit where it affects the analysis.

14.2.1 Mass

- SI: kilogram (kg)
- Imperial: pound-mass (lb)

14.2.2 Volume

- SI: liter (L), cubic meter (m³)
- Imperial: gallon (US gal), cubic foot (ft³)

Boiler capacity and steam-space volume are always given in these units.

14.2.3 Temperature

- SI: degrees Celsius (°C), kelvin (K)
- Imperial: degrees Fahrenheit (°F), Rankine (°R)
- $T_{Kelvin} = T_{Celsius} + 273$
- $T_{Rankine} = T_{Fahrenheit} + 459.670$

Key point: Δ_T uses K or °R (°C and °F cannot be mixed directly).

14.2.4 Pressure

- SI: kilopascal (kPa), bar
- Imperial: pounds per square inch (psi)
- 1 kPa = 100 bar
- 1 bar = 14.504 psi

Steam tables use absolute pressure (relative to a perfect vacuum); boiler gauges show gauge pressure (relative to atmospheric pressure).

14.2.5 Energy

- SI: joule (J), kilojoule (kJ), megajoule (MJ)
 - $F = M \cdot A$ (Newton's second law)
 - $1 \text{ N} = 1 \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$
 - $1 \text{ J} = 1 \text{ m} \cdot \text{N} = 1 \frac{\text{kg} \cdot \text{m}^2}{\text{s}^2}$
- Imperial: British thermal unit (BTU)
 - $1 \text{ BTU} = 1055.056 \text{ J}$

Used for sensible heat, latent heat, and preheating energy.

Intuitively, 1 joule is the energy required to:

- lift a small apple about 100 cm (40 inches) against gravity
- operate a 1-watt device for 1 second
- raise the temperature of 1 gram of water by about 0.239°C

1 BTU is the amount of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit at standard pressure.

14.2.6 Power

- SI: watt (W), kilowatt (kW)
- Imperial: BTU/h, boiler horsepower (BHP) $1 \text{ BHP} = 33,475 \text{ BTU/h} = 9.81 \text{ kW}$.

Intuitively, energy is the capacity to do work, while power is the rate at which that work is done or energy is transferred.

14.2.7 Heat

14.2.7.1 Specific Heat

- SI: kJ/(kg·K)
- Imperial: BTU/(lb·°F)

Used in all heat calculations: $Q = m \cdot c \cdot \Delta_t$ where Q is energy, m is mass, c is a coefficient determined by the type of mass, and Δ_t is the change in temperature.

Material	Phase	Specific Heat kJ/kg·°C	Temp Range approx.
Water	Solid (ice)	2.1	< 0 °C
Water	Liquid	4.18	0–100 °C
Water	Gas (steam)	2.0	> 100 °C
Steel	Solid	0.49	< 1500 °C
Steel	Liquid	0.80	~1500–2800 °C
Steel	Gas (vapor)	1.0	> 2800 °C

14.2.7.2 Latent Heat

- SI: kJ/kg
- Imperial: BTU/lb

Latent heat of fusion: used when a solid changes phase to liquid.

Latent heat of vaporization: used when a liquid changes phase to vapor

Phase Change	Water		Steel	
	Heat	Temp	Heat	Temp
Fusion	334 kJ/kg	0 °C	247 kJ/kg	1538 °C
Vaporization	2257 kJ/kg	100 °C	6090 kJ/kg	2861 °C

14.2.8 Specific Volume

- SI: m³/kg
- Imperial: ft³/lb

Explains why tiny steam masses occupy large volumes.

Specific volume is the inverse of density; thermodynamics prefers it because energy and state equations are cleaner when written per unit mass.

14.2.9 Unit Table

Quantity	SI Unit	Imperial Unit	Notes
Mass	kg	lb	Used in all heat calculations
Volume	L, m ³	gal, ft ³	Boiler capacity, steam space
Temperature	°C, K	°F, °R	ΔT uses K or °R
Pressure	kPa, bar	psi	Steam tables use absolute
Energy	kJ, MJ	BTU	Warm-up energy, latent heat
Power	kW	BTU/h, BHP	1 BHP = 9.81 kW
Specific heat	kJ/kg·K	BTU/lb·°F	Water ≈ 4.18 kJ/kg·K
Latent heat	kJ/kg	BTU/lb	Steam formation
Specific volume	m ³ /kg	ft ³ /lb	Key for pressure rise

14.3 Steam tables

Steam tables give the thermodynamic properties of water and steam at different temperatures and pressures. Every table is built around three core ideas:

- Saturation — the boundary between liquid water and steam
- Phase — whether the substance is liquid, vapor, or a mixture
- Property sets — the values needed for energy and volume calculations

Steam tables are not derived from simple formulas; they are compilations of experimentally determined data. Over limited ranges, however, portions of the data can be approximated numerically, allowing tabulated values to be represented by fitted equations for computational use.

How to Read Steam Tables

14.3.1 Identify the table type

- Saturated table: use when water is boiling (T and P linked).
- Superheated table: use when steam is hotter than saturation.
- Compressed water table: rarely needed in boiler work.

14.3.2 Convert gauge pressure to absolute

- $P_{abs} = P_{gauge} + 101.300 \text{ kPa}$ (or 14.7 psi).

14.3.3 In the saturated table

- Find the row for your pressure or temperature.
- numerically

$$T_{sat(P)} \rightarrow 100 + 35.400 \ln P$$

- Read: $v_f, v_g, h_f, h_{fg}, h_g$ where the subscripts f and g stand for fluid and gas.
- Latent heat: $h_{fg} = h_g - h_f$.

14.3.4 For wet steam (quality x)

- $h = h_f + x \cdot h_{fg}$
- $v = v_f + x \cdot (v_g - v_f)$
- Numerically,

$$v_{v(P)} \rightarrow \frac{0.004(T_{sat(P)} + 273)}{P}$$

$$H_{v(P)} \rightarrow 2257 - 2.300(T_{sat}(P) - 100)$$

The factor x applies only in the two-phase (wet steam) region where liquid water and steam coexist at saturation conditions. Its value ranges from 0 (dry steam) to 1 (wet steam).

14.3.5 In the superheated table

- Start with pressure section.
- Move across to the temperature column.
- Read h , u , v for superheated vapor.

14.3.6 Common mistakes to avoid

- Using gauge pressure instead of absolute.
- Mixing SI and Imperial units.
- Confusing h_f (liquid) with h_g (vapor).
- Assuming latent heat is constant.
- Misreading v_g (steam volume) by orders of magnitude.

14.4 Numerical approximation

Accounting for warm-up, boiling, pressurization at the boiling point, and pressurization to the operating pressure, the system's response can be modeled as a piecewise process in which added energy raises temperature and pressure over distinct regimes.

14.4.1 Piecewise numerical model

This model describes the three physical stages a boiler goes through as it warms from ambient temperature to operating pressure. Each stage corresponds to a distinct thermodynamic regime.

$$T_{(P_{set}, T_0, V_s, m_w, m_s, q)} \rightarrow \begin{cases} T_0 & \text{if } q < 0 \\ T_0 + \frac{q}{C_{warm}} & \text{if } 0 \leq q < q_1 \\ T_{sat}(1) & \text{if } q_1 \leq q < q_2 \\ T_{sat}(P(q)) & \text{if } q_2 \leq q < q_3 \\ T_{sat}(P_{set}) & \text{if } q \geq q_3 \end{cases} \text{ where } \begin{cases} C_{warm} \rightarrow m_w \cdot c_w + m_s \cdot c_s \\ q_1 \rightarrow C_{warm} \cdot (T_{sat}(1) - T_0) \\ \Delta_q \rightarrow \frac{V_s}{v_v(1)} \cdot H_v(1) \\ q_2 \rightarrow q_1 + \Delta_q \\ q_3 \rightarrow q_2 + C_{warm} \cdot (T_{sat}(P_{set}) - T_{sat}(1)) + \frac{V_s \cdot H_v(P_{set})}{v_v(P_{set})} \\ P_{(q)} \rightarrow 1 + \frac{(P_{set}-1) \cdot (q-q_2)}{q_3-q_2} \\ c_w \rightarrow 4.190 \\ c_s \rightarrow 0.490 \\ T_{sat}(P) \rightarrow 100 + 35.400 \ln P \\ v_v(P) \rightarrow \frac{0.004(T_{sat}(P)+273)}{P} \\ H_{v(P)} \rightarrow 2257 - 2.300(T_{sat}(P) - 100) \end{cases}$$

The model might look complicated at first glance, but that's because it's a composition of several pieces. The first and last pieces ($q < 0$ and $q \geq q_3$) are there to catch out-of-bound inputs. The middle three pieces capture the ideas of warmup, conversion to steam, and raising pressure. The definition items to the right are there to provide all of the supporting ideas in one place.

The model is used to create the graph in [Fig. 36](#). But first,

$$bar_{(psig)} \rightarrow (psig + 14.700) \cdot 0.069$$

is a convenience function to convert PSI to bar and

$$T_{(q)} \rightarrow T(bar(125), 20, 0.340, 1190, 9980, q)$$

applies model parameters for set pressure, initial temperature, volume of steam space, mass of water space and mass of boiler steel to produce a simple function that maps energy onto temperature. That is, as the amount of energy increases, the result of the model determines the temperature that would be achieved by applying that amount of energy.

The plot is produced by connecting adjacent points in the following sequence with line segments.

$$\left(\left\langle \frac{q}{10666.700}, T(q) \right\rangle \mid q \in 0^{100000} 2000000 \right)$$

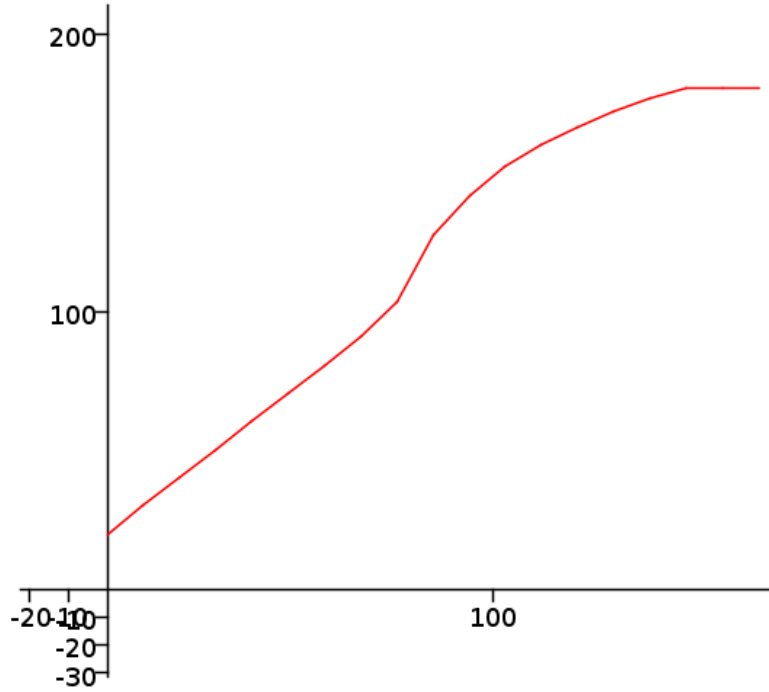


Fig. 36 Temperature vs Energy

The Y-axis is in degrees Celsius and the X-axis is scaled in increments of 10666.700 J units to accommodate the range 0 to 2 mJ in steps of 100 kJ.

14.5 Boiler warmup model

14.5.1 Warmup: Heating water + steel from ambient to 100 °C (1 bar)

Energy range: $0 \leq q < q_1$

At first, all the heat goes into raising the temperature of the water and the steel shell. Nothing boils yet. Pressure stays at 1 bar.

The required energy is:

$$q_1 \rightarrow C_{warm}(100 - T_0) \text{ where } C_{warm} \rightarrow m_w \cdot c_w + m_s \cdot c_s$$

Physical meaning: Heat is being applied to a large thermal mass. No steam is produced. No pressure rise occurs. The temperature increases.

14.5.2 Boiling at constant temperature: Filling the steam space at 1 bar

Energy range: $q_1 \leq q < q_2$

Once the water reaches 100 °C, temperature stops rising. All additional heat now goes into phase change—boiling water to fill the steam space with saturated steam at 1 bar.

The energy required is:

$$\Delta q = \frac{V_s}{v_v(1)} \cdot H_v(1)$$

$$q_2 = q_1 + \Delta q$$

Physical meaning: Temperature stays at 100 °C while enough 1-bar steam is generated to fill the steam space. This is pure latent heat—no temperature change.

14.5.3 Pressurization: Heating to the saturation temperature at P_{set}

Energy range: $q_2 \leq q < q_3$

After the steam space is filled at 1 bar, further heat does two things:

a. Sensible heating of the entire boiler

$$C_{\text{warm}} [T_{\text{sat}}(P_{\text{set}}) - 100]$$

This raises the temperature of:

- all the water
- all the steel
- and the existing steam

from 100 °C to the saturation temperature at the final pressure.

b. Additional steam generation at higher pressure

$$\frac{V_s}{v_v(P_{\text{set}})} H_v(P_{\text{set}})$$

At higher pressure, steam is denser, so the same steam space contains more mass. this additional mass of steam must be generated at the higher pressure.

Physical meaning: Pressure rises only after the steam space is full. Everything is heated to the higher saturation temperature and the extra steam mass required at that pressure is generated.

14.5.4 Final state: Boiler at operating pressure

Energy range: $q \geq q_3$

Once q_3 is reached, the boiler is:

- full of saturated steam at P_{set}
- water and steel at $T_{\text{sat}}(P_{\text{set}})$
- ready for work

Temperature stays fixed at the saturation temperature for that pressure.

Terms explained

$$T_{\text{sat}}(P) \rightarrow 100 + 35.400 \ln P$$

“Saturated steam” is steam that is in equilibrium with liquid water at a given pressure. That means:

- the water and the steam have the same temperature, and
- that temperature is fixed by the pressure, not by how much heat is added.

This is why boiling water stays at 100 °C at 1 bar: the system is pinned to the saturation curve.

If the pressure is increased on boiling water, the boiling point goes up. This is a fundamental property of water:

- At 1 bar, water boils at 100 °C
- At 2 bar, it boils around 120 °C
- At 10 bar, it boils around 180 °C

So the saturation temperature is a monotonically increasing function of pressure.

The T_{sat} function is a simple empirical approximation to the real steam-table saturation curve.

- The 100 anchors the curve at 1 bar:
- The $35.400 \ln P$ term gives the correct shape: -- slow rise at low pressure -- faster rise at moderate pressure -- flattening at high pressure

This logarithmic form is a common engineering shortcut because it mimics the curvature of real saturation-temperature data without needing full steam tables. It's not exact, but it's good enough for conceptual modeling, plotting, and energy-budget calculations.

$$H_{v(P)} \rightarrow 2257 - 2.300(T_{sat}(P) - 100)$$

This is the latent heat of vaporization: the amount of energy needed to turn 1 kg of saturated water into 1 kg of saturated steam at the same pressure.

At 1 bar, this value is about 2257 kJ/kg. That's the energy needed to break the liquid-phase bonds without raising temperature. This is why boiling takes so much heat even though the temperature stays fixed.

As pressure rises:

- the saturation temperature increases
- liquid water becomes more like the vapor phase
- the energy gap between liquid and vapor shrinks

So the latent heat gets smaller at higher pressure. This is a fundamental thermodynamic trend: near the critical point, latent heat goes to zero.

$$v_{v(P)} \rightarrow \frac{0.004(T_{sat}(P) + 273)}{P}$$

This is the specific volume of saturated steam at pressure P. Put simply, it tells how much space 1 kg of saturated steam occupies at a given pressure.

- At low pressure, steam is "fluffy" → large volume per kg
- At high pressure, steam is denser → smaller volume per kg

This is why the same steam space V_s contains more mass at higher pressure. Think of a balloon at atmospheric pressure and imagine its size at 300 feet below the surface of a lake.

Saturated steam always sits on the saturation curve:

- Pressure determines the saturation temperature
- Temperature and pressure together determine the density of the vapor

The expression $v_v(P) \propto \frac{T}{P}$ is essentially the ideal gas law in engineering form: $v = \frac{RT}{P}$

Steam is not a perfect ideal gas, but at boiler pressures it behaves close enough that this approximation captures the right trend:

- Increase pressure → volume per kg decreases

- Increase temperature → volume per kg increases slightly

The expression: $v_v(P) = 0.00417 \frac{T_{\text{sat}}(P)+273}{P}$ is a simplified engineering approximation derived from:

- the ideal gas law
- a fitted gas constant for water vapor
- the need to express temperature in Kelvin (hence +273)
- the desire for a compact formula that tracks real steam-table values reasonably well

The constant 0.00417 is a tuned coefficient that makes the curve match saturated-steam data around the 1–10 bar range.

$$\Delta_q \rightarrow \frac{V_s}{v_v(1)} \cdot H_v(1)$$

Δ_q is the energy needed to boil enough water at 1 bar to fill the steam space with steam at 1 bar.

$\frac{V_s}{v_v(1)}$ gives the mass of steam needed to fill the steam space at 1 bar.

- V_s = steam-space volume
- $v_v(1)$ = specific volume of saturated steam at 1 bar
- So $\frac{V_s}{v_v(1)}$ = kilograms of steam required At 1 bar, steam is very “fluffy,” so $v_v(1)$ is large and the mass is small.

$H_v(1)$ is the latent heat of vaporization at 1 bar—the energy needed to turn 1 kg of 100 °C water into 1 kg of 1-bar saturated steam. At 1 bar, this is about 2257 kJ/kg.

Δ_q uses 1-bar values because it describes the last thing that happens before pressure begins to rise. At this stage:

- the boiler is at 100 °C
- the pressure is still 1 bar
- all steam generated is 1-bar saturated steam

Pressure rise only begins after the steam space is full.

The model predicts only a very brief interval during which the boiler temperature remains at 100 °C before pressurization begins. This behavior is consistent with the underlying thermodynamics of the system.

First, once the water and steel structure reach 100 °C, no further sensible heating of these components occurs during the initial formation of saturated steam. Because the steel mass represents a substantial portion of the total thermal capacity during warm-up, the cessation of metal heating significantly reduces the energy required to maintain the system at 100 °C.

Second, the steam space volume is relatively small, and the specific volume of saturated steam at 1 bar is large. As a result, the total mass of steam required to fill the steam space is minimal. The latent heat needed to generate this small mass of vapor is correspondingly small, producing only a narrow energy interval between the completion of sensible heating and the onset of pressure rise.

Together, these factors explain why the model produces a very short plateau at 100 °C: the system transitions rapidly from saturated boiling at atmospheric pressure to the pressurization phase, with only a negligible dwell time at the boiling point.

Summary The model describes a boiler warming through three regimes—heating to 100 °C, boiling at constant temperature to fill the steam space, and then heating + generating denser steam to reach the final pressure—each with its own clean, physically meaningful energy requirement.

Pressure			T_{sat}		H_v	
psig	bar	psia	°C	°F	kJ/kg	BTU/lb
100	7.91	114.7	170	338	2048	880
105	8.25	119.7	172	342	2042	877
110	8.60	124.7	174	345	2036	874
115	8.94	129.7	176	349	2030	871
120	9.28	134.7	178	352	2024	868
125	9.63	139.7	180	356	2018	865

14.6 Worked Example: How Long Does It Take to Boil a Kettle?

A simple, everyday problem that uses exactly the same physics as a boiler warm-up.

Step 1 — Identify the known quantities

- Mass of water:

$$M = 2.0 \text{ kg}$$

- Initial temperature:

$$T_{\text{initial}} = 20^\circ\text{C}$$

- Final temperature:

$$T_{\text{final}} = 100^\circ\text{C}$$

- Temperature rise:

$$\Delta T = T_{\text{final}} - T_{\text{initial}} = 100 - 20 = 80 \text{ K}$$

- Specific heat of water:

$$c \approx 4.18 \text{ kJ}/(\text{kg} \cdot \text{K})$$

- Heater power:

$$\dot{Q} = 2.0 \text{ kW} = 2.0 \text{ kJ/s}$$

Step 2 — Compute the energy required

Use sensible heat:

$$Q = m \cdot c \cdot \Delta T$$

$$Q = 2.0 \text{ kg} \cdot 4.18 \text{ kJ}/(\text{kg} \cdot \text{K}) \cdot 80 \text{ K}$$

$$Q \approx 2.0 \cdot 4.18 \cdot 80 \text{ kJ}$$

$$Q \approx 668.8 \text{ kJ}$$

We can round this to: $Q \approx 670 \text{ kJ}$

Step 3 — Convert energy and power into time

Time is energy divided by power:

$$t = 335 \text{ s}$$

Convert to minutes:

Result With a 2.0 kW kettle, heating 2.0 kg of water from 20 °C to 100 °C (with no losses) takes about:

$$t \approx 5.5\text{--}6\text{minutes}$$

Why this example matters This is the exact same structure you'll use for a boiler:

- compute $Q = m \cdot c \cdot \Delta T$ for the water mass,
- divide by the net heat rate $\dot{Q}$ to get time. The only difference at boiler scale is that m is hundreds of kilograms and $\dot{Q}$ comes from fuel and efficiency, not a neat 2 kW label on the side.

14.7 Raising Pressure in a Sealed Boiler

Once boiling begins, temperature and pressure follow the saturation curve. The entire water mass must be heated from $T_{\text{sat}}(0 \text{ psig})$ to $T_{\text{sat}}(P_{\text{target}})$: $Q_{\text{pressurize}} = m c (T_{\text{sat,target}} - T_{\text{sat,initial}})$

Latent heat contributes only a small amount because the steam space contains very little mass: $m_s = \frac{V_{\text{steam space}}}{v_g}$

14.7.1 Effect of Firing Rate

Increasing firing rate increases heat transfer $\dot{Q}$, reducing the time required to raise pressure even though the energy requirement is large.

14.7.2 Relating Firing Rate to Time

$$t = \frac{Q}{\dot{Q}}$$

This relation underlies all warm-up and pressure-rise calculations.

14.8 How a Boiler Heats: From Cold Water to Working Pressure

1. Heating Water Before Boiling

A cold boiler behaves like a large, heavy pot of water. All heat goes into raising the temperature of liquid water.

- Heat capacity of water is high: $c \approx 4.18 \text{ kJ/kg} \cdot \text{K}$.
- Temperature rise is slow and predictable.
- Pressure barely changes because liquid water expands very little.

The governing relation is: $Q = m \cdot c \cdot \Delta T$ Example: 100 kg of water heated from 20 °C to 100 °C requires about 33 MJ of heat. At a 50 kW firing rate, that's roughly 11 minutes just to reach boiling. Take-away: Before boiling, the boiler is sluggish. Lots of heat, slow temperature rise, almost no pressure.

2. Reaching the Boiling Point (0 psig)

At 100 °C (212 °F) the water reaches its saturation temperature at atmospheric pressure. From this point onward, temperature and pressure are locked together by the saturation curve. This is the transition into the "pressure-building" regime.

3. Heating During Boiling (Two-Phase Region)

Once boiling begins, the physics changes completely.

- Added heat no longer raises temperature much.
- Instead, it converts liquid water into steam.
- Steam occupies hundreds of times the volume of the same mass of liquid.
- The boiler volume is fixed, so pressure must rise.

The pressure–temperature relationship is governed by: $\frac{dP}{dT} = \frac{L}{T(v_g - v_f)}$ Because $v_g \gg v_f$, the slope is steep. A few degrees of temperature increase can mean tens of psi. Take-away: After boiling starts, pressure rises rapidly. This is the “live” part of boiler operation.

4. Time to Raise Pressure

Raising pressure from 0 psig to 50 psig requires:

- Only ~48 °C of temperature rise (100 °C → 148 °C)
- But a large amount of latent heat to generate the steam that forces pressure up

This stage is much faster than the pre-boil warm-up because the temperature rise is small, but the pressure response is large.

5. Foreshadowing Injectors: Why Steam Velocity Matters

Steam at boiler pressure has:

- Huge specific volume
- High speed of sound (~450–500 m/s)
- Nozzle velocities of 300–500 m/s

Water at the same pressure moves only ~40–50 m/s through a nozzle. This velocity difference is the foundation of injector operation: a high-velocity steam jet entrains water, condenses, and drives the mixture into the boiler. Take-away: The same physics that makes pressure rise quickly also makes steam extremely fast—fast enough to power an injector.

14.9 Worked Example: Heating a 25 BHP Traction Boiler From Cold to 100 psi

This example models a typical 25 BHP traction-engine boiler:

- Water capacity: 250 gal ($\approx$ 946 kg or 2,085 lb)
- Heating surface: 250 ft²
- Fuel: wood
- Initial condition: cold start, ~68 °F (20 °C)
- No steam usage: the boiler is not powering anything until 100 psi is reached
- Target pressure: 100 psi ($\approx$ 170 °C / 338 °F saturation temperature)

The heating process has two distinct phases:

- Heating liquid water from cold to first boil (0 psig)
- Raising pressure from 0 psig to 100 psig with no steam consumption

A third phase—fueling while working—belongs in the horsepower section and is not included here.

14.9.1 Aside — water space and steam space

The water space is the volume in the boiler occupied by water. The steam space, the volume above the water space, is occupied by steam. The sum of the two volumes is the volume of the boiler. We are going to be interested in the weight of water in the boiler as well as the weight of steam.

We will need several auxiliary functions. The first calculates the volume of a cylinder, which is the area of a circle times the length of the cylinder.

$$V_{cyl(D,L)} \rightarrow \left(\pi \left(\frac{D}{2} \right)^2 L \right)$$

The second function calculates the steam space, which lies above the water line. A transverse view of steam space shows the barrel as a circle and the water line as a horizontal chord. The area above the chord is called a circular segment. Knowing the radius R of the barrel and the perpendicular distance H from the chord to the boiler (along a radius intersecting the centre point of the chord),

$$A_{seg(R,H)} \rightarrow R^2 \cdot \cos^{-1} \left(\frac{R-H}{R} \right) - (R-H) \cdot \sqrt{2RH - H^2}$$

Multiplying the area of a circular segment by the length of a cylinder gives the volume of the segment projected along the cylinder.

$$V_{seg(D,H,L)} \rightarrow A_{seg} \left(\frac{D}{2}, H \right) \cdot L$$

14.9.2 Boiler volumes

To calculate the total boiler volume, calculate the volume of the barrel, the wrapper, and the dome; from the sum of these, subtract the volume of the tubes and the firebox.

$$V_{barrel} \rightarrow V_{cyl}(D_{barrel}, L_{barrel}) \text{ where } \begin{cases} D_{barrel} \rightarrow 30 \text{ in} \\ L_{barrel} \rightarrow 96 \text{ in} \end{cases}$$

$$V_{wrapper} = (V_{lower} + V_{upper}) \text{ in}^3 \text{ where } \begin{cases} V_{lower} \rightarrow H_{wrapper} \cdot L_{wrapper} \cdot W_{wrapper} \\ V_{upper} \rightarrow \frac{V_{cyl}(D_{wrapper}, L_{wrapper})}{2} \\ L_{wrapper} \rightarrow 48 \text{ in} \\ H_{wrapper} \rightarrow 31 \text{ in} \\ D_{wrapper} \rightarrow 31 \text{ in} \\ W_{wrapper} \rightarrow 31 \text{ in} \end{cases}$$

$$V_{dome} \rightarrow V_{cyl}(D_{dome}, H_{dome}) \text{ where } \begin{cases} D_{dome} \rightarrow 14 \text{ in} \\ H_{dome} \rightarrow 18 \text{ in} \end{cases}$$

$$V_{firebox} \rightarrow (L_{firebox} \cdot W_{firebox} \cdot H_{firebox}) \text{ in}^3 \text{ where } \begin{cases} L_{firebox} \rightarrow 44 \text{ in} \\ W_{firebox} \rightarrow 25 \text{ in} \\ H_{firebox} \rightarrow 33 \text{ in} \end{cases}$$

$$V_{flues} \rightarrow (V_{cyl}(D_{tube}, L_{tube}) \cdot N_{tube}) \text{ where } \begin{cases} N_{tube} \rightarrow 40 \\ D_{tube} \rightarrow 2 \text{ in} \\ L_{tube} \rightarrow 96 \text{ in} \end{cases}$$

$$V_{barrel}^{steam} \rightarrow V_{seg}(D_{barrel}, H_{steam}, L_{barrel} + L_{wrapper}) \text{ in}^3 \text{ where } \begin{cases} H_{steam} \rightarrow 7 \text{ in} \\ D_{barrel} \rightarrow 30 \text{ in} \\ L_{barrel} \rightarrow 93 \text{ in} \\ L_{wrapper} \rightarrow 48 \text{ in} \end{cases}$$

$$V_{steam} \rightarrow V_{barrel}^{steam} + V_{dome}$$

Volume	<i>inch</i> ³	<i>ft</i> ³
V_{barrel}	67858.401 in ³	39.270 ft ³
$V_{wrapper}$	64242.423 in ³	37.177 ft ³
$V_{firebox}$	36300 in ³	21.007 ft ³
V_{flues}	12063.716 in ³	6.981 ft ³
V_{dome}	2770.885 in ³	1.604 ft ³
V_{barrel}^{steam}	17674.336 in ³	10.228 ft ³
V_{steam}	20445.220 in ³	11.832 ft ³

Then

$$\begin{aligned} V_{boiler}^{total} &= (V_{barrel} + V_{wrapper} + V_{dome} - V_{firebox} - V_{flues}) \\ &= 86507.993 \text{ in}^3 \end{aligned}$$

$$\begin{aligned} V_{boiler} &= \frac{V_{barrel} + V_{wrapper} + V_{dome} - V_{firebox} - V_{flues}}{12^3} \frac{\text{ft}^3}{\text{in}^3} \\ &= 50.062 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} V_{boiler}^{steam} &= \frac{V_{steam}}{12^3} \frac{\text{ft}^3}{\text{in}^3} \\ &= 11.832 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} V_{boiler}^{water} &= (V_{boiler} - V_{boiler}^{steam}) \text{ ft}^3 \\ &= 38.231 \text{ ft}^3 \end{aligned}$$

$$\begin{aligned} V_{boiler}^{water} &= \left(V_{boiler}^{water} \cdot 6.229 \frac{\text{gal}}{\text{ft}^3} \right) \\ &= 238.132 \text{ gal} \end{aligned}$$

In SI:

$$\begin{aligned} V_{boiler}^{SI} &= (V_{boiler} \cdot 0.028) \text{ m}^3 \\ &= 1.418 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} V_{boiler}^{steam}^{SI} &= (V_{boiler}^{steam} \cdot 0.028) \text{ m}^3 \\ &= 0.335 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} V_{boiler}^{water}^{SI} &= ((V_{boiler} - V_{boiler}^{steam}) \cdot 0.028) \text{ m}^3 \\ &= 1.083 \text{ m}^3 \end{aligned}$$

14.9.3 Boiler mass

To calculate the total boiler mass, calculate the plate area of each boiler section, multiply by thickness to get plate volume and multiply by mass per unit of boiler plate to get section mass. The sections are the barrel, the front tube sheet, the wrapper, the throat sheet, the backhead, the dome and the tubes; subtract the holes in the front and rear tubesheets.

$$D_{mp} \rightarrow 0.284 \frac{\text{lb}}{\text{in}^3}$$

$$T_{bp} \rightarrow 0.375 \text{ in}$$

$$T_{tube} \rightarrow 0.135 \text{ in}$$

$$A_{barrel} = (\pi D_{barrel} L_{barrel}) \text{ in}^2 \text{ where } \begin{cases} D_{barrel} \rightarrow 30 \text{ in} \\ L_{barrel} \rightarrow 120 \text{ in} \end{cases}$$

$$A_{wrapper} = (A_{lower} + A_{upper}) \text{ in}^2 \text{ where } \begin{cases} A_{lower} \rightarrow 2(H_{wrapper} \cdot L_{wrapper}) \text{ in}^2 \\ A_{upper} \rightarrow \left(\frac{\pi D_{wrapper}}{2} L_{wrapper} \right) \text{ in}^2 \\ L_{wrapper} \rightarrow 48 \text{ in} \\ H_{wrapper} \rightarrow 31 \text{ in} \\ D_{wrapper} \rightarrow 31 \text{ in} \end{cases}$$

$$A_{throat} = \left(D_{wrapper} \cdot H_{wrapper} - \frac{\pi \left(\frac{D_{wrapper}}{2} \right)^2}{2} \right) \text{ in}^2 \text{ where } \begin{cases} L_{wrapper} \rightarrow 48 \text{ in} \\ H_{wrapper} \rightarrow 31 \text{ in} \\ D_{wrapper} \rightarrow 31 \text{ in} \end{cases}$$

$$A_{backhead} = \left(D_{wrapper} \cdot H_{wrapper} + \frac{\pi \left(\frac{D_{wrapper}}{2} \right)^2}{2} \right) \text{ in}^2 \text{ where } \begin{cases} L_{wrapper} \rightarrow 48 \text{ in} \\ H_{wrapper} \rightarrow 31 \text{ in} \\ D_{wrapper} \rightarrow 31 \text{ in} \end{cases}$$

$$A_{dome} = (\pi D_{dome} H_{dome}) \text{ in}^2 \text{ where } \begin{cases} D_{dome} \rightarrow 14 \text{ in} \\ H_{dome} \rightarrow 18 \text{ in} \end{cases}$$

$$A_{firebox} = 2(L_{firebox} \cdot H_{firebox} + W_{firebox} \cdot H_{firebox}) \text{ in}^2 \text{ where } \begin{cases} L_{firebox} \rightarrow 44 \text{ in} \\ W_{firebox} \rightarrow 25 \text{ in} \\ H_{firebox} \rightarrow 33 \text{ in} \end{cases}$$

$$A_{crown} = (L_{firebox} \cdot W_{firebox}) \text{ in}^2 \text{ where } \begin{cases} L_{firebox} \rightarrow 44 \text{ in} \\ W_{firebox} \rightarrow 25 \text{ in} \\ H_{firebox} \rightarrow 33 \text{ in} \end{cases}$$

$$A_{flues} = (N_{tube} \cdot (\pi D_{tube} L_{tube})) \text{ in}^2 \text{ where } \begin{cases} N_{tube} \rightarrow 40 \\ D_{tube} \rightarrow 2 \text{ in} \\ L_{tube} \rightarrow 96 \text{ in} \end{cases}$$

$$A_{flue}^{holes} = \left(2N_{tube} \cdot \pi \left(\frac{D_{tube}}{2} \right)^2 \right) \text{ in}^2 \text{ where } \begin{cases} N_{tube} \rightarrow 40 \\ D_{tube} \rightarrow 2 \text{ in} \end{cases}$$

$$A_{boiler} = (A_{barrel} + A_{wrapper} + A_{throat} + A_{backhead} + A_{dome} + A_{firebox} + A_{crown} - A_{flue}^{holes})$$

$$M_{boiler}^{lb} = (A_{boiler} \cdot T_{bp} \cdot D_{mp} + A_{flues} \cdot T_{tube} \cdot D_{mp})$$

Section	Plate Area	Plate Volume	Mass
Area	in^2	in^3	lbs
A_{barrel}	11309.734	4241.150	1204.487
$A_{wrapper}$	5313.345	1992.504	565.871
A_{throat}	583.616	218.856	62.155
$A_{backhead}$	1338.384	501.894	142.538
A_{dome}	791.681	296.881	84.314
$A_{firebox}$	4554	1707.750	485.001
A_{crown}	1100	412.500	117.150
A_{flues}	24127.432	3245.140	921.620
A_{flue}^{holes}	251.327	71.377	26.766
M_{boiler}^{lb}			3556.369

In SI:

$$M_{boiler} = \left(M_{boiler} \cdot 0.454 \right) \text{ kg}$$

$$= 1613.142 \text{ kg}$$

14.9.4 Phase 1 — Heating From Cold to First Boil (0 psig)

Energy required

Water mass:

$$M_{water} = \frac{V_{water} \cdot 10 \frac{\text{lb}}{\text{gal}}}{2.200 \frac{\text{lb}}{\text{kg}}}$$

$$= 1082.417 \text{ kg}$$

Temperature rise:

$$20^{\circ}\text{C} \rightarrow 100^{\circ}\text{C} \quad (68^{\circ}\text{F} \rightarrow 212^{\circ}\text{F})$$

Sensible heat:

$$Q_{water} = M_{water} \cdot c \cdot \Delta_T \text{ where } \begin{cases} c \rightarrow 4.180 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \\ \Delta_T \rightarrow 80 \text{ K} \end{cases}$$

$$= 361960.381 \text{ kJ}$$

$$Q_{boiler} = M_{boiler} \cdot c \cdot \Delta_T \text{ where } \begin{cases} c \rightarrow 0.490 \frac{\text{kJ}}{\text{kg}\cdot\text{K}} \\ \Delta_T \rightarrow 80 \text{ K} \end{cases}$$

$$= 63235.164 \text{ kJ}$$

$$Q_{required} = (Q_{water} + Q_{boiler})$$

$$= 425195.544 \text{ kJ}$$

Observed warm-up time: operators report ~2 hours to “lift the pin.”

Net power requirement

$$\dot{Q} = \left(\frac{Q_{required}}{7200 \text{ s}} \cdot 1 \frac{\text{kW}\cdot\text{s}}{\text{kJ}} \right)$$

$$= 59.055 \text{ kW}$$

This is the actual heat reaching the water and the boiler, not the heat released by the fuel.

What this implies about wood firing

Realistic field values:

- Wood LHV: 8–12 MJ/kg (3,500–5,200 BTU/lb)
- Boiler efficiency on wood: 30–45%

$$M_{poplar} \rightarrow 460 \frac{\text{kg}}{\text{m}^3}$$

Using mid-range values ($Q_{fuel} = 10000 \frac{\text{kJ}}{\text{kg}}$, $\eta = 0.350$ efficiency):

$$Q_{fuel} = \frac{Q_{required}}{\eta}$$

$$= 1214844.412 \text{ kJ}$$

$$M_{wood} = \frac{Q_{fuel}}{10000 \frac{\text{kJ}}{\text{kg}}}$$

$$= 121.484 \text{ kg}$$

$$\begin{aligned} M_{wood}^{lb} &= \left(M_{wood} \cdot 2.200 \frac{lb}{kg} \right) \\ &= 267.266 lb \end{aligned}$$

Phase 1 summary: A 25 BHP traction boiler warming from cold to first boil in ~2 hours is realistically burning just under 150 lb of wood per hour, depending on moisture and firing quality. At the point of boiling, approximately 300 lb of wood has been contributed, and whatever fuel remains in the firebox will contribute energy to the next phase.

14.9.5 Phase 2 — Raising Pressure From 0 psig to 100 psig

Once boiling begins, the physics changes:

- Temperature and pressure are locked by the saturation curve.
- Almost all added heat goes into latent heat (making steam), not temperature.
- The boiler is not venting and not using steam, so the steam space is compressed by newly generated steam.

Required auxiliary functions

$$\begin{aligned} \text{Convert PSIG to bar} \quad & bar_{(psig)} \rightarrow (psig + 14.700) \cdot 0.069 \\ \text{Temperature at pressure} \quad & T_{sat}(P) \rightarrow 100 + 35.400 \ln \frac{P}{1} \\ \text{Specific volume of vapor at pressure} \quad & V_v(P) \rightarrow \frac{0.004(T_{sat}(P) + 273)}{P} \\ \text{Latent heat of vaporization} \quad & H_v(P) \rightarrow 2257 - 2.300(T_{sat}(P) - 100) \end{aligned}$$

100 psi is 7.909 bar so use 8 bar.

Saturation temperature at 8 bar $\approx 170^\circ\text{C}$ (338 °F) (from the steam tables) or 173.612 C using the interpolative formula.

$$\Delta T = 170 - 100 = 70^\circ\text{C} \quad (338 - 212 = 126^\circ\text{F})$$

Heat for phase 2 includes sensible heat for both the water and the boiler as well as the latent heat required to produce a mass of steam sufficient to pressurise the steam space.

Recall the volumes:

$$M_{water} \rightarrow 1082.417 \text{ kg}$$

$$M_{boiler} \rightarrow 1613.142 \text{ kg}$$

$$\frac{SI}{V_{boiler}^{steam}} \rightarrow 0.335 \text{ m}^3$$

$$Q_{water}(P) = M_{water} \cdot c_w \cdot \Delta_t \text{ where } \begin{cases} c_w \rightarrow 4.180 \\ \Delta_t \rightarrow T_{sat}(P) - 100 \end{cases}$$

$$Q_{boiler}(P) = M_{boiler} \cdot c_s \cdot \Delta_t \text{ where } \begin{cases} c_s \rightarrow 0.490 \\ \Delta_t \rightarrow T_{sat}(P) - 100 \end{cases}$$

$$Q_{steam}(P) = M_{steam} \cdot h_{fg} \text{ where } \begin{cases} M_{steam} \rightarrow \frac{SI V_{boiler}^{steam}}{V_v(P)} \\ h_{fg} \rightarrow H_v(P) \end{cases}$$

$$\begin{aligned} Q_{phase2} &= (Q_{water}(8) + Q_{boiler}(8) + Q_{steam}(8)) \\ &= 394377.172 \text{ kJ} \end{aligned}$$

Breaking the three summands into individual values:

$$Q_{water}(8) \quad 333058.888 \text{ kJ}$$

$$Q_{boiler}(8) \quad 58186.018 \text{ kJ}$$

$$Q_{steam}(8) \quad 3132.267 \text{ kJ}$$

Phase 2 Summary: The energy requirement in Phase 2 is very similar to that in Phase 1. This is not surprising because Phase 1 raised water 80 degrees while Phase 2 raised it 70 degrees with an additional small amount of energy used to water to steam pressure.

Other factors to consider:

- the two hour time for Phase 1 includes building the fire. It takes 20 to 30 minutes from light-off to build a fire to its full energy production phase. In addition, a good operator will warm a boiler gently to reduce thermal shock.
- Phase 2 benefits from the use of steam-induced draft after 5 to 10 PSI is achieved.
- the boiler efficiency is subject to a more detailed analysis

The value for $Q_{steam}(8)$ requires some explanation. Raising boiler pressure does not require boiling all the water — only forming enough steam to occupy the available volume. It accounts for the energy necessary to fill the steam space with enough steam to pressurise the boiler.

14.9.6 Latent-heat component

In a sealed boiler, pressure rise is dominated by:

- the latent heat needed to generate steam
- the steam-space volume
- the enormous ratio v_g/v_f

Even a small mass of steam dramatically increases pressure because steam occupies hundreds of times the volume of liquid. For a typical traction boiler steam space (0.335 m^3 where $\begin{cases} gal_{US} \rightarrow 88.520 \\ gal_{imp} \rightarrow 73.700 \end{cases}$), the

latent-heat requirement to reach 100 psi is small compared to the sensible heat needed to raise the entire water and steel mass from 100 °C to 170 °C.

Practical result With no steam usage:

- The dominant energy requirement is the 70 °C (126 °F) temperature rise of the entire water mass.
- The latent-heat component is relatively small.
- Therefore, the time from 0 psig → 100 psig at the same firing rate is on the order of 1.5–2 hours, similar to the warm-up time.

Chapter 15 Boiler Water Treatment

The main objectives of boiler water treatment are to:

1. Prevent scale
2. Prevent corrosion
3. Control sludge
4. Prevent foaming and carryover
5. Maintain proper water chemistry

These effects improve efficiency, safety, steam quality, and boiler life.

15.1 Water Treatment Adjustments

The following rules provide a practical water-treatment guide for a steam traction boiler. If you remember only one section from this chapter, remember this one.

Sodium carbonate (washing soda or soda ash) can be used to address most water chemistry problems.

- If hardness is high, add sodium carbonate.
- If pH is low, add sodium carbonate.
- If alkalinity is low, add sodium carbonate.
- If TDS is high, perform a blowdown.

Because sodium carbonate affects hardness, pH, and alkalinity simultaneously, boiler water should be retested after treatment to ensure all parameters remain within their desired ranges.

The remainder of this chapter explains the measurements, the chemistry behind them, and the procedures used to obtain them.

15.2 Minimal Low-Cost Monitoring Kit

1. pH strips
2. Hardness test strips
3. Alkalinity test kit
4. TDS/conductivity meter

These four tests cover most of the important indicators for:

- Scale prevention
- Corrosion prevention
- Sludge control
- Carryover control
- General water chemistry control

15.3 Water Hardness

Water hardness is the concentration of dissolved calcium and magnesium salts in the water. These minerals are the primary cause of scale formation in boilers. As water is heated and steam is produced, hardness minerals can precipitate from solution and form deposits on boiler tubes, heating surfaces, and other internal components.

Scale acts as an insulator, reducing heat transfer and increasing fuel consumption. Severe scale formation can lead to overheating of boiler metal and reduced boiler life.

Hardness is typically reported in parts per million (ppm) as CaCO_3 .

15.3.1 Measuring Hardness

The simplest method for a steam traction boiler is to use hardness test strips. The strip is immersed in the water sample for the time specified by the manufacturer and then compared with a colour chart.

Hardness test kits based on titration may also be used. These generally provide more accurate results than test strips.

15.3.2 Interpreting Results

For practical traction-boiler operation, the following classifications are useful:

0–50 ppm	Low hardness
50–100 ppm	Moderate hardness
100–200 ppm	High hardness
Above 200 ppm	Very high hardness

For a steam traction boiler, hardness should be kept as low as practical. Lower hardness means less scale formation and reduced need for chemical treatment.

15.3.3 Treatment

The most common treatment for hardness in a steam traction boiler is sodium carbonate (Na_2CO_3), also known as washing soda or soda ash.

Sodium carbonate reacts with dissolved calcium salts and converts them into calcium carbonate sludge. The sludge can then be removed by blowdown rather than remaining as a hard scale that deposits on heating surfaces.

Adding sodium carbonate therefore:

- Reduces scale-forming hardness.
- Increases alkalinity.
- Raises pH.

Because sodium carbonate affects all three parameters, the boiler water should be retested after treatment.

15.4 pH

pH measures how acidic or alkaline the boiler water is.

For a steam traction boiler, the water should remain mildly alkaline. A pH between approximately 9 and 11 is generally preferred. Low pH increases the risk of corrosion, while excessively high pH may contribute to foaming and other water-quality problems.

pH is easily measured using pH test strips or a pH meter.

If pH is too low:

- Add sodium carbonate.
- Retest after treatment.

15.5 pH vs Alkalinity

pH and alkalinity are two different but related controls.

- pH measures how alkaline the water is.
- Alkalinity determines how much reserve capacity the water has to stay alkaline when conditions change.

To explain further, imagine a shallow shelf cut into a steep hillside.

- pH determines the height of a position on the shelf.
- Alkalinity measures the width of the shelf.

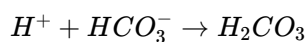
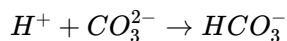
Acidic contamination pushes the position along the shelf, changing its height. If the shelf is wide, a change in position results in only a small change in height. If the shelf is narrow, the same change in position results in a much larger change in height as the position approaches the steeper slope.

For example, two boilers could both have a pH of 10.0, but one has low alkalinity and the other has high alkalinity. If acidic contamination enters:

- The boiler with low alkalinity will experience a rapid drop in pH.
- The boiler with high alkalinity will experience only a small change in pH.

The alkalinity acts as a chemical buffer, absorbing the effects of the contamination and helping maintain a stable pH. Chemically, this buffering action is provided primarily by hydroxide (OH^-), carbonate (CO_3^{2-}),

and bicarbonate (HCO_3^-) ions dissolved in the water. These species react with incoming acids before the acids can significantly change the pH. When acid enters the water, these species consume it:



as long as enough buffering species remain.

The key insight is: pH measures the current condition of the boiler water. Alkalinity measures how resistant that condition is to change. Testing becomes most useful when boiler-water chemistry is being actively adjusted and there is a desire to understand why pH is changing rather than simply observing that it has changed.

Adding washing soda: Na_2CO_3 does two useful things. First, it raises the shelf; that is, pH increases. Second, it widens the shelf; causing alkalinity to increase. So washing soda both:

1. Makes the water more alkaline.
2. Makes that alkalinity more resistant to change.

15.6 Protonation of the Carbonate Ion

Before continuing, a brief warning: what follows is one of those perfectly innocent chemistry questions that starts with "Where did the hydrogen ion come from?" and somehow ends forty minutes later with atoms, electrons, molecular polarity, and the nature of matter. If you're already happy with "carbonate picks up a hydrogen ion," feel free to move on. The dull roar of pages turning means you're not alone.

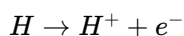
15.6.1 What Is a Proton?

A **proton** is a subatomic particle with a **+1 charge**.

A hydrogen atom has:

- 1 proton
- 1 electron

When a hydrogen atom loses its electron, it becomes a hydrogen ion:



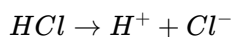
For the most common isotope of hydrogen, the remaining H^+ is simply a **proton**.

All protons are identical. A proton from hydrochloric acid (HCl) is indistinguishable from a proton that came from any other acid.

15.6.2 What Does the Notation Mean?

- H^+ = hydrogen ion (a proton)
- The **+** indicates a positive charge.
- Acids can donate H^+ ions to other substances.

For example:



Hydrochloric acid releases a proton (H^+) and leaves behind a chloride ion (Cl^-).

15.6.3 What Is Protonation?

Protonation is the process of adding a proton (H^+) to a molecule or ion.

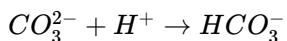
Simple definition:

Protonation = gaining H^+

The opposite process is **deprotonation**, which means losing H^+ .

15.6.4 Protonation of Carbonate

The carbonate ion can accept a proton:



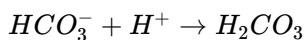
- CO_3^{2-} is the **carbonate ion**.
- H^+ is the **proton**.
- HCO_3^- is the **bicarbonate (hydrogen carbonate) ion**.

In simple terms:

Carbonate picks up a proton and becomes bicarbonate.

15.6.5 The Next Step: Formation of Carbonic Acid

Bicarbonate can accept another proton:

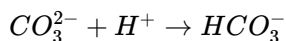


- HCO_3^- is the bicarbonate ion.
- H_2CO_3 is **carbonic acid**.

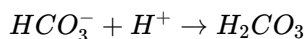
This is a second protonation step.

15.6.6 Summary

1. Acids release protons (H^+).
2. A proton is essentially a hydrogen atom that has lost its electron.
3. Protonation means adding H^+ to a molecule or ion.
4. Carbonate is protonated to form bicarbonate:



5. Bicarbonate can be protonated again to form carbonic acid:

**15.7 Determining the Alkalinity Endpoint**

The alkalinity endpoint is reached when enough acid has been added to consume the water's buffering capacity. Once these substances have been neutralized, the water has lost its ability to resist further decreases in pH.

The most accurate method of determining the endpoint is to use a pH meter. A measured sample of boiler water is placed in a container and a standard acid, usually sulfuric acid or hydrochloric acid, is added slowly while the sample is stirred. The pH is monitored continuously. For a total alkalinity determination, the endpoint is reached when the pH falls to approximately 4.5. The volume of acid required to reach this pH is then used in the alkalinity calculation.

A simpler and more traditional method uses an indicator dye such as methyl orange. A few drops of indicator are added to the boiler-water sample before the acid is introduced. The indicator changes colour

as the pH decreases. The endpoint is reached when the solution changes from yellow to a persistent orange-red colour, which corresponds approximately to a pH of 4.5. The volume of acid added up to that point is recorded and used to calculate the alkalinity.

The test process is called titration: a method of chemical measurement in which a reagent of known concentration is added to a sample until a defined endpoint is reached, allowing the concentration of the substance being measured to be determined.

Commercial alkalinity test kits operate on exactly the same principle. The sample is treated with an indicator and then titrated with a standardized acid solution. The endpoint is identified by a colour change, and the number of drops of acid required is converted directly into alkalinity expressed as parts per million as calcium carbonate (ppm as CaCO_3).

Returning to the shelf analogy, the endpoint represents the point at which the entire shelf has been crossed. The acid has consumed all of the available buffering capacity. Water with low alkalinity reaches the endpoint after only a small amount of acid is added, whereas water with high alkalinity requires a much larger amount of acid before the endpoint is reached. Thus, the volume of acid required to reach the endpoint is a direct measure of the water's buffering capacity.

15.8 Determining alkalinity

Alkalinity is measured in **parts per million (ppm) as CaCO_3** . For a steam traction boiler, a practical target range is **100–300 ppm as CaCO_3** . Below about **100 ppm**, the boiler water has limited buffering capacity and may respond rapidly to acidic contamination. Above about **300 ppm**, the water may become more prone to foaming, carryover, and elevated dissolved solids.

To measure alkalinity, a standard acid such as **sulfuric acid (H_2SO_4)** or **hydrochloric acid (HCl)** is added drop by drop to a measured sample of boiler water. The acid gradually neutralizes the buffering chemicals in the water, primarily hydroxide, carbonate, and bicarbonate ions. When the alkalinity endpoint is reached, the volume of acid used is recorded.

Alkalinity is then calculated as:

$$A = \frac{V_a \cdot N \cdot 50000}{V_s} \text{ where } \begin{cases} A \rightarrow \text{alkalinity} \\ V_a \rightarrow \text{volume}_{\text{acid}} \\ N \rightarrow \text{normality}_{\text{acid}} \\ V_s \rightarrow \text{volume}_{\text{sample}} \end{cases}$$

For the common case of a **100 mL sample** titrated with **0.02 N acid**, the calculation simplifies to:

$$A = V_a \cdot 10$$

Examples:

10 mL acid = 100 ppm alkalinity
 15 mL acid = 150 ppm alkalinity
 20 mL acid = 200 ppm alkalinity
 25 mL acid = 250 ppm alkalinity

The greater the volume of acid required to reach the endpoint, the greater the alkalinity and the greater the water's ability to resist changes in pH.

15.9 Procedure for Determining Boiler-Water Alkalinity Using a Test Kit

This procedure assumes that a commercial alkalinity test kit is available and that the kit provides a standard acid reagent and an endpoint indicator.

15.9.1 Equipment

- Alkalinity test kit
- Clean sample container
- Boiler-water sample
- Measuring cylinder or test tube supplied with the kit

15.9.2 Procedure

1. Collect a representative sample of boiler water and allow it to cool to room temperature.
2. Fill the test tube with the volume of sample specified by the test kit instructions. Many kits use either a 50 mL or 100 mL sample.
3. Add the number of drops of indicator specified in the test-kit instructions. This is typically a small fixed quantity, such as 2 to 5 drops, and does not vary from sample to sample.
4. Gently mix the sample to distribute the indicator.
5. Add the standard acid reagent one drop at a time while gently swirling the sample after each drop.
6. Continue adding acid until the indicator changes colour permanently. For most total alkalinity tests, the endpoint is indicated by a colour change corresponding to a pH of approximately 4.5.
7. Record the total number of drops or the total volume of acid required to reach the endpoint.

15.9.3 Calculating Alkalinity

Commercial alkalinity test kits are usually calibrated so that the number of drops of acid required to reach the endpoint can be converted directly to alkalinity. The conversion factor is supplied by the manufacturer and is based on the acid concentration, sample size, and drop volume. In some kits, each drop corresponds to a fixed alkalinity value such as 10 ppm as CaCO_3 . In other kits, the drop count must first be converted to a volume of acid before the alkalinity equation can be applied.

15.10 Total Dissolved Solids (TDS)

TDS limits vary widely between boilers and treatment programs. Operators should establish a baseline reading and monitor trends over time. A steadily rising reading indicates increasing concentration of dissolved solids and the eventual need for blowdown.

A TDS meter does not directly measure dissolved solids. Instead, it measures the electrical conductivity of the water and then estimates the concentration of dissolved solids from that measurement.

Pure water is a poor conductor of electricity. When minerals and salts dissolve in water, they form ions that carry electrical current. As the concentration of dissolved ions increases, the conductivity increases.

Examples of dissolved substances that contribute to TDS include:

- Sodium carbonate (Na_2CO_3)
- Sodium sulfate (Na_2SO_4)
- Sodium chloride (NaCl)
- Calcium salts
- Magnesium salts
- Various boiler-treatment chemicals

The TDS meter reports the estimated concentration of dissolved solids, usually in parts per million (ppm).

For a steam traction boiler, TDS is useful because it indicates how concentrated the boiler water has become. As steam is produced, pure water leaves the boiler while most dissolved solids remain behind. The concentration of dissolved solids therefore increases with time.

A rising TDS reading indicates that dissolved salts are accumulating in the boiler water. Excessive TDS can contribute to foaming, carryover, and the deposition of solids. When TDS becomes excessive, blowdown is used to remove a portion of the concentrated boiler water and replace it with fresh feedwater.

Unlike a hardness test, which measures specific scale-forming minerals, a TDS meter measures the combined effect of all dissolved ionic substances in the water. It therefore provides a general indication of water concentration rather than the concentration of any particular chemical.

15.11 Summary

A simple traction-boiler water treatment program can be managed using four measurements:

Measurement	Purpose	Typical Action
Hardness	Detect scale-forming minerals	Add sodium carbonate
pH	Detect corrosion risk	Add sodium carbonate
Alkalinity	Measure buffering capacity	Add sodium carbonate
TDS	Measure concentration of dissolved solids	Blow down boiler

By regularly monitoring these four values, boiler water can be maintained in a condition that minimizes scale, corrosion, foaming, and carryover.

Chapter 16

Injector Fundamentals

16.1 What an Injector Does

An injector uses steam from the boiler to force water into the boiler, against boiler pressure, with no moving mechanical parts.

An injector works because it converts pressure into momentum in the steam, transfers that momentum to water, and then converts it back into pressure.

16.2 The Intuition

If a hole is opened in the steam space of a boiler, steam escapes at very high velocity. Because steam is compressible, the pressure drop causes it to expand and accelerate until the flow becomes choked, after which the escape velocity is limited to approximately the speed of sound.

If a second hole is opened in the water space, water also escapes, but at a much lower velocity. Liquid water is effectively incompressible, so the pressure drop does work directly on the mass of water, converting pressure energy into kinetic energy according to Bernoulli's relation. The resulting velocity is set by the available pressure difference and the density of the water, and is typically only tens of metres per second.

Although steam and water escape at very different speeds, both openings experience the same boiler pressure. If the steam space and water space are connected together with a simple conduit such as a gauge glass, no sustained motion results. The pressures equalize, forces balance, and no mechanism exists to convert pressure into net momentum.

Replacing the gauge glass with an injector changes the situation fundamentally. An injector does not merely connect two regions of equal pressure; it forces steam to pass through a nozzle, deliberately converting pressure into velocity. The resulting high-velocity steam jet carries significant momentum. When this steam condenses upon contact with cold water, its velocity collapses and that momentum is transferred to the water. The combined jet then enters a diffuser, where velocity is converted back into pressure.

In this way, the injector exploits the different ways in which steam and water respond to a pressure drop. Steam supplies high velocity through compressible expansion, while water accepts transferred momentum and recovers pressure. A simple connection cannot produce motion because it transmits only pressure; an injector produces motion because it manufactures momentum and then recovers it as pressure.

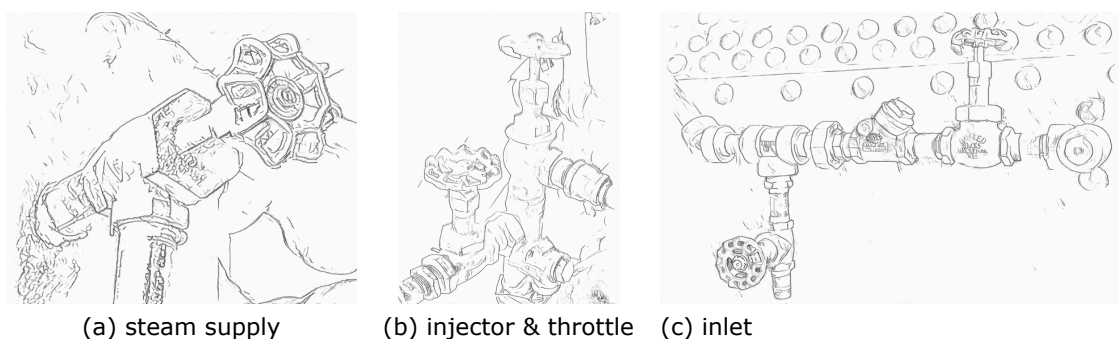


Fig. 37 Injector circuit

[Fig. 37](#) shows how an injector is plumbed into the boiler.

- steam supply from dome or wagon top with isolation valve
- injector with steam throttle, water throttle and overflow check
- inlet with inspection tee, isolation valve, check valve, and cheater

Steam is supplied from the dome or wagon top through an isolation valve. [@fig:figcic

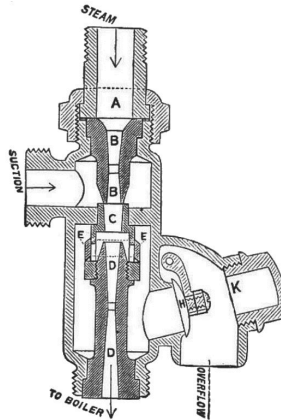


Fig. 38 Penberthy injector

[Fig. 38](#) is cross-sectional drawing of a Penberthy steam injector, showing the internal flow paths and labeled parts:

- A. steam inlet
- B. Converging steam nozzle
- C. Combining cone where steam entrains water
- D. delivery cone leading toward the boiler
- E. Overflow passages
- F. K — Overflow valve assembly

The diagram illustrates how high-velocity steam from the top nozzle (A–B) creates a vacuum that draws water in from the suction side, mixes it in the combining cone (C), and then forces it through the delivery cone (D) into the boiler once condensation restores pressure balance. The overflow valve (K) vents excess water or steam during startup.

16.3 How the Overflow Check Valve Works

In [Fig. 38](#), the overflow system consists of:

E — Overflow passages and H/K — Overflow valve assembly

This assembly is the injector’s safety and priming system. It has one job:

Let water/steam escape when the injector is not yet “picked up,” but automatically close once the injector begins delivering water to the boiler.

Here’s the sequence.

1. Startup: Steam enters the steam nozzle (A → B). When you first crack the steam valve: High-velocity steam shoots down the steam nozzle (A → B). This creates a partial vacuum in the combining cone (C). That vacuum begins to draw water from the suction side. But at this moment: The steam jet is not yet fully condensed. The mixture is chaotic: slugs of water, slugs of steam. Pressure in the delivery cone (D) is nowhere near boiler pressure. So the injector cannot push water into the boiler yet.
2. The overflow valve is OPEN during this phase. Because the injector is not yet “working,” the pressure in the combining cone (C) and delivery cone (D) is:
 - below atmospheric, or
 - oscillating, or
 - not high enough to lift the boiler check valve

So the overflow valve (H/K) stays open. This allows:

- excess steam,

- uncondensed steam,
- water slugs,
- or air

to escape through the overflow passages (E). This is the “spitting” or “overflowing” you see when starting an injector. If the overflow valve did not open, the injector would never prime.

3. The injector “picks up” — condensation becomes complete. As the water flow stabilizes: The steam jet condenses completely inside the combining cone (C). This sudden condensation collapses the steam volume. The mixture accelerates through the delivery cone (D). Velocity is converted into pressure. At this moment, the injector transitions from “spitting” to “working.”
4. The overflow valve CLOSES automatically. Once the pressure in the delivery cone (D) rises above atmospheric: The overflow valve (H/K) is pushed shut by the pressure differential. The injector stops discharging through the overflow. All flow is now directed toward the boiler check valve. This is the moment when the injector becomes silent and smooth. The overflow valve is now acting as a check valve, preventing backflow.
5. If the injector loses its pickup, the overflow valve reopens. If anything interrupts the condensation process:
 - water supply falters
 - steam pressure fluctuates
 - scale or debris disrupts the jet
 - operator throttles incorrectly

then the pressure in the delivery cone collapses. When that happens:

- The overflow valve reopens
- The injector begins “spitting” again

The operator knows instantly that the injector has dropped out. This prevents boiler pressure from forcing water backward through the injector.

16.3.1 What happens if the overflow check valve is stuck closed when the steam valve is open?

In short, the circuit from steam to water becomes a closed loop, just like a gauge glass. Nothing moves.

16.3.2 Why does flow continue if it has started and the overflow check valve closes?

The boiler check valve opens and the overflow check valve closes because internal pressure is greater than atmospheric pressure. At this point, the injector is no longer a steam jet device; it is a pure water pump powered by the collapse of steam volume. And pumps do not need an open discharge to atmosphere.

16.4 The Three-Nozzle System

An injector has three functional stages:

- Steam nozzle
 - Expands steam to very high velocity (hundreds of m/s)
 - Steam jet entrains surrounding water
- Combining cone
 - Steam condenses inside the water stream
 - Momentum of the mixture increases
 - Pressure begins to recover
- Delivery cone
 - Converts velocity back into pressure

- Final pressure exceeds boiler pressure
- Water flows into the boiler

16.5 Velocity of water

Water escaping from the water space of a boiler is reduced in pressure. Bernoulli's relation expresses the conversion of pressure energy into kinetic energy: a pressure drop does work on a fluid, and that work appears as velocity, scaled by the mass density that must be accelerated.

We are working with bar as a unit of pressure, but bar is not a base-unit in SI. To convert bar to SI, we need conversion that looks like this:

$$bar_{si}(P) \rightarrow P \text{ bar} \cdot 100000 \frac{\text{kg}}{\text{bar} \cdot \text{s}^2 \cdot \text{m}}$$

Now Bernoulli's relation can be expressed as

$$v_{water}(P) = \sqrt{\frac{2\Delta P}{\rho}} \text{ where } \begin{cases} \Delta P \rightarrow bar_{si}(P) \frac{\text{kg}}{\text{m} \cdot \text{s}^2} \\ \rho \rightarrow 1000 \frac{\text{kg}}{\text{m}^3} \end{cases}$$

$$\text{and } v_{water}(8) = v_{water}(8) = 40 \frac{\text{m}}{\text{s}}$$

The resulting water velocity is small compared to steam velocity because liquids store pressure energy primarily as mass acceleration rather than compressible expansion.

16.6 Velocity of steam

At 100–150 psig:

- Saturated steam specific volume: ~0.2–0.3 m³/kg
- Speed of sound: ~450–500 m/s
- Nozzle exit velocity: 300–500 m/s

The steam supply nozzle of an injector operates under choked-flow conditions. As steam expands from boiler pressure, its velocity increases until it reaches the local speed of sound, beyond which further acceleration is impossible. The steam therefore enters the injector at approximately sonic velocity, providing the high momentum needed to entrain feedwater.

16.7 Condensation as a Power Source

Inside the combining cone:

- The steam jet condenses into the water
- The steam's enormous volume collapses
- Momentum is conserved
- The mixture's pressure rises sharply

This is why injectors can deliver water above boiler pressure.

16.8 Operating Sensitivities

Injectors depend on:

- Correct steam pressure
- Adequate water supply
- Clean cones
- Proper temperature (too hot → injector fails)
- No air leaks on the suction side

These sensitivities all trace back to the same physics: steam velocity, condensation, and momentum transfer.

16.9 Linking Back to Boiler Heating

The injector relies on the same physics as the rapid pressure rise when a boiler reaches the boiling point:

- Steam has enormous specific volume
- Steam accelerates to extreme velocities
- Condensation collapses that volume
- Pressure is recovered from velocity

The boiler's rapid pressure rise during boiling is the "other side" of the same phenomenon.

16.10 Low-Pressure vs High-Pressure Steam Injectors

16.10.1 Definitions

- **Low-pressure injector:** Designed to start and operate with **low boiler steam pressure**.
- **High-pressure injector:** Designed to operate efficiently at **high boiler steam pressure**.

The terms refer to the **boiler steam pressure range the injector can work over**, not the pressure delivered to the boiler.

16.10.2 Low-Pressure Injectors

16.10.2.1 Typical Pressure Range

- ~15–80 psi (sometimes up to ~100 psi depending on design)

16.10.2.2 Design Characteristics

- Larger steam nozzle
- Larger combining cone
- Larger water passages
- Gentler cone angles

16.10.2.3 Operating Characteristics

- Easy starting at low pressure
- Tolerant of cold feedwater
- Tolerant of minor scale or dirt
- Less sensitive to adjustment

16.10.2.4 Limitations

- Inefficient at high pressure
- Tendency to overflow above design pressure

16.10.2.5 Typical Applications

- Early locomotives
 - Traction engines
 - Stationary boilers
 - Systems with slowly rising boiler pressure
-

16.10.3 High-Pressure Injectors

16.10.3.1 Typical Pressure Range

- ~125–300+ psi (design dependent)

16.10.3.2 Design Characteristics

- Smaller steam nozzle
- Tighter combining cone throat
- Sharper delivery cone geometry
- More precise internal dimensions

16.10.3.3 Operating Characteristics

- High efficiency at rated pressure
- Smooth delivery at high boiler pressure
- Minimal steam waste once running

16.10.3.4 Limitations

- Difficult or impossible to start at low pressure
- Sensitive to:
 - Warm feedwater
 - Scale or dirt
 - Incorrect nozzle sizing

16.10.3.5 Typical Applications

- Later steam locomotives
- High-pressure stationary boilers
- Marine boilers
- Systems with steady operating pressure

16.10.4 Comparison Summary

Feature	Low-Pressure Injector	High-Pressure Injector
Starting pressure	Very low	Moderate to high
Steam nozzle size	Large	Small
Dirt/scale tolerance	High	Low
Feedwater temp tolerance	Good	Poor
Efficiency at pressure	Lower	Higher
Ease of starting	Easy	Difficult

16.11 Common Locomotive Practice

- Two injectors often fitted:
 - **Low-pressure injector** for starting and low-pressure operation
 - **High-pressure injector** for efficient running at road pressure
-

16.12 Key Principle

Injector pressure range is fixed by geometry:

- Steam cone diameter
- Combining cone throat
- Delivery cone shape

Changing pressure range requires **changing nozzles**, not valve adjustment.

Chapter 17

Piping

17.1 Pipe Markings and What They Mean

Manufactured pipe is marked with information that allows tradespeople, inspectors, and engineers to identify exactly what material has been installed. While the specific format varies by manufacturer, most carbon steel pipe contains a series of markings printed, stenciled, or rolled onto the outside surface.

A typical marking might look something like:

ABC PIPE
ASTM A106 GR B
ASME SA106 GR B
NPS 2 SCH 80
SMLS
HEAT 12345

17.1.1 Common Markings

Manufacturer Name

Identifies who produced the pipe.

ASTM / ASME Specification

Identifies the material standard. ASTM A106 and ASME SA106 are essentially the same material specification, with the ASME designation being adopted for pressure-retaining equipment and piping constructed under ASME codes.

Grade

Identifies the material grade. For example, Grade B is commonly used in steam and process piping.

NPS (Nominal Pipe Size)

Indicates the nominal pipe size, such as 1", 1-1/2", or 2".

Schedule

Indicates wall thickness, such as Schedule 40 or Schedule 80.

Manufacturing Method

May include designations such as:

- ERW (Electric Resistance Welded)
- SMLS (Seamless)
- EFW (Electric Fusion Welded)

Heat Number

A unique identifier that links the pipe back to the steel mill's production records and material test reports (MTRs).

17.1.2 Why the Heat Number Matters

Of all the markings on a pipe, the **heat number** is often the most important from a quality-control perspective.

During steel production, each batch (or "heat") of steel receives a unique number. The material properties, chemical composition, and test results for that batch are recorded on a **Material Test Report (MTR)**.

By matching the heat number on the pipe to the heat number on the MTR, an inspector can verify:

- The correct material was supplied.

- The pipe meets the required specification.
- The chemical composition is acceptable.
- Mechanical test results meet code requirements.

17.1.3 Why Pipefitters Should Care

A pipe marking is much more than a label. It tells you:

- What size the pipe is.
- How thick the wall is.
- What material it is made from.
- How it was manufactured.
- Which MTR belongs to it.

When pipe is cut into short pieces, good shops often transfer the heat number to each remaining piece so traceability is not lost. Once the markings are removed or painted over without being transferred, proving material compliance can become difficult or impossible.

17.1.4 Key Takeaway

The markings printed on a pipe are its identity card. They provide the information needed to confirm size, schedule, material specification, manufacturing method, and traceability back to the original Material Test Report. For work performed under ASME, CSA, or other quality systems, preserving these markings is often just as important as making a good fit-up or weld.

This process is known as **material traceability**.

The heat number is the link between the physical pipe and the documentation that proves its compliance. The document used for this purpose is the Material Test Report (MTR), which will be discussed in the next section.

17.2 Schedule 40 vs. Schedule 80

One of the first surprises for new pipefitters is that **nominal pipe size (NPS)** is not the actual inside or outside diameter. For a given NPS, the **outside diameter (OD) remains constant** regardless of schedule. As wall thickness increases, the **inside diameter (ID) decreases**, reducing flow area and increasing pressure capability.

The term "nominal" means the size is a designation rather than an actual measurement. For example, a 2" pipe does not measure 2" outside diameter or 2" inside diameter. It is simply identified as NPS 2, and the actual dimensions are defined by published standards.

For steam systems, the practical difference between Schedule 40 and Schedule 80 is usually:

- Schedule 80 has thicker walls and greater pressure tolerance.
- Schedule 80 is heavier and more expensive.
- Schedule 80 has a smaller internal flow area, which increases velocity for a given flow rate.
- Most low- and medium-pressure steam systems use Schedule 40 unless design conditions require the additional wall thickness.

17.2.1 Common Small-Bore Pipe Sizes

NPS	OD (in.)	Sch 40 Wall (in.)	Sch 40 ID (in.)	Sch 80 Wall (in.)	Sch 80 ID (in.)
1/2"	0.840	0.109	0.622	0.147	0.546
3/4"	1.050	0.113	0.824	0.154	0.742
1"	1.315	0.133	1.049	0.179	0.957
1-1/4"	1.660	0.140	1.380	0.191	1.278
1-1/2"	1.900	0.145	1.610	0.200	1.500
2"	2.375	0.154	2.067	0.218	1.939

Source dimensions from ASME B36.10 pipe schedules. 【1-d8d563】 【2-b99ff3】 【4-b548f6】

17.2.2 Internal Flow Area Comparison

The reduction in flow area is often more significant than people expect.

NPS	Sch 40 Area (in ²)	Sch 80 Area (in ²)	Reduction
1/2"	0.304	0.234	23.0%
3/4"	0.533	0.432	18.9%
1"	0.864	0.719	16.8%
1-1/4"	1.496	1.283	14.2%
1-1/2"	2.036	1.767	13.2%
2"	3.356	2.953	12.0%

Flow area calculated as $A = nD^2/4$ using the published inside diameters. 【1-d8d563】 【2-b99ff3】

17.2.3 Key Takeaway

Notice that while the OD never changes, a 1/2" Schedule 80 pipe has roughly **23% less flow area** than a 1/2" Schedule 40 pipe. The difference becomes less pronounced as pipe size increases, but even at 2" there is still about a **12% reduction in flow area**. This is why pipe schedule affects not only pressure rating but also fluid velocity and system performance.

Because a Schedule 80 pipe has a smaller internal diameter than a Schedule 40 pipe of the same nominal size, steam velocity increases for the same flow rate. A 1" Schedule 80 pipe carries steam about 20% faster than a 1" Schedule 40 pipe, while a 1/2" Schedule 80 pipe carries it about 30% faster. This increase in velocity results in greater pressure loss, noise, and potential erosion within the piping system.

Since velocity is inversely proportional to flow area:

$$V = \frac{Q}{A}$$

A reduction in area always results in an increase in velocity when flow rate remains constant.

17.3 Threaded Pipe Connections

Before welded systems became commonplace, much of the steam industry was built using threaded pipe. Even today, small-bore steam piping (typically 2" NPS and below) is frequently assembled using threaded fittings.

A threaded connection is created by machining a helical groove—called a **thread**—onto the outside of a pipe and the inside of a fitting. As the pipe is screwed into the fitting, the mating threads pull the components together and create a pressure-tight joint.

17.3.1 National Pipe Thread (NPT)

The most common thread form used in North America is **National Pipe Taper (NPT)**.

Unlike a machine bolt, which has straight threads, NPT threads are tapered. Both the male and female threads become slightly narrower toward the end. As the connection is tightened, the threads wedge together, creating the seal.

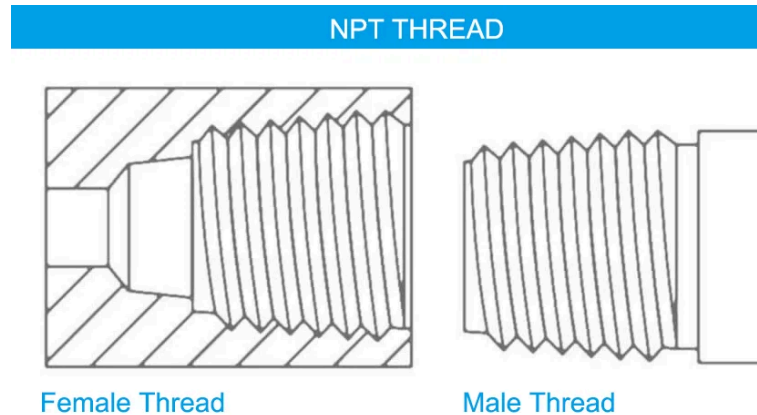


Fig. 39 NPT male and female thread

The taper is approximately 1 in 16, meaning the diameter changes by 1 inch over 16 inches of thread length.

17.3.2 How Threads Are Cut

Pipe threads are usually cut using a manual ratchet threader or a powered threading machine.

The process is straightforward:

1. Cut the pipe square.
2. Ream the inside to remove burrs.
3. Secure the pipe in the threader.
4. Apply cutting oil.
5. Advance the die head onto the pipe.
6. Cut until the thread reaches the proper length.
7. Clean and inspect the threads.

A properly cut thread will:

- Have a smooth finish.
- Show no torn or flattened crests.
- Allow hand-tight engagement for several turns.
- Tighten progressively as the taper engages.

17.3.3 Thread Engagement

A common misconception is that the seal occurs at the end of the pipe. In reality, the seal forms along the flanks of the tapered threads as they wedge together during tightening.

NPT threads are designed to seal through the tapered interference of the mating threads. As the joint is tightened, the thread flanks wedge together, producing metal-to-metal contact and slight deformation that forms the primary seal. Thread sealants such as PTFE tape or pipe dope are used to lubricate assembly and fill microscopic leak paths that remain due to manufacturing tolerances and surface roughness.

17.3.4 Schedule 40 vs. Schedule 80 and Threading

An interesting consequence of thicker pipe walls is that Schedule 80 pipe develops deeper, stronger threads than Schedule 40 pipe.

Because more metal remains beneath the thread root:

- Thread strength increases.
- Resistance to thread damage improves.
- The connection is generally better suited to higher-pressure service.

On smaller pipe sizes, this difference is easy to see when comparing freshly cut threads side by side.

This is one reason Schedule 80 threaded piping is often specified where pressure, temperature, or mechanical stresses exceed the limits of Schedule 40.

17.3.5 Thread Sealants

Although the tapered threads provide the primary seal, standard NPT threads contain microscopic leak paths caused by manufacturing tolerances and surface roughness.

Thread sealants serve two important purposes:

- Filling spiral leak paths.
- Lubricating the threads during assembly.

Common sealants include:

- PTFE (Teflon) tape
- Pipe dope (thread compound)
- PTFE tape combined with pipe dope

For steam service, the sealant must be rated for the system temperature and pressure.

It is worth noting the difference between standard NPT and NPTF (National Pipe Taper Fuel, commonly called Dryseal pipe thread). In NPTF connections, the thread roots and crests are designed to deliberately crush and deform into each other during tightening. This metal-to-metal deformation completely eliminates the spiral leak path, allowing for a mechanical "dry seal" without requiring tape or paste (though lubricant is still often used to ease installation).

17.3.6 Why Overtightening Is a Problem

New pipefitters are often tempted to tighten threaded joints as much as possible. Excessive torque can:

- Crack cast-iron fittings.
- Distort valve bodies.
- Damage thread profiles.
- Make future disassembly extremely difficult.

The objective is not maximum torque; it is proper thread engagement and sealing.

17.3.7 Galling in Threaded Joints

Galling is a form of severe adhesive wear in which two metal surfaces slide against one another under pressure and small portions of the two metals cold-weld together. As the joint continues to turn, these microscopic welds tear apart, transferring material between the threads. In practical terms, galling is a form of metal-to-metal seizure.



Fig. 40 Galling

Pipe dope and PTFE tape are not just sealants—they are also lubricants that reduce friction, prevent galling, and allow the tapered threads to seat properly.

A small amount of thread deformation is expected and desirable in an NPT joint. Galling is excessive, uncontrolled deformation that damages the threads.

17.3.8 Why Galling Occurs

Galling is promoted by:

- High contact pressure
- Lack of lubrication
- Repeated assembly and disassembly
- Similar metals rubbing together
- Soft, ductile materials

It is particularly common with:

- Stainless-steel fasteners
- Stainless threaded pipe fittings
- Brass and bronze components
- High-torque threaded connections

Carbon steel pipe generally experiences less galling than stainless steel, but it is not immune.

17.3.9 What It Looks Like

A galled thread often appears:

- Rough and torn
- Smeared or scored
- Covered with metallic debris
- Difficult or impossible to turn

In severe cases, the threads effectively seize together.

Many mechanics have experienced a stainless bolt that suddenly becomes impossible to turn in either direction. That is classic galling.

17.3.10 Why Pipefitters Care

When assembling threaded pipe, friction between the mating threads can become very high.

Without a lubricant:

- More torque is required.
- Threads can tear or deform.
- Proper engagement may not be achieved.
- Disassembly becomes difficult years later.

This is one reason thread compounds are valuable even when the threads themselves provide the primary seal.

17.3.11 How Pipe Dope and PTFE Tape Help

Thread sealants serve several functions:

1. Fill microscopic leak paths.
2. Lubricate the threads.
3. Reduce friction during assembly.
4. Minimize galling and thread damage.
5. Allow deeper thread engagement before excessive torque develops.

A lubricated NPT joint typically tightens farther than a dry joint using the same wrench force. The result is often a better mechanical seal and less damage to the threads.

17.3.12 Key Takeaway

A threaded connection seals because tapered male and female threads wedge together as they are tightened. The threads provide mechanical strength, while a thread sealant fills the microscopic leak paths that would otherwise allow steam, water, or air to escape. Proper thread cutting, adequate engagement, and avoiding overtightening are essential skills for reliable piping work.

Chapter 18 Valves

Pipe carries fluid. Fittings direct it. Valves control it.

A valve is a mechanical device installed in a piping system to start, stop, regulate, direct, or prevent the flow of a fluid. In steam systems, valves are used for isolation, throttling, pressure control, overpressure protection, and preventing reverse flow.

Selecting the correct valve is critical. A valve intended for on-off service may perform poorly when used for throttling, while a valve designed for regulation may be damaged if used as a simple stop valve.

Understanding the purpose and limitations of each valve type is an essential skill for anyone working with steam systems.

18.1 Basic Valve Components

While valve designs vary, most valves contain the same basic parts.

Body

The body is the main pressure-retaining component of the valve.
It contains the flow passage and connects the valve to the piping system.

Bonnet

The bonnet forms the cover of the valve body and provides support for the stem.

Stem

The stem transfers motion from the handwheel, lever, or actuator to the internal closure element.

Seat

The seat is the sealing surface against which the closure element closes.

Disc, Plug, or Ball

The closure element blocks, permits, or regulates flow.
The name depends on the valve type.

Packing

Packing prevents leakage around the moving stem. Packing glands can often be adjusted to compensate for wear.

18.2 Valve Position Indication

An operator should be able to determine whether a valve is open, closed, or partially open without having to guess. Many valve designs provide a visible indication of valve position.

Understanding these indications helps prevent operating errors and improves safety during maintenance and isolation procedures.

18.2.1 Valve Handles

Quarter-turn valves, such as ball valves and plug valves, typically use a lever handle.

The position of the handle indicates the position of the internal closure element.

When the handle is perpendicular to the pipe, the valve is closed. When the handle is parallel to the pipe, the valve is open.

Because the handle provides an immediate visual indication of valve position, ball valves are often preferred where quick verification is important.

18.2.2 Rising-Stem Valves

Many gate valves and globe valves use a rising stem.

As the valve opens, the stem moves outward from the valve body.

The amount of exposed stem indicates approximately how far the valve is open.

Advantages:

- Easy visual confirmation of valve position.
- Valve position can often be determined from a distance.

18.2.3 Non-Rising-Stem Valves

Some valves use a non-rising stem design.

In these valves, the stem rotates but does not move outward as the valve opens.

Because the stem does not change position, the operator must rely on the handwheel position, valve indicator, or operating records to determine the valve's status.

Non-rising stems are often used where headroom is limited.

18.2.4 Position Indicators

Some valves incorporate dedicated position indicators.

These may include:

- Pointer plates
- Mechanical indicators
- Colored markers
- Electrical limit switches

Position indicators are commonly found on:

- Actuated valves
- Motor-operated valves
- Control valves

- Remote-operated valves

18.2.5 Why Valve Position Matters

Many operating incidents occur because a valve is believed to be in one position when it is actually in another.

Before starting equipment or placing a system into service, operators should verify:

- The correct valve.
- The intended valve position.
- The actual valve position.

Never assume a valve is open or closed based solely on previous operation or labeling.

18.2.6 Key Takeaway

Good valve designs provide a visible indication of position. Lever-operated valves typically show position through the orientation of the handle, while rising-stem valves show position through stem movement. Operators should always verify valve position rather than relying on assumptions.

18.3 Bonnet Designs

The bonnet provides access to the internal components of a valve and supports the valve stem. Several bonnet designs are used in steam service.

18.3.1 Screwed Bonnet

In a screwed-bonnet valve, the bonnet threads directly into the valve body.

This design is simple and economical, and it is commonly found on smaller valves.

One disadvantage is that the bonnet usually provides only a limited wrenching surface. After years of service at elevated temperatures, the bonnet may become difficult to remove.

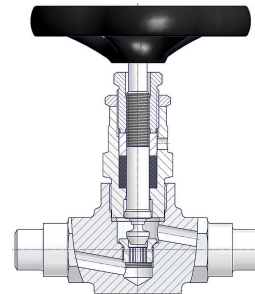


Fig. 41 Valve with screwed bonnet

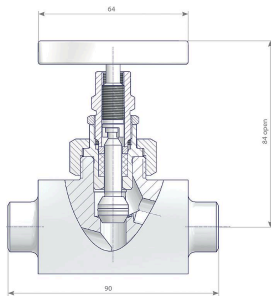


Fig. 42

Valve with union bonnet

18.3.2 Union Bonnet

In a union-bonnet valve, the body screws into the bonnet and is secured by a union nut. The union nut provides a larger wrenching surface and greater mechanical advantage during disassembly.

Many steam operators and restorers prefer union-bonnet valves because they can usually be dismantled more easily after years of service.

18.3.3 Why Bonnet Design Matters

Steam valves often operate at temperatures approaching 400°F (200°C) or higher. Repeated heating and cooling cycles can cause threaded components to become extremely tight.

Periodic disassembly is often required for:

- Inspection

- Cleaning
- Seat maintenance
- Packing replacement
- Long-term layup

With a screwed-bonnet valve, the relatively small wrenching surfaces may require considerable force during disassembly. Excessive force can damage wrench flats or, in extreme cases, distort the valve body.

Union-bonnet valves typically provide larger wrenching surfaces and allow disassembly with less risk of damage to the valve body.

For this reason, many experienced steam operators regard the union-bonnet design as more service-friendly, particularly on valves that are inspected regularly or exposed to repeated thermal cycling.

18.3.4 Practical Considerations

When evaluating a valve, consider not only how it performs in service but also how it will be maintained.

A valve that is easy to inspect, repair, and reassemble may provide significant advantages over its service life, especially in steam applications where periodic inspection is required.

18.4 What Valves Do

Most valves perform one of five functions:

- Isolate flow
- Regulate flow
- Prevent reverse flow
- Control pressure
- Protect equipment from overpressure

Although some valves can perform more than one function, every valve is designed with a primary purpose in mind.

18.5 Isolation Valves

Isolation valves are intended primarily for fully open or fully closed service.

18.5.1 Gate Valves

Gate valves use a wedge-shaped or parallel gate that moves perpendicular to the flow.

When fully open, the gate is completely removed from the flow path.

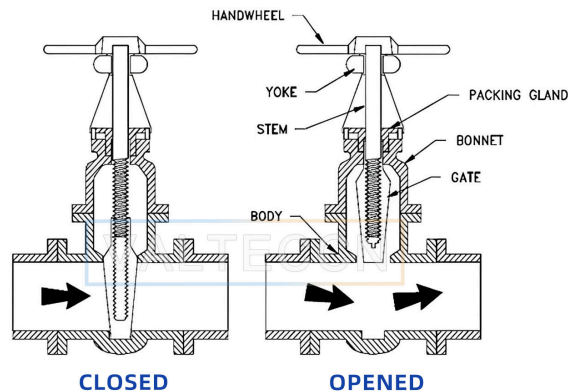


Fig. 43 Gate Valve

Typical characteristics:

- Excellent isolation
- Low pressure drop when open
- Poor throttling performance

Advantages:

- Minimal flow restriction
- Good shutoff capability

Disadvantages:

- Slow operation
- Can be damaged when partially open

Gate valves should generally be either fully open or fully closed.

18.5.2 Ball Valves

Ball valves use a drilled spherical ball that rotates within the valve body. A quarter-turn rotates the ball between fully open and fully closed positions.

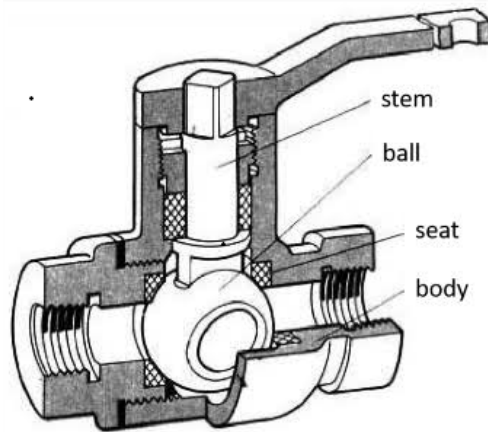


Fig. 44 Ball Valve

Advantages:

- Quick operation
- Excellent shutoff
- Compact design

Disadvantages:

- Not ideal for precise flow control

Ball valves are among the most common valves found in modern steam and utility systems.

18.5.3 Plug Valves

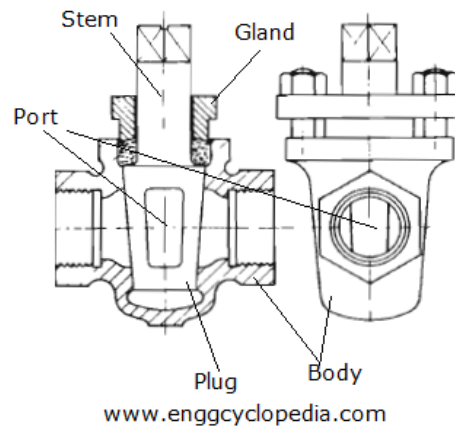


Fig. 45 Plug Valve

Plug valves use a tapered or cylindrical plug with a flow passage drilled through it. Like ball valves, they are typically quarter-turn valves. Plug valves are commonly used where quick operation and positive shutoff are required.

18.6 Flow Regulation Valves

Regulating valves are designed to control flow rate rather than simply stop flow.

18.6.1 Globe Valves

The globe valve is one of the most common throttling valves. Flow passes through the valve seat while a disc moves toward or away from that seat.

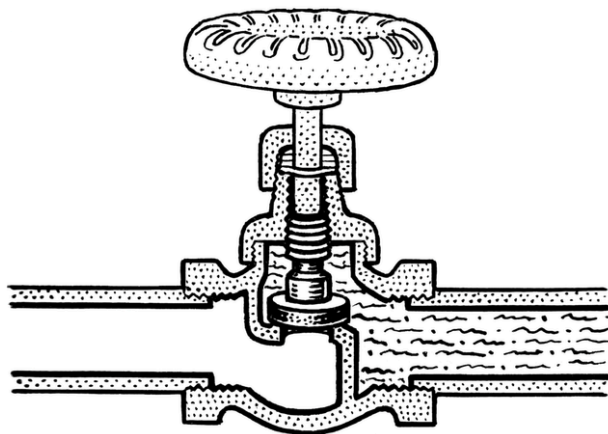


Fig. 46 0 Globe Valve

Advantages:

- Excellent throttling capability
- Good flow control
- Reliable operation

Disadvantages:

- Higher pressure drop
- More tortuous flow path

Globe valves are frequently used where steam flow must be adjusted or controlled.

18.6.2 Angle Globe Valves

An angle globe valve performs the same function as a standard globe valve but changes the direction of flow by 90 degrees.

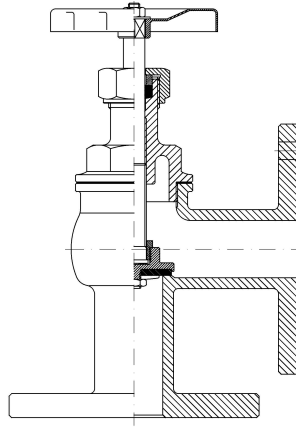


Fig. 47 Angle Globe Valve

By combining a valve and an elbow into a single component, an angle globe valve can reduce the number of fittings required in a piping system.

Advantages:

- Good throttling capability
- Eliminates the need for a separate elbow
- Compact installation

Disadvantages:

- Higher pressure drop than straight-through valves

18.6.3 Flow Direction

The direction of flow is particularly important for globe valves and angle globe valves.

In most applications, pressure should enter beneath the disc and seat rather than above them. When pressure acts beneath the seat:

- Valve operation requires less force.
- The stem packing experiences less pressure.
- The valve is easier to control.
- Wear is reduced.

For this reason, globe valves are usually marked with a flow-direction arrow and should be installed according to the manufacturer's recommendations.

18.6.4 Y-Valves

A Y-valve is a specialized form of globe valve in which the seat and stem are positioned at an angle to the flow path.

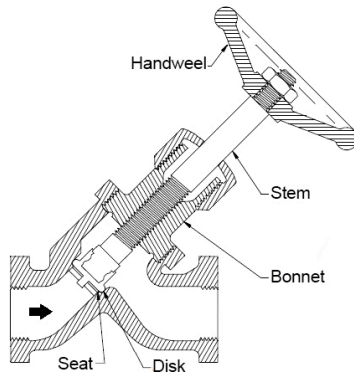


Fig. 48 Y Globe Valve

The more direct flow path reduces pressure loss compared with a conventional globe valve while still providing positive shutoff.

Advantages:

- Lower pressure drop than a standard globe valve
- Excellent resistance to wire drawing and erosion
- Well suited to high-temperature service
- Self-cleaning design

The inclined body and more direct flow path make Y-valves less prone to sediment accumulation than conventional globe valves. Scale, rust, and suspended solids are more easily carried through the valve rather than collecting beneath the seat.

Because sediment is less likely to interfere with the seating surfaces, Y-valves maintain reliable shutoff even in services where deposits may be present.

Common applications include:

- Boiler blowdown lines
- Continuous blowdown systems
- High-pressure steam service

Y-valves are frequently used for boiler blowdown because they can withstand the high velocities, erosive conditions, and suspended solids that occur when hot water and steam are discharged from a boiler.

18.6.5 Needle Valves

Needle valves are a specialized form of globe valve. The closure element is shaped like a needle, allowing extremely precise flow control.

Common applications include:

- Instrument connections
- Gauge lines
- Sampling systems

18.6.6 Why Valve Selection Matters

A common mistake is using a gate valve to throttle flow.

Partially open gate valves can experience:

- Vibration
- Erosion
- Seat damage

For flow regulation, a globe or needle valve is generally preferred.

18.7 Check Valves

Check valves allow flow in one direction while automatically preventing reverse flow. No operator action is required. Check valves must be installed with the flow arrow pointing in the correct direction.

18.7.1 Swing Check Valve

A hinged disc swings open when flow moves in the desired direction. When flow reverses, the disc closes against the seat.

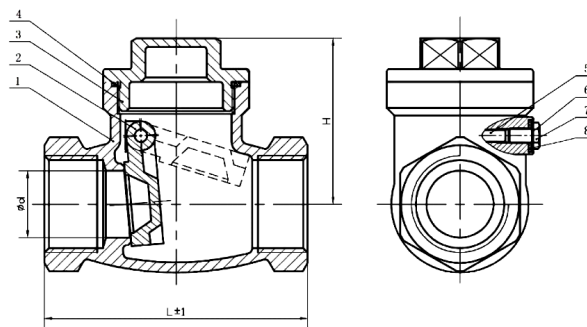


Fig. 49 Swing Check Valve

18.7.2 Lift Check Valve

A lift check valve uses a vertical moving disc. Flow lifts the disc from the seat. Reverse flow forces the disc back onto the seat.

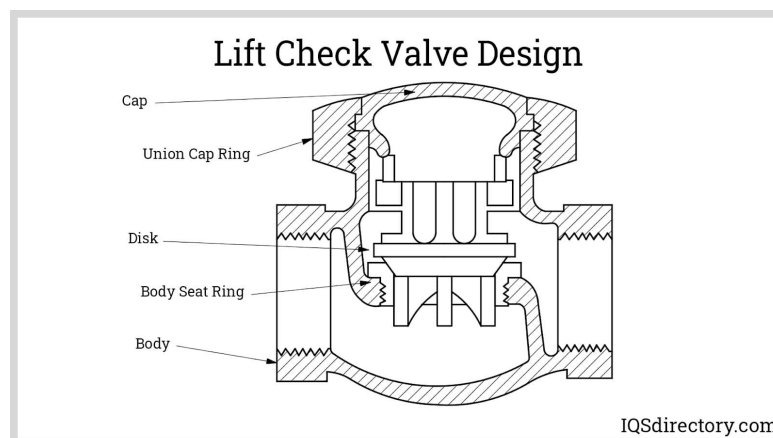


Fig. 50 Lift Check Valve

18.7.3 Why Check Valves Matter

Reverse flow can cause:

- Equipment damage

- Pump damage
- Water hammer
- Process upset

Check valves are commonly installed downstream of pumps and other critical equipment.

18.8 Pressure Control Valves

Some valves are designed to maintain a desired pressure automatically.

18.8.1 Pressure Reducing Valves (PRVs)

A pressure reducing valve lowers a higher inlet pressure to a lower controlled outlet pressure. For example, a 150 PSI steam supply can be reduced to a 30 PSI supply. PRVs are widely used in steam distribution systems but are seldom found in steam traction applications.

Benefits include:

- Improved safety
- More efficient equipment operation
- Better process control

PRVs reduce pressure, but they do not provide overpressure protection. A separate safety valve may still be required downstream if the protected equipment could be exposed to excessive pressure.

18.9 Safety Valves

Safety valves protect equipment from dangerous overpressure conditions.

18.9.1 How a Safety Valve Works

A safety valve remains closed during normal operation. The valve disc is held against its seat by a calibrated spring. As system pressure increases, an upward force is applied to the disc.

When the pressure reaches the valve's set pressure, the force exerted by the fluid overcomes the spring force and the disc begins to lift.

The action of a safety valve is more sophisticated than simply opening and closing at a single pressure. As the disc initially lifts, additional areas of the valve are exposed to system pressure. This increases the upward force acting on the disc and allows the valve to open rapidly to a greater lift.

As a result, the valve "pops" open rather than merely cracking open. Once open, the valve remains fully lifted until the pressure falls below the set pressure by a predetermined amount.

This intentional pressure difference between opening and closing is known as **blowdown**.

For example, a safety valve set at 150 psi may not reseal until the pressure falls to approximately 147 psi. The valve is therefore allowed to discharge enough steam to reduce system pressure before closing.

Without blowdown, the valve could repeatedly open and close in rapid succession, a condition known as **chatter**. Chattering causes excessive wear on the valve seat and can reduce the reliability of the safety device.

18.9.2 Key Concepts

- **Set Pressure:** The pressure at which the valve begins to open.
- **Blowdown:** The difference between the opening pressure and the reseating pressure.
- **Chatter:** Rapid repeated opening and closing of a valve due to unstable operating conditions.

A properly functioning safety valve opens quickly, remains open long enough to relieve excess pressure, and then reseats only after the system pressure has fallen sufficiently below the set point.

18.9.3 Why Safety Valves Are Critical

Without overpressure protection:

- Boilers may be damaged.
- Pressure vessels may fail.
- Piping systems may rupture.

Safety valves are among the most important protective devices in any steam system.

Safety valves should never be isolated from the equipment they protect unless specific approved procedures are followed.

18.9.4 Safety Valve Set Pressure

The set pressure of a safety valve is not selected arbitrarily. It is determined by the Maximum Allowable Working Pressure (MAWP) of the equipment being protected.

For boilers, pressure vessels, and other pressure-retaining equipment, the safety valve set pressure must be coordinated with the MAWP so that the equipment cannot be subjected to pressures exceeding its allowable limits.

For historical boilers, the MAWP is often determined through a combination of:

- Non-destructive examination (NDE)
- Inspection of material condition
- Measurement of remaining thickness
- Engineering calculations using applicable boiler formulae and code requirements

Once the MAWP has been established, the safety valve set pressure is selected to ensure that the boiler remains protected from overpressure conditions.

A safety valve must not be adjusted above the MAWP of the equipment it is intended to protect.

In jurisdictions where boilers are subject to periodic inspection and certification, adjusting a safety valve above the boiler's certified MAWP may result in the boiler being declared non-compliant. An inspector may withdraw or refuse certification until the condition is corrected and the safety valve is returned to an approved setting.

18.9.5 Safety Valve Adjustment and Sealing

The set pressure of a safety valve is adjusted and certified by qualified valve technicians working under an approved quality assurance program. After testing and adjustment, the valve is sealed so that any subsequent adjustment is immediately evident.

The seal provides assurance that the valve remains set at its certified pressure and has not been altered in service. A broken or missing seal typically requires the valve to be removed from service and reinspected.

Under normal operating conditions, a modern boiler safety valve should rarely, if ever, operate. Frequent lifting of a safety valve usually indicates a problem with boiler operation, pressure control, or valve sizing.

18.9.6 Historical Boiler Operation

Steam traction engines and other historical boilers often operate differently from modern industrial boilers.

In many cases, inspections and engineering assessments have resulted in a modern MAWP that is lower than the boiler's original design pressure. Operators may therefore work relatively close to the safety-valve set pressure during normal operation. For example, a traction engine driving a sawmill may experience occasional safety-valve operation when steam demand suddenly decreases while the boiler is still producing steam at a high rate.

Frequent operation can affect a valve's ability to reseal properly and may increase wear on the seating surfaces.

Some jurisdictions permitted the use of an antique "pop valve" as a regulating device. In such arrangements, the regulating valve was set to open at a lower pressure than the primary safety valve. This allowed pressure control to occur without repeatedly lifting the certified safety valve, sometimes called the "government valve." The term "government valve" reflects its role as the officially certified overpressure protection device for the boiler.

The certified safety valve remained the final overpressure protection device and would operate only if the regulating valve failed to control the pressure.

18.9.7 Safety Valve Key Takeaway

A safety valve is the final line of defense against overpressure. It is a protective device, not a pressure-regulating device, and its set pressure is determined by the MAWP of the equipment it protects.

18.10 Protective Valves

Some valves are designed not to control normal operation, but to protect equipment and personnel during abnormal conditions.

18.10.1 Automatic Gauge Glass Valves

Water-column and gauge-glass installations commonly utilize automatic gauge-glass valves. These valves contain a small ball checks that normally remain clear of the flow passage during operation.

If the gauge glass breaks, the sudden increase in flow causes the ball to move against its seat, restricting or stopping the discharge of steam and water.

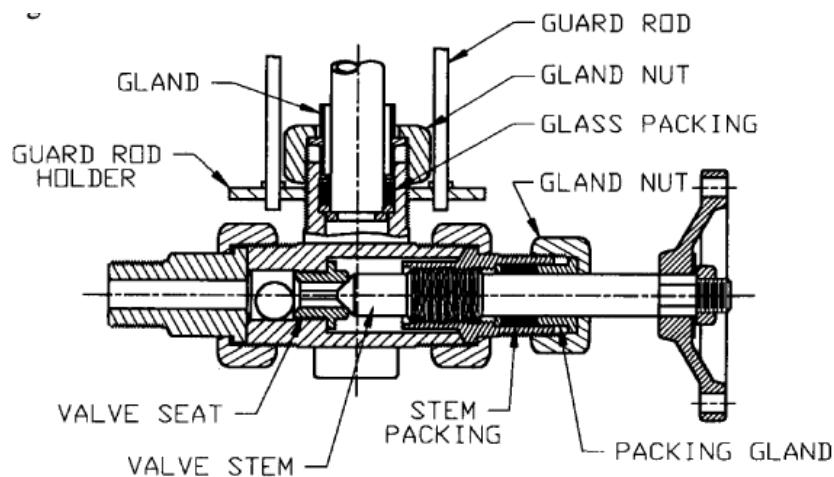


Fig. 51 Ball-Check Valve

Automatic gauge-glass valves provide an additional measure of protection, but they should not be relied upon as the sole means of isolation. Manual gauge-glass shutoff valves must remain accessible so that a damaged gauge glass can be isolated safely.

18.11 Valve End Connections

Valves are manufactured with a variety of end connections.

Threaded

Common on smaller piping systems.

Socket-Weld

Frequently used for small-bore high-pressure service.

Butt-Weld

Common on larger industrial piping systems.

Flanged

Used where equipment may require removal or maintenance.

18.12 Valve Ratings and Markings

Valves are typically marked with information including:

- Manufacturer
- Size
- Material
- Pressure class
- Flow direction (where applicable)
- CRN (where applicable)

Examples include:

2
150
A216 WCB

or

1
800
A105

These markings help verify that the valve is suitable for the intended service.

18.13 Reading a Valve

A valve marked:

ABC
2
300
A216 WCB

can be interpreted as:

- Manufacturer: ABC
- Size: 2"
- Class: 300
- Material: Cast carbon steel (A216 WCB)

Like pipe and fittings, valve markings are an important part of quality control and traceability.

18.14 Why Pipefitters Should Care

Valves are among the most expensive and critical components in a piping system. Proper selection, installation, and operation directly affect system safety and performance.

Before installing a valve, verify:

- Size
- Material
- Pressure class
- Flow direction
- Intended function

Never assume two valves are interchangeable simply because they have the same pipe size.

18.15 Key Takeaway

Valves control the flow of fluids within a piping system. Different valve types are designed for different functions, including isolation, throttling, reverse-flow prevention, pressure control, and overpressure protection. Understanding how each valve operates and where it should be used is essential for safe and reliable steam system operation. ``

Chapter 19

Fittings

A piping system is much more than a collection of straight pieces of pipe. At some point the line must turn a corner, connect to equipment, split into branches, change size, or be closed off. These functions are performed by fittings.

Fittings are the components that join sections of pipe together and direct the flow of steam, water, air, or other fluids through the system. Common fittings include elbows, tees, reducers, couplings, unions, caps, and plugs.

Understanding the purpose and limitations of each fitting is an essential skill for anyone involved in piping installation, maintenance, or inspection.

19.1 What Fittings Do

Most fittings perform one of five functions:

- Change direction
- Create a branch
- Change pipe size
- Connect or disconnect equipment
- Close the end of a pipe

The fitting selected for a particular application depends on the operating pressure, temperature, material, connection type, and service conditions.

19.2 Changing Direction

The most common fittings in any piping system are elbows.

19.2.1 90° Elbow

A 90° elbow changes the direction of flow by ninety degrees and is commonly used where space is limited.

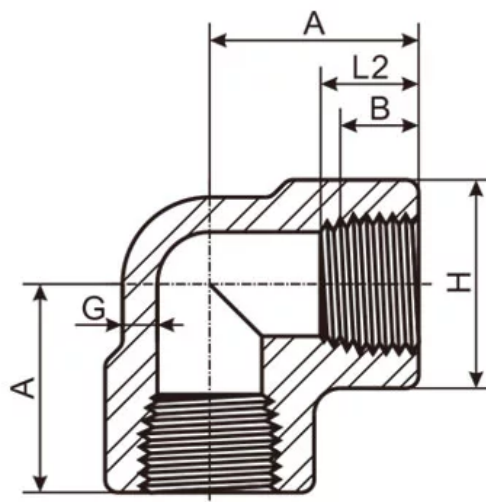


Fig. 52 90-Degree Elbow

19.2.2 45° Elbow

A 45° elbow changes direction more gradually and generally produces less pressure loss than a 90° elbow.

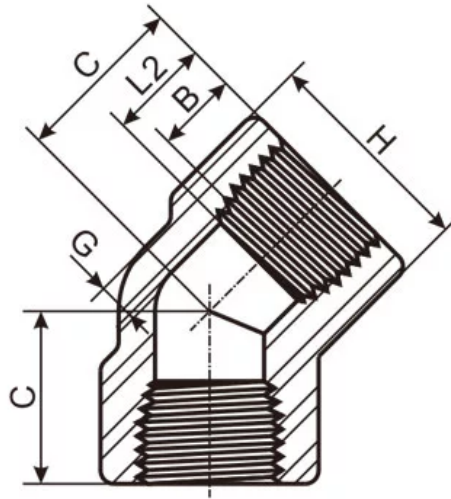


Fig. 53 45-Degree Elbow

19.2.3 Long-Radius and Short-Radius Elbows

Elbows are manufactured with different bend radii.

- Long-radius (LR) elbows have a centerline radius equal to 1.5 times the pipe diameter.
- Short-radius (SR) elbows have a centerline radius equal to the pipe diameter.

Long-radius elbows produce less turbulence and lower pressure loss. For this reason they are commonly used in steam and process piping systems.

19.2.4 Street Elbows

A street elbow has a male connection on one end and a female connection on the other. This allows it to connect directly to another fitting without requiring a short piece of pipe between them.

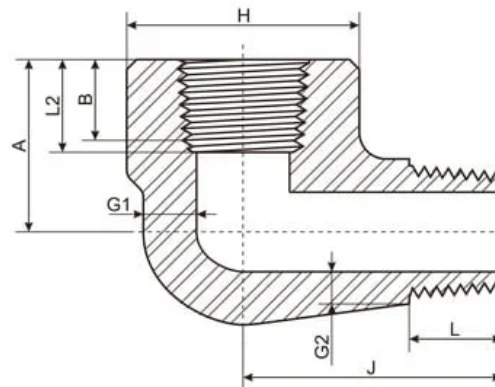


Fig. 54 Street Elbow

19.2.5 Why Direction Changes Matter

Every change in direction creates resistance to flow.

As fluid passes through an elbow:

- Velocity distribution changes.
- Turbulence increases.
- Pressure is lost.

For this reason, piping systems should avoid unnecessary direction changes whenever practical.

19.3 Creating Branches

At some point a piping system must divide flow into two or more paths.

19.3.1 Tee

A tee has three openings and is the most common branch fitting.

A standard tee provides a branch connection that is the same size as the run.

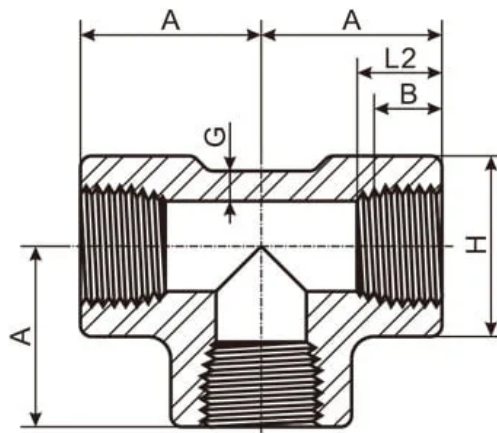


Fig. 55 Tee

19.3.2 Cross

A cross has four openings.

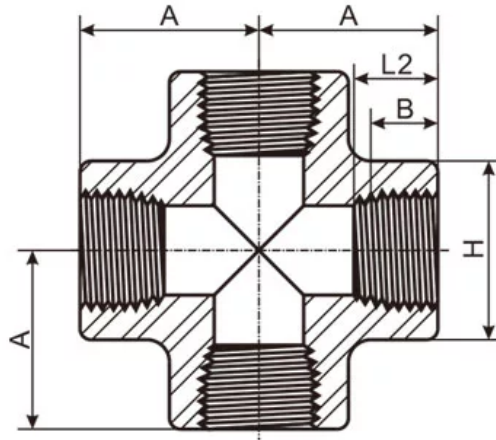


Fig. 56 Cross

19.3.3 Reducing Tee

A reducing tee provides a branch connection that is smaller than the main run.

For example:

- Run: 2"
- Branch: 1"

19.3.4 Lateral

A lateral fitting creates a branch at an angle, typically 45°.

Because the flow path is smoother than a standard tee, pressure losses may be reduced.

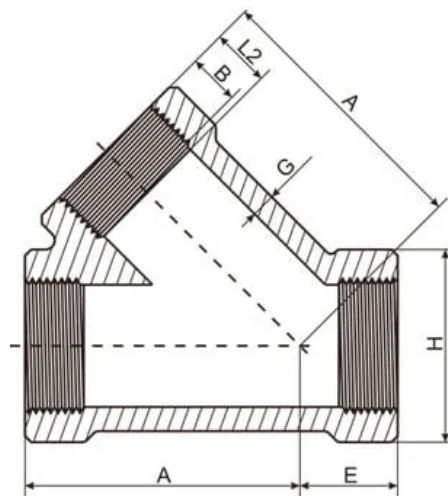


Fig. 57 Lateral Tee

19.3.5 Branch Connection Considerations

Branch connections can experience significant stresses from:

- Internal pressure
- Thermal expansion
- Vibration

- External loads

As pipe size and pressure increase, branch reinforcement requirements become increasingly important.

19.4 Changing Size

Pipe size often changes within a system as flow rates increase or decrease.

Size reductions can be accomplished using either reducing fittings or reducers. The choice depends on the amount of space available, the desired flow characteristics, and the service conditions.

A bushing reduces a fitting; a reducer reduces a pipe.

19.4.1 Bushings

A bushing is a fitting that threads into a larger fitting and provides a smaller threaded opening.

For example, a 1" × 3/4" bushing allows a 3/4" pipe to be connected to a 1" fitting.

Because the reduction occurs within the fitting itself, a bushing requires very little space.

Advantages:

- Compact installation
- Lower cost
- Fewer fittings required

Disadvantages:

- Creates an abrupt change in flow area
- Concentrates stress in a small area
- Can be more difficult to remove after years of service

Bushings are commonly used on instrument connections, drain lines, vent connections, and small auxiliary piping.

19.4.2 Reducing Couplings

A reducing coupling joins two different pipe sizes in a straight run.

For example:

- 1" × 3/4"
- 1-1/4" × 1"
- 2" × 1-1/2"

Unlike a bushing, a reducing coupling occupies additional length in the piping system but generally provides a stronger and more conventional connection.

Advantages:

- Better mechanical support
- Easier maintenance
- Commonly accepted piping practice

Disadvantages:

- Requires more space
- Adds another fitting to the system

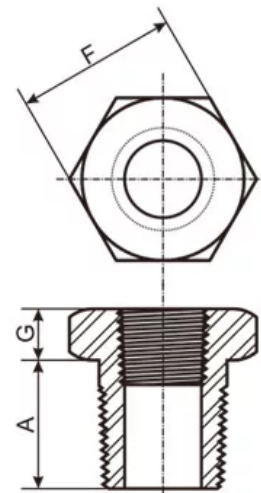


Fig. 58 Bushing

19.4.3 Reducers

In welded piping systems, pipe size changes are usually accomplished using reducers.

Common examples include:

- 2" × 1-1/2"
- 4" × 3"
- 6" × 4"

Reducers are available in two styles:

- Concentric
- Eccentric

A reducer connects two different pipe sizes.

Common examples include:

- 2" × 1-1/2"
- 4" × 3"
- 6" × 4"

19.4.4 Concentric Reducers



Fig. 59 Concentric Reducer

A concentric reducer maintains a common centerline.

Concentric reducers are commonly used in vertical piping systems.

19.4.5 Eccentric Reducers



Fig. 60 Eccentric Reducer

An eccentric reducer maintains one side of the pipe in a straight line.

In steam systems, eccentric reducers are often installed with the flat side down in horizontal lines to prevent condensate from collecting in the pipe.

19.4.6 Why Reducer Selection Matters

Poor reducer selection can create:

- Condensate pockets
- Air traps
- Increased turbulence
- Water hammer conditions

Proper orientation is especially important in steam service.

19.5 Joining Pipe Sections

Some fittings primarily exist to connect sections of pipe together.

19.5.1 Couplings

A coupling joins two pieces of pipe in a straight line.

Threaded couplings are common in smaller piping systems.

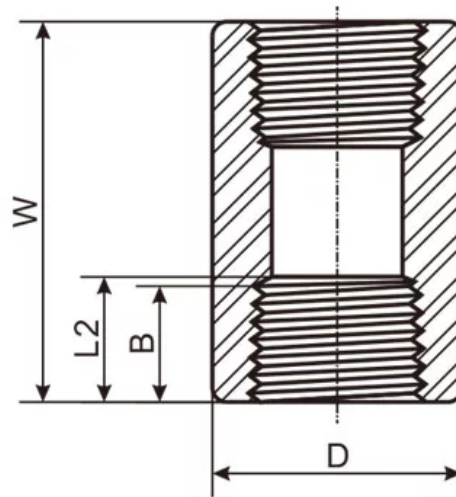


Fig. 61 coupling

19.5.2 Half Couplings

A half coupling is essentially half of a coupling and is commonly welded to a vessel or larger pipe to create a branch connection.

19.5.3 Unions

A union provides a means of disconnecting piping without rotating the pipe.

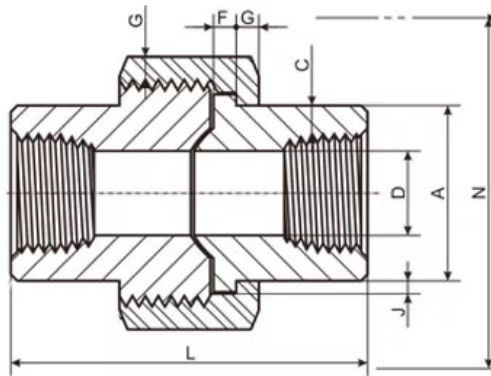


Fig. 62 Union

Unions are commonly installed near:

- Valves
- Steam traps
- Pumps
- Instruments

They simplify maintenance and replacement.

19.5.4 Why Use a Union?

Without a union, disassembly may require removing a large section of piping.

A union allows components to be removed quickly for servicing.

19.6 Closing Pipe Ends

Sometimes a piping system requires a temporary or permanent closure.

19.6.1 Caps

A cap fits over the end of a pipe and closes it.

A useful way to think of a cap is that it fits over the outside of the pipe.

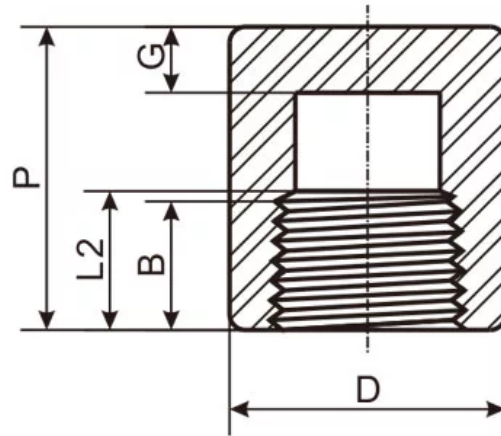


Fig. 63 Cap

19.6.2 Plugs

A plug screws into a threaded fitting and closes an opening.

A plug fits into a fitting rather than over a pipe.

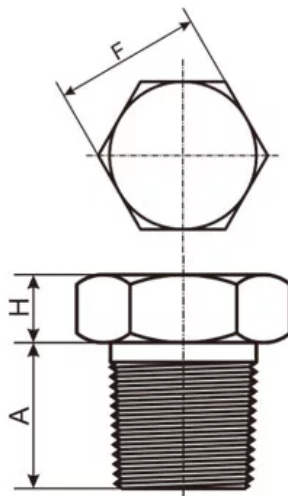


Fig. 64 Hex-head Plug

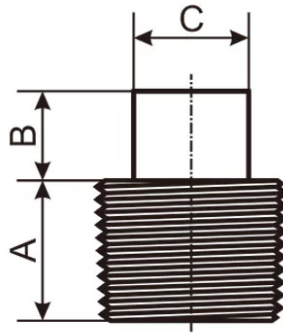


Fig. 65 Square-head Plug

19.6.3 Remembering the Difference

A useful memory aid is:

- A cap goes over a pipe.
- A plug goes into a fitting.

19.7 End Connections

Fittings are available with several different end connections.

19.7.1 Threaded

Used primarily on smaller pipe sizes.

Advantages:

- Easy to assemble
- No welding required

Disadvantages:

- Potential leak paths
- Limited pressure and temperature capability

19.7.2 Socket-Weld

The pipe is inserted into a socket and welded around the outside.

Advantages:

- Strong connection
- Suitable for higher-pressure service

Disadvantages:

- Requires welding
- More difficult to inspect internally

19.7.3 Butt-Weld

The pipe and fitting are welded directly end-to-end.

Advantages:

- Highest strength
- Smooth internal bore
- Preferred for larger steam systems

Disadvantages:

- Requires qualified welding procedures

19.8 Key Takeaway

Fittings make a piping system practical. They allow pipe to change direction, create branches, change size, connect equipment, and terminate lines. Proper fitting selection affects not only how easily a system can be assembled, but also its pressure capability, maintainability, and long-term reliability.

19.9 Nipples

A nipple is a short length of pipe with external threads on both ends. Nipples are used to connect two threaded fittings or components.

Unlike most fittings, which are cast or forged into a particular shape, a nipple is essentially a short piece of pipe prepared for threaded service

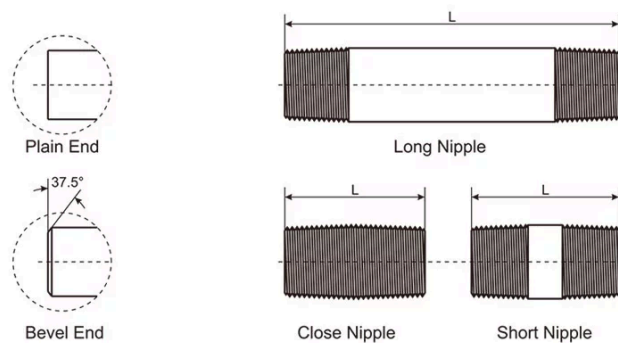


Fig. 66 Nipples: Close, Short and Long

Common uses include:

- Connecting valves to fittings
- Extending a branch line
- Installing pressure gauges
- Connecting steam traps
- Creating spacing between components

19.9.1 Common Nipple Lengths

Nipples are available in a variety of standard lengths, including:

- Close
- Shoulder
- Short
- Long
- Custom-cut

The exact dimensions vary by manufacturer and pipe size.

19.9.2 Close Nipples

A close nipple has threads over its entire length.

When assembled, very little of the nipple remains visible between the fittings.

Close nipples are useful where space is limited, but they can be difficult to remove because there is no unthreaded section available for a pipe wrench.

19.9.3 Shoulder Nipples

A shoulder nipple, also called a short, contains a short unthreaded section between the threaded ends.

The unthreaded "shoulder" is visible after assembly and may provide limited wrench grip.

19.9.4 Long Nipples

Long nipples are simply longer sections of threaded pipe.

They are commonly used to:

- Create space between components
- Bridge short distances
- Position instruments or valves for easier access

19.9.5 Barrel Nipples

A barrel nipple has threads only near the ends, with an unthreaded section in the middle.

This style is commonly used when greater length is required while minimizing the amount of threading.

19.9.6 Running Nipples

A running nipple is a nipple that is threaded continuously from end to end, similar to a long close nipple.

Running nipples are useful when one fitting must be rotated onto the nipple during assembly.

19.9.7 Why Pipefitters Care

Nipples may appear simple, but they are often the components that determine whether a system can be assembled and maintained efficiently.

The correct nipple length can:

- Provide wrench clearance
- Allow valve handles to move freely
- Improve accessibility
- Simplify future maintenance

Poor nipple selection can leave components difficult or impossible to service.

19.9.8 Common Steam-Service Examples

Nipples are frequently found:

- Between a steam trap and isolation valve
- Between a pressure gauge and gauge valve
- Between a tee and a drain valve
- Between a boiler nozzle and a valve assembly
- In instrument and control piping

19.9.9 Key Takeaway

A nipple is a short piece of threaded pipe used to connect fittings and components. Although simple in appearance, proper nipple selection is important for accessibility, assembly, maintenance, and overall piping layout.

19.10 Flanges

A flange is a mechanical method of connecting pipe, valves, vessels, and other equipment. Unlike threaded or welded joints, flanges can be disassembled relatively easily, making them ideal for equipment that requires periodic inspection, maintenance, or replacement.

A flanged joint consists of:

- Two mating flanges
- A gasket
- Bolts and nuts

As the bolts are tightened, the flanges compress the gasket and create a pressure-tight seal.

19.10.1 Why Use Flanges?

Flanges are commonly used where equipment must be removable.

Typical examples include:

- Valves
- Steam traps
- Pumps
- Heat exchangers
- Pressure vessels
- Boilers

Without flanges, removing large equipment would often require cutting and rewelding the piping.

19.10.2 Common Flange Types

Several flange designs are commonly encountered in piping systems.

19.10.2.1 Weld Neck Flange

The weld neck flange is considered the preferred flange for many pressure piping applications.

The tapered hub provides a smooth transition between the pipe and flange, reducing stress concentrations.

Advantages:

- Excellent strength
- Good fatigue resistance
- Suitable for high pressure and temperature service

Common applications:

- Steam systems
- Process piping
- High-pressure service

19.10.2.2 Slip-On Flange

A slip-on flange slides over the outside of the pipe and is welded in place.

Advantages:

- Easy alignment
- Lower cost
- Simplified fit-up

Disadvantages:

- Lower strength than weld neck flanges
- More susceptible to fatigue

19.10.2.3 Threaded Flange

A threaded flange contains internal pipe threads and does not require welding.

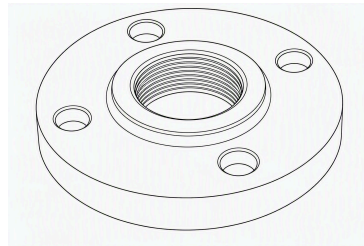


Fig. 67 Threaded flange

Advantages:

- No welding required
- Convenient for small piping systems

Disadvantages:

- Limited pressure and temperature capability
- Potential leak paths through the threads

19.10.2.4 Socket Weld Flange

A socket weld flange contains a recessed socket into which the pipe is inserted before welding.

Socket weld flanges are commonly used on smaller high-pressure piping systems.

19.10.2.5 Blind Flange

A blind flange is a solid plate used to close the end of a flanged connection.

Common uses include:

- Future expansion points
- Equipment isolation
- Pressure testing

19.10.3 Gaskets

A flange alone does not normally provide the seal.

The seal is created by a gasket compressed between the flange faces.

Common gasket materials include:

- Compressed fiber
- Graphite
- PTFE
- Spiral wound metal gaskets

The gasket material must be suitable for the system temperature, pressure, and fluid.

19.10.3.1 Why Gaskets Matter

An improperly selected gasket can result in:

- Steam leaks
- Blowouts
- Loss of pressure
- Equipment damage

In steam service, gasket selection is often just as important as flange selection.

19.10.4 Flange Faces

The flange face is the surface that contacts the gasket.

19.10.4.1 Flat Face (FF)

A flat-face flange has a completely flat sealing surface.

Flat-face flanges are commonly used with cast-iron equipment.

Raised Face (RF)

A raised-face flange contains a small raised sealing surface around the bore.

Raised-face flanges are the most common type found in industrial piping systems.

The raised face concentrates gasket loading and improves sealing performance.

19.10.4.2 Ring-Type Joint (RTJ)

RTJ flanges use a machined metal ring seated in precision grooves.

They are typically reserved for:

- Very high-pressure service
- High-temperature service
- Specialized industrial applications

19.10.5 Bolting and Tightening

The bolts in a flanged joint do not directly seal the pipe. Their purpose is to compress the gasket with sufficient force to maintain a seal.

Proper tightening is important because:

- Uneven tightening can damage the gasket.
- Excessive tightening can crush the gasket.
- Insufficient tightening can cause leaks.

Bolts are normally tightened in a crisscross or star pattern to ensure even gasket compression.

This pattern distributes the load evenly around the flange.

19.10.6 Flange Ratings

Flanges are manufactured with pressure-temperature ratings known as classes.

Common ratings include:

- Class 150
- Class 300
- Class 600
- Class 900
- Class 1500
- Class 2500

A higher class generally indicates a flange capable of higher pressure service.

A common misconception is that a Class 150 flange is limited to 150 psi. In reality, flange ratings vary with both material and temperature. The actual allowable pressure must be determined from the applicable standard.

19.10.7 Why Pipefitters Should Care

Flanges are among the most common connection methods in industrial piping systems. Proper alignment, gasket selection, bolting techniques, and pressure-class selection all affect the safety and reliability of the system.

Many steam leaks occur not because the flange was defective, but because the joint was assembled incorrectly.

19.10.8 Key Takeaway

Flanges provide a removable method of connecting piping and equipment. A flanged joint consists of two flanges, a gasket, and bolting. Understanding flange types, gasket selection, flange ratings, and proper assembly practices is essential for anyone working with steam systems.

19.11 Fitting Ratings and Markings

Like pipe, fittings are marked with information that identifies their size, material, pressure class, and manufacturer. Understanding these markings helps ensure that the correct fitting is selected for the intended service.

19.11.1 Why Markings Matter

A fitting may look identical to another fitting while having a completely different pressure rating, material specification, or intended service.

Before installation, the markings should be checked to verify:

- Size
- Material
- Pressure class
- Manufacturing standard
- Traceability requirements

Installing the wrong fitting can compromise the safety and reliability of the entire piping system.

19.11.2 Pressure Classes

Most forged steel threaded and socket-weld fittings are marked with a pressure class.

Common examples include:

3000
6000
9000

A fitting marked: 3000 is often referred to as a "three-thousand pound fitting."

19.11.2.1 A Common Misunderstanding

The pressure class is not the maximum allowable working pressure in psi.

For example, a Class 3000 fitting is not necessarily limited to 3000 psi, nor is it automatically suitable for 3000 psi service.

The actual pressure rating depends on:

- Material
- Temperature
- Applicable standards
- Service conditions

The pressure class simply identifies the fitting's rating category.

19.11.3 Material Markings

Fittings are commonly marked with a material specification.

Examples include:

A105
A182 F304
A182 F316

These markings identify the material from which the fitting was manufactured.

19.11.3.1 Common Materials

A105

Forged carbon steel. Commonly used in steam and process piping.

A182 F304

Forged 304 stainless steel.

A182 F316

Forged 316 stainless steel.

Material markings help ensure compatibility with the piping system and service environment.

19.11.4 Manufacturing Standards

Many fittings are marked with the standard to which they were manufactured.

Examples include:

B16.11
B16.9

19.11.4.1 ASME B16.11

Applies to:

- Forged threaded fittings
- Socket-weld fittings

Examples include:

- Couplings
- Unions
- Tees
- Elbows
- Bushings

19.11.4.2 ASME B16.9

Applies to:

- Factory-made wrought butt-weld fittings

Examples include:

- Welded elbows
- Reducers
- Tees
- Caps

Knowing the standard helps verify that the fitting is suitable for the intended piping system.

19.11.5 Size Markings

Most fittings are marked with their nominal size.

Examples:

1
1-1/2
2

Reducing fittings may show both sizes.

Examples:

2 × 1
1-1/2 × 3/4

These markings indicate the pipe sizes for which the fitting is intended.

19.11.6 Manufacturer Identification

Most fittings contain the manufacturer's trademark, logo, or identification code.

This marking provides:

- Product identification
- Traceability
- Quality-control verification

If questions arise regarding material or certification, the manufacturer marking helps identify the source of the fitting.

19.11.7 Heat Numbers and Traceability

Higher-grade piping systems may require fittings to be traceable to their material test reports.

In such cases, fittings may carry a heat number that links the fitting to:

- Chemical analysis records
- Mechanical test records
- Material certifications

Like pipe markings, these numbers are used to establish material traceability.

19.11.8 Canadian Registration Numbers (CRNs)

Many pressure-retaining components used in Canada carry a Canadian Registration Number (CRN).

A CRN indicates that the design has been accepted by the appropriate regulatory authority for use in Canadian pressure systems.

A fitting may therefore contain markings such as: CRN 0C12345.5C.

The details of CRNs and their interpretation are discussed in a later chapter.

19.11.9 Reading a Typical Fitting

A fitting marked:

ABC
3000
A105
1
B16.11

can be interpreted as:

- Manufacturer: ABC
- Pressure class: 3000
- Material: ASTM A105 forged carbon steel
- Size: 1"
- Standard: ASME B16.11

From a few simple markings, a pipefitter can determine a great deal about the fitting.

19.11.10 Key Takeaway

Fitting markings are the component's identification card. They provide information about size, material, pressure class, manufacturing standard, and traceability. Learning to read these markings is an important skill for pipefitters, inspectors, and maintenance personnel because many fittings appear similar even though their pressure ratings and intended applications may be very different.

19.12 Cast vs. Forged Fittings

Although many fittings may appear similar from the outside, they are not all manufactured in the same way. One of the most important distinctions is whether a fitting is cast or forged.

The manufacturing method affects:

- Strength
- Pressure capability
- Toughness
- Reliability
- Suitable service applications

19.12.1 Cast Fittings

Cast fittings are manufactured by pouring molten metal into a mold and allowing it to solidify.

Common cast fitting materials include:

- Cast iron
- Malleable iron
- Cast steel
- Bronze

A cast fitting can be produced in complex shapes with relatively little machining.

19.12.2 Advantages of Cast Fittings

- Lower manufacturing cost
- Complex shapes are easy to produce
- Suitable for many low-pressure applications

19.12.3 Disadvantages of Cast Fittings

- Generally lower toughness
- More susceptible to casting defects
- Less resistant to shock loading
- Lower pressure ratings than forged equivalents

19.12.4 Forged Fittings

Forged fittings are manufactured by mechanically forming heated metal under high pressure.

Rather than being poured into a mold, the metal is compressed into shape.

The forging process improves the grain structure of the steel and produces a stronger component.

19.12.5 Advantages of Forged Fittings

- Higher strength
- Better toughness
- Improved fatigue resistance
- Higher pressure capability
- Greater reliability in severe service

19.12.6 Disadvantages of Forged Fittings

- Higher cost
- More machining may be required

19.12.7 Visual Differences

A forged fitting often has:

- Smooth machined surfaces
- Clearly stamped markings
- Class ratings such as 3000, 6000, or 9000

A cast fitting often has:

- A rougher surface finish
- Cast-in markings
- Pressure ratings such as 125 lb or 150 lb

While appearance can provide clues, markings should always be used for positive identification.

19.12.8 Which Type Is Used in Steam Service?

For most industrial steam systems, forged steel fittings are preferred.

Common examples include:

- ASTM A105 forged carbon steel fittings
- ASME B16.11 threaded fittings
- ASME B16.11 socket-weld fittings
- ASME B16.9 butt-weld fittings

These fittings are designed to withstand the temperatures and pressures commonly encountered in steam service.

19.12.9 Malleable Iron Fittings

Malleable iron threaded fittings are common in:

- Compressed-air systems
- Water systems
- Low-pressure utility piping

Historically, malleable iron fittings have been used in some low-pressure steam systems. However, many industrial facilities now prefer forged steel fittings because of their superior strength and durability.

When working on an existing installation, it is common to encounter both types.

19.12.10 Cast Iron Fittings

Cast iron fittings should generally be viewed with caution in steam service.

Cast iron is:

- Strong in compression
- Relatively brittle
- Less tolerant of thermal stress and mechanical shock

A cast iron fitting that performs satisfactorily in water service may not be suitable for higher-temperature steam applications.

19.12.11 A Typical Comparison

110 lb Malleable Iron Elbow vs. 3000 lb A105 Forged Elbow

Cast construction	Forged construction
Lower pressure rating	Higher pressure capability
Utility service	Industrial steam service

Although both fittings may be the same nominal size, they are intended for very different operating conditions.

19.12.12 Why Pipefitters Should Care

Two fittings may have identical dimensions and threads yet possess vastly different pressure and temperature capabilities. Before installing a fitting, verify:

- Material
- Pressure class
- Manufacturing standard
- Service suitability Never assume a fitting is acceptable simply because it fits.

19.12.13 Key Takeaway

Cast and forged fittings may look similar, but their performance can be very different. Forged steel fittings are the preferred choice for most industrial steam systems because they provide greater strength, toughness, and pressure capability. Cast and malleable iron fittings are commonly used in lower-pressure utility services but may not be suitable for demanding steam applications.

Chapter 20

Material Test Reports (MTRs)

A Material Test Report (MTR) is a document that provides evidence that a material meets a specified standard. MTRs are commonly used for pipe, fittings, flanges, valves, pressure vessel components, and structural materials used in pressure systems.

An MTR answers a simple but important question:

How do we know this material is what the supplier claims it is?

Without documentation, it is often impossible to determine whether a piece of steel is suitable for a particular service simply by looking at it.

20.1 Why MTRs Matter

Many materials appear identical while possessing very different mechanical and chemical properties.

For example:

- ASTM A53 pipe
- ASTM A106 pipe
- Stainless steel pipe
- Alloy steel pipe

may appear similar, yet have very different service limitations.

An MTR provides documented evidence of:

- Chemical composition
- Mechanical properties
- Manufacturing information
- Traceability information

MTRs are therefore an important part of quality control and pressure equipment safety.

20.2 What Is a Heat?

Steel is manufactured in batches known as heats.

During production, molten steel is processed in a furnace and assigned a unique heat number.

The heat number identifies the specific batch of material from which a component was produced.

20.3 Heat Numbers

A heat number provides the connection between a physical component and its documentation.

For example:

Pipe Marking:

ASTM A106 GR B
HEAT 12345

The heat number allows inspectors to locate the corresponding MTR and verify the material properties of that batch.

This process is called **material traceability**.

20.4 Information Found on an MTR

Although formats vary by manufacturer, most MTRs contain:

- Manufacturer name
- Material specification
- Material grade
- Heat number
- Chemical composition
- Mechanical test results
- Applicable standards
- Certification information

20.5 Chemical Composition

An MTR typically lists the chemical composition of the material.

Examples include:

- Carbon (C)
- Manganese (Mn)
- Silicon (Si)
- Phosphorus (P)
- Sulfur (S)

Additional alloying elements may also be listed.

The reported values are compared against the limits established by the applicable specification.

20.6 Mechanical Properties

An MTR typically includes test results for:

- Tensile strength
- Yield strength
- Elongation

These properties help demonstrate that the material has the required strength and ductility.

20.7 Reading a Typical MTR

An inspector reviewing an MTR may verify:

1. The material specification.
2. The material grade.
3. The heat number.
4. Chemical composition.
5. Mechanical properties.

The heat number on the MTR must match the heat number marked on the component.

If the numbers do not match, traceability has been lost.

20.8 Maintaining Traceability

Traceability is only useful if it is preserved.

When pipe is cut into shorter sections, shops often transfer the heat number to each piece.

Common methods include:

- Paint markers
- Metal tags
- Stamping

- Traceability records

If the heat number is lost, proving material compliance may become difficult or impossible.

20.9 Missing Traceability

A component does not necessarily become defective if its heat number is lost.

However, it may no longer be possible to prove:

- What specification it meets
- Which heat it came from
- Which MTR applies to it

In code work, lack of traceability can create significant problems during inspection.

20.10 Why Pipefitters Should Care

Material traceability is not solely an engineering concern.

When markings are removed, painted over, or discarded, the connection between the component and its documentation may be lost.

Maintaining traceability helps ensure that the correct materials are installed and that compliance can be demonstrated during inspections.

20.11 Key Takeaway

A Material Test Report is the document that proves a material meets its specified requirements. The heat number provides the link between the physical component and the MTR. Maintaining that link is essential for material traceability, quality control, and code compliance.

20.12 Sample Documents

The following examples illustrate how material traceability is established in practice.

Notice that no single document contains all of the information. Instead, the invoice, material certificates, and heat numbers work together to create a chain of traceability linking the purchased component to the manufacturer's test records.

20.12.1 Invoice

The invoice identifies the material that was purchased and received.

10	PSX05 1/2 XS SRL BLK A106B SML PIPE HT# _____ MF _____ 054 001 02L CUT ABOVE PIPE INTO (3) PCES	FT	21.00	21.00	✓	.00	3.7800	79.38
40	CUT011 LABOR-CUT ON 1/8"-1" STL PIPE 100 000 00A	UN	3.00	3.00	✓	.00	4.9500	14.85
60	PSX03 3/8 XS BLK A106B SML PIPE HT# _____ MF _____ 054 001 02K CUT ABOVE PIPE INTO (3) PCES	FT	21.00	21.00	✓	.00	2.8500	59.85
90	TFS07 3/4" THRD 105N FS 3000# TEE HT# _____ MF _____ 011 002 01A	UN	15.00	.00	15.00		11.3200	
100	TFS1 1" THRD 105N FS 3000# TEE HT# _____ MF _____ 011 002 01J	UN	15.00	12.00	✓	3.00	14.3700	172.44

Fig. 68 Invoice with Heat Numbers

The invoice provides information such as:

- Part number
- Material description
- Size
- Quantity
- Manufacturer
- Purchase information

In this example, the handwritten heat numbers create the connection between the items on the invoice and the supporting material certificates.

For item 10, the handwritten heat number **18R103** identifies the corresponding pipe certificate.

For item 100, the handwritten heat code **CA1314** identifies the corresponding tee certificate.

The invoice therefore acts as the first link in the traceability chain.

20.12.2 Mill Test Certificate

The heat number **18R103** and the description **1/2" XH X WT 0.147" X 21 FEET Long** connect this document to line 10 of the invoice.

MILL TEST CERTIFICATE																		
CERTIFICATE ACCORDING TO EN 10204 3.1																		
PURCHASER NAME :		ALBERTA PIPE FITTINGS LTD					TEST CERTIFICATE No.:		0754/2022									
PURCHASER ORDER No.:		APF/LB04					Date :		22-03-2022									
WORK ORDER No.:		LBST / WO / EXP / 5971					Date :		06-04-2022									
NAME OF STEEL SUPPLIER :		RASHTRIYA ISPAT NIGAM LIMITED - INDIA - Melt & Pour					INVOICE NO:		LBSTEXP2223068									
STEEL MAKING METHOD :		BOF-LF/IRUT-CCM-ROUND METHOD, Fully Killed and Fine Grain Practice.																
PROCESS OF PIPE MANUFACTURE :		CDS / CS / PIPES																
MANUFACTURE PROCESS ROUTE :		PM-HI-STP-CD-HT-Finishing-NDT-P&F-Dispatch.					CUSTOMER UID NO		-									
SPECIFICATION & GRADE :		ASTM A106 GR.B(Ed.2015)/ASME SA106 GR.B(Ed.2019), CSAZ245.1 CAT 1 GRADE 290(Ed.2018), NACE MR0175/ISO 15156(Ed.2020), NACE MR0103/ISO 17545(Ed.2016)																
Sr. No.	LBST HEAT NO	SUPPLIER HEAT NO	SIZE			Quantity			General									
			OD (INCH)	ID (INCH)	WT (INCH)	Length (FEET)	Nos.	FEET.	MT.	End Condition	Coating							
1	18R103	22E00436	1/2" XH X WT 0.147" X 21 FEET Long.			135	2835.09	1,400	Plain End	Black Paint								
CHEMICAL COMPOSITION (%)																		
Sr. No.	HEAT NO	REQUIRED	%C	%Mn	%Si	%S	%P	%Cr	%Ni	%Cu	%Mo	%V	%Nb	%B	%Ca	%Al	%N	
1	18R103	Min	0.29	0.10	-	-	-	-	-	-	-	-	-	-	-	-	-	
		Max	0.30	1.35	-	0.025	0.025	0.30	0.40	0.40	0.12	0.08	-	-	-	-	-	
		L/A	0.18	0.61	0.15	0.005	0.017	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030	0.287
		P1/A	0.18	0.61	0.14	0.005	0.017	0.016	0.002	0.004	0.001	0.002	0.001	0.001	0.003	0.029	0.288	
		P2/A	0.18	0.61	0.15	0.005	0.016	0.018	0.002	0.004	0.001	0.002	0.001	0.001	0.003	0.029	0.288	
MECHANICAL PROPERTIES																		
Sr. No.	HEAT NO	REQUIRED	YIELD STRENGTH (MPa)	TENSILE STRENGTH (MPa)	ELONGATION (%)	HARDNESS(BHN)	IMPACT TEST	BEND TEST	FLARING TEST	GRAIN SIZE								
1	18R103		G.L. x 50 mm, Pipe tested by full section (Orientation- Longitudinal)															
		Min	240	415	30	-	-	-	-	-								
		Max	-	-	-	200	-	-	-	-								
			329.44	460.21	49.00	119 - 121	NA	OK	NA	7.0 - 7.5								
NON-DESTRUCTIVE TEST																		
Sr. No.	HEAT NO	STRAIGHTNESS	HYDRO-STATIC TEST as Per ASTM A630 and holding time 8 sec min(100%)	E.C.T. as Per ASTM E 208 (100%) (Orif hole-1.4 mm)	U.T. AS PER ASTM E 213 (100%)	VDI	IN SIDE / OUT SIDE	RA VALUE	PMI									
1	18R103	Satisfactory	2500 PSI, OK	OK	NA	Satisfactory	Satisfactory	NA	Satisfactory									
Heat Treatment : Heat Treated Above 650°C (1200°F), Annealed condition																		
MARKING: LBST / 18R103 CDS / ASTM A106B/ASME SA106B/CSAZ245.1 CAT 1 GRADE 290/NACE MR0175/ISO MR15156/ NACE MR 0103/ ISO 17545 / 1/2", XH X WT 0.147" X 21.0 FEET/ HEAT NO. 18R103 / NDE/HYD. 2500 PSI/MADE IN INDIA																		

Fig. 69 Mill Test Certificate

A typical mill test certificate contains:

- Manufacturer information
- Material specification
- Material grade
- Heat number
- Size and dimensions
- Chemical composition
- Mechanical properties

- Heat treatment information
- Hydrostatic test results
- Non-destructive examination results
- Certification statement

In this example, the certificate identifies the pipe as:

- ASTM A106 Grade B
- ASME SA106 Grade B
- Heat Number 18R103
- 1/2" extra-heavy seamless pipe

The chemical analysis demonstrates that the material composition meets the applicable specification, while the mechanical test results demonstrate that the required strength properties have been achieved.

20.12.3 Certificate of Test

The Heat Code **CA1314**, Heat Number **382611Z**, and description **1 3M THD TEE 105N** connect this document to line 100 of the invoice.



Certificate of Test

ITEM INFORMATION														
Part Number:	0366708154				Description:	1 3M THD TEE 105N								
Heat Code:	CA1314				Heat Number:	382611Z								
Reference No.:														
Part Specification:	ASTM A105/A105M-21 / ASME SA105-19													
CHEMICAL ANALYSIS %														
C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Cb/Nb	N	CE	TI	CE
0.19	1.06	0.014	0.002	0.21	0.03	0.02	0.06	0.01	0.002	0.002	0.005	0.38	0.002	0.384
CE (LONG FORMULA) = 0.384														
PHYSICAL PROPERTIES														
Yield KSI	Yield PSI	Yield MPA	Tensile KSI	Tensile PSI	Tensile MPA	Elongation	REDUCTION OF AREA %	HARDNESS 1 BHN/HRC	HARDNESS 2 BHN/HRC					
55.0	55000	379	76.9	76900	530	38	70	147	149					
Heat Treatment: NORMALIZED.														

Fig. 70 Certificate of Test

A certificate of test for a fitting typically contains:

- Manufacturer information
- Part number
- Material specification
- Heat code
- Heat number
- Chemical composition
- Mechanical properties
- Heat treatment information

In this example, the certificate identifies the fitting as:

- ASTM A105 / ASME SA105 forged carbon steel
- 1" threaded tee

- Class 3000 fitting
- Heat Code CA1314
- Heat Number 382611Z

The document also provides the chemical analysis and mechanical properties of the material from which the fitting was manufactured.

20.12.4 Following the Traceability Chain

The process of traceability can now be followed from one document to another:

```

Invoice
↓
Heat Number 18R103
↓
Pipe Mill Test Certificate

Invoice
↓
Heat Code CA1314
↓
Certificate of Test for Tee

```

An inspector reviewing the installation can therefore verify:

- What material was purchased.
- Which heat the material came from.
- The chemical composition of the material.
- The mechanical properties of the material.
- Compliance with the specified standard.

This ability to follow the chain from component to certificate is the foundation of material traceability.

20.13 Material Identification vs. Material Certification

A marking on a pipe, fitting, or valve identifies the component. An MTR provides the documentation that supports that identification.

For example, a pipe marked ASTM A106 Grade B may appear to be suitable for service, but without the corresponding MTR there may be no way to verify the material's chemistry, mechanical properties, or traceability.

Markings and documentation work together. One does not replace the other.

20.14 Not Every Component Requires an MTR

Material test reports are common for pressure-retaining components such as pipe, fittings, flanges, and valves used in code construction.

However, not every item in a plant will have an associated MTR. The documentation requirements depend on the governing code, quality program, purchaser requirements, and intended service.

20.15 The Inspector's Question

When reviewing a pressure system, an inspector is often asking a simple question:

"Can you prove that this component is what you say it is?"

The purpose of markings, heat numbers, and material test reports is to provide that proof.

If the traceability chain can be followed from the installed component back to the supporting documentation, the material can be verified. If that chain is broken, verification may no longer be possible.

Chapter 21

Canadian Registration Numbers (CRNs)

A Material Test Report (MTR) helps prove that a component is made from the correct material. A Canadian Registration Number (CRN) serves a different purpose.

A CRN demonstrates that the design of a pressure-retaining component has been reviewed and accepted for use by the applicable Canadian regulatory authority.

In simple terms:

- An MTR helps prove the material is acceptable.
- A CRN helps prove the design is acceptable.

Both may be required before a component can be installed in a pressure system.

21.1 What Is a CRN?

CRN stands for **Canadian Registration Number**.

A CRN is issued after a pressure-retaining design has been reviewed and accepted by the appropriate regulatory authority.

CRNs are commonly found on:

- Valves
- Fittings
- Pressure vessels
- Boilers
- Heat exchangers
- Pressure piping components

A component that requires registration may not be legally installable until an appropriate CRN has been obtained.

21.2 Why CRNs Exist

Pressure equipment can store a tremendous amount of energy.

If a component fails, the consequences may include:

- Serious injury
- Property damage
- Loss of production
- Environmental damage

CRNs provide a mechanism for verifying that pressure-containing designs meet the requirements of applicable codes and standards before they are placed into service.

21.3 CRNs and MTRs

MTRs and CRNs are often confused because both involve documentation.

However, they answer different questions.

Question	Document
Is the material acceptable?	MTR
Is the design acceptable?	CRN

A valve may have:

- A valid MTR for its material.
- A valid CRN for its design.

Both forms of documentation may be required.

21.4 Typical CRN Format

A typical CRN may appear similar to: 0C12345.5C or 0F56789.2.

The format can vary, but the CRN typically contains two important pieces of information:

- A registration number.
- One or more jurisdiction identifiers.

The meaning of the jurisdiction code is discussed later in this chapter.

21.5 Where Is the CRN Found?

The CRN may appear on:

- A nameplate
- A casting
- A stamping
- A manufacturer's data report
- Product documentation

Examples include markings on:

- Pressure vessels
- Safety valves
- Fittings
- Strainers
- Heat exchangers

When inspecting a component, both the physical marking and the supporting documentation should be reviewed.

21.6 Components That Commonly Have CRNs

Steam operators frequently encounter CRNs on:

21.6.1 Valves

Examples include:

- Safety valves
- Pressure reducing valves
- Control valves

21.6.2 Fittings

Examples include:

- Forged steel fittings
- Specialized branch fittings
- Strainers

21.6.3 Pressure Vessels

Examples include:

- Air receivers
- Steam separators
- Heat exchangers
- Boiler components

21.7 Reading a CRN

A CRN is not intended to provide material properties or operating pressures.

Instead, the CRN acts as a reference that links the component design to the registration records maintained by the regulatory authority.

The CRN does not replace:

- MTRs
- Pressure ratings
- Nameplate information
- Code markings

Rather, it supplements them.

21.8 Why Pipefitters Should Care

Pipefitters, inspectors, and owners are often responsible for verifying that the correct components have been installed.

During inspections, questions may include:

- Does this component require a CRN?
- Is a CRN present?
- Does the documentation match the component?

Understanding where to find a CRN and what it represents can help avoid delays during inspection and certification.

21.9 Common Misconception

Many people assume that a CRN proves a component is safe to use. In reality, a CRN only demonstrates that the design has been reviewed and accepted.

The condition of the component must still be verified by inspection, testing, and proper maintenance.

For example, a valve may have a valid CRN but still be:

- Worn
- Damaged
- Improperly installed
- Unsuitable for the intended service

A CRN demonstrates acceptance of the design, not the condition of the individual component.

21.10 Example CRN Registration

The following document is part of a CRN registration for Crane valves.

		STATUTORY DECLARATION (Manufacturer: Crane Valves) ATTACHMENT – SCOPE OF REGISTRATION		THIS IS PART OF NOC 1287.5 Technical Standards & Safety Authority Boilers & Pressure Vessels		Crane Valves 254 Henry Street Brampton, Ontario Canada N3T 5T7 Toll Free/800-361-6377 Tel: 519-759-3977 Fax: 519-759-3970 http://www.cranewalve.com/	
Design Code/Standard: MSS SP-80 Valve type/description: Bronze Gate, Globe and Check Valves		Safety Program		Size Range		Jenkins Crane	
200 CWP	ASTM B62	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Soldered Ends	1/2" to 3"	---	---	---	1320
300 CWP	ASTM B62	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Soldered Ends	1/2" to 3"	313J*004	1324*004	---	---
125 WSP / 200 CWP	ASTM B62	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Threaded Ends	1/2" to 3"	310J	---	---	438
150 WSP / 300 CWP	ASTM B62	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Threaded Ends	1/4" to 3"	2310J	---	---	437
150 WSP / 225 CWP	ASTM B62	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Flanged Ends	1" to 3"	2429J	---	---	429
200 WSP / 400 CWP	ASTM B61	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Union Bonnet, SS Seat Rings, Threaded Ends	1/2" to 2"	2272J	---	---	426
300 WSP / 1000 CWP	ASTM B61	Bronze Gate Valve, Non-Rising Stem, Solid Wedge, Union Bonnet, SS Seat Rings, Threaded Ends	1/4" to 2"	2282J	---	---	636E
200 CWP	ASTM B62	Bronze Gate Valve, Rising Stem, Solid Wedge, Soldered Ends	1/2" to 3"	---	---	---	1330
300 CWP	ASTM B62	Bronze Gate Valve, Rising Stem, Solid Wedge, Soldered Ends	1/2" to 3"	---	---	---	---
125 WSP / 200 CWP	ASTM B62	Bronze Gate Valve, Rising Stem, Solid Wedge, Threaded Ends	1/2" to 3"	810J	---	---	428
150 WSP / 300 CWP	ASTM B62	Bronze Gate Valve, Rising Stem, Solid Wedge, Threaded Ends	1/4" to 3"	2810J	---	---	634
200 WSP / 400 CWP	ASTM B61	Bronze Gate Valve, Rising Stem, Solid Wedge, Union Bonnet, Integral Bronze Seat, Threaded Ends	1/4" to 2"	---	---	---	422
300 WSP / 1000 CWP	ASTM B61	Bronze Gate Valve, Rising Stem, Solid Wedge, Union Bonnet, Integral Bronze Seat, Threaded Ends	1/4" to 2"	---	---	---	622E
300 WSP / 600 CWP	ASTM B61	Bronze Gate Valve, Rising Stem, Solid Wedge, Union Bonnet, Integral Bronze Seat, Threaded Ends	2 1/2" to 3"	---	---	---	622E
200 WSP / 400 CWP	ASTM B61	Bronze Gate Valve, Rising Stem, Solid Wedge, Union Bonnet, SS Seat Rings, Threaded Ends	1/4" to 3"	2270JJ	---	---	424
300 WSP / 1000 CWP	ASTM B61	Bronze Gate Valve, Rising Stem, Solid Wedge, Union Bonnet, SS Seat Rings, Threaded Ends	1/4" to 3"	2280JJ	---	---	634E
300 WSP / 600 CWP	ASTM B61	Bronze Gate Valve, Rising Stem, Solid Wedge, Union Bonnet, SS Seat Rings, Threaded Ends	1/4" to 3"	2290JJ	---	---	634E
125 WSP / 200 CWP	ASTM B62	Bronze Gate Valve, Rising Stem, Union Bonnet Solid Wedge, Threaded Ends	1/4" to 3"	47CUJ	---	---	437UB
150 WSP / 300 CWP	ASTM B62	Bronze Gate Valve, Rising Stem, Union Bonnet Solid Wedge, Threaded Ends	1/4" to 3"	106BJ	---	---	7TF
300 CWP	ASTM B62	Bronze Globe Valve, #6 PTFE Disc, Soldered Ends	1/4" to 3"	---	---	---	---
150 WSP / 300 CWP	ASTM B62	Bronze Globe Valve, #6 PTFE Disc, Threaded Ends	1/4" to 3"	---	---	---	---
150 WSP / 300 CWP	ASTM B62	Bronze Globe Valve, Rising Stem, Union Bonnet, SS Seat Ring, Renewable Disc, Threaded Ends	1/4" to 2"	2032J	---	---	141/2P

Fig. 71 Crane CRN

This document illustrates an important concept: a CRN is usually issued for a family of pressure-retaining designs rather than for a specific serial-numbered valve.

The registration identifies:

- The manufacturer
- The applicable design standard
- The types of valves covered
- Materials of construction
- Pressure ratings
- Size ranges
- Manufacturer model numbers

In this example, the registration applies to a variety of bronze gate, globe, and check valves manufactured in accordance with MSS SP-80.

21.10.1 What Does the CRN Cover?

A common misconception is that a CRN certifies an individual valve. In reality, the CRN applies to the design of the valve.

For example, a particular model listed in the registration may be available in:

- Several sizes
- Multiple pressure ratings
- Different end connections

All of these configurations may be covered by the same registration provided they fall within the approved scope.

21.10.2 What Does the CRN Not Cover?

A CRN does not:

- Prove the material composition
- Replace the MTR
- Verify the condition of a valve

- Guarantee proper installation

Those matters are addressed through material certification, inspection, testing, and maintenance.

21.10.3 The Relationship Between MTRs and CRNs

The previous chapter discussed Material Test Reports (MTRs).

The relationship can be summarized as: MTR proves the material while CRN proves the design.

Both may be required to demonstrate that a pressure-retaining component is acceptable for service.

21.11 Understanding the Province and Territory Suffixes

The digits and letters that appear after the decimal point in a CRN identify the jurisdictions in which the design has been accepted.

The first digit or letter after the decimal point indicates the province or territory where the design was first registered.

Code Province or Territory

1	British Columbia
2	Alberta
3	Saskatchewan
4	Manitoba
5	Ontario
6	Quebec
7	New Brunswick
8	Nova Scotia
9	Prince Edward Island
0	Newfoundland and Labrador
N	Nunavut
T	Northwest Territories
Y	Yukon

21.11.1 Examples

A CRN such as: 4321.5 indicates a design that was first registered in Ontario.

A CRN such as: 4321.52 indicates a design first registered in Ontario and subsequently accepted in Alberta.

Likewise, 4321.15 indicates a design first registered in British Columbia and later accepted in Ontario.

The order of the suffixes is important because the first jurisdiction shown is the jurisdiction that originally issued the registration. A design registered in Ontario and later accepted in Alberta is not the same registration history as a design first registered in Alberta and later accepted in Ontario.

21.11.2 The Meaning of "C"

Many modern CRNs end with the letter c. For example: 0C12877.5C. The letter **C** indicates that the design has been accepted in all Canadian jurisdictions.

In this example:

- The design was first registered in Ontario (5).
- The design was subsequently accepted throughout Canada (C).

This abbreviation is commonly used because listing every individual province and territory would make the CRN unnecessarily long.

21.11.3 Example from the Crane Registration

The Crane valve registration shown in [Fig. 71](#) carries the CRN: 0C12877.5. The .5 indicates that Ontario was the first jurisdiction to register the design.

If the registration subsequently receives acceptance across Canada, the CRN may be shown using the abbreviated form: 0C12877.5C where C indicates Canada-wide acceptance.

21.11.4 Why Pipefitters Should Care

When reviewing a valve, fitting, or pressure vessel, the presence of a CRN demonstrates that the design has been reviewed and accepted by the relevant regulatory authority.

Understanding the suffix allows you to determine:

- Where the design was first registered.
- Whether the design has been accepted in multiple jurisdictions.
- Whether the design has Canada-wide acceptance.

This becomes particularly important when purchasing pressure equipment that may be installed in different provinces or territories.

21.12 Historical Boilers and CRNs

Most modern valves, fittings, and pressure vessels are manufactured from standardized designs and are covered by a CRN that applies to an entire family of products.

Historical boilers are often very different.

Because many heritage boilers were built as individual machines, modified over their operating lives, repaired using a variety of methods, or constructed before modern design standards were established, each boiler may require its own unique registration and evaluation.

In Manitoba, heritage boilers are typically assigned an individual CRN because each boiler has a unique construction history, repair and alteration history, and inspection history.

21.12.1 Relationship Between CRN and MAWP

The CRN for a historical boiler is closely tied to the boiler's Maximum Allowable Working Pressure (MAWP).

The MAWP is established through a combination of:

- Inspection
- Non-destructive examination (NDE)
- Thickness measurements
- Engineering calculations
- Applicable code requirements

As the boiler ages, periodic inspections may reveal changes in condition, including corrosion, wastage, repairs, or other factors that affect strength.

Under the National Board Inspection Code (NBIC), historical boilers are periodically re-evaluated. If the results of inspection or NDE lead to a change in the calculated MAWP, the boiler's registration records must be updated to reflect the new allowable pressure.

A reduction in MAWP normally requires a corresponding change to the boiler's registered maximum allowable operating pressure and may require revisions to safety-valve settings, inspection records, and registration documentation.

21.12.2 Why This Matters

For modern catalogued valves and fittings, the CRN is primarily a design-registration document.

For historical boilers, the CRN becomes part of an ongoing process of inspection, engineering evaluation, and regulatory oversight.

As a result, a historical boiler's CRN may evolve over time as new inspection information becomes available and the boiler's allowable operating pressure is reassessed.

This is one reason why pressure ratings, safety-valve settings, inspection certificates, and CRN records must all remain consistent with the boiler's current MAWP.

21.13 Key Takeaway

A Canadian Registration Number (CRN) is evidence that a pressure-retaining component design has been reviewed and accepted by the applicable Canadian regulatory authority. While an MTR helps prove the material is acceptable, a CRN helps prove the design is acceptable. Both play important roles in demonstrating compliance and ensuring the safety of pressure equipment.

Chapter 22 Engine Types

22.1 Introduction

The steam engine was the first practical machine capable of converting heat energy into continuous mechanical power on a large scale. From the pumping engines of the eighteenth century to the great marine engines of the twentieth, steam engines powered mines, factories, railways, and ships throughout the industrialized world.

Although steam engines appeared in many forms, their operation was based on the same fundamental principle. Steam produced in a boiler enters a cylinder and exerts pressure on a piston. The piston's reciprocating motion is converted through a connecting rod and crank into rotary motion that can drive machinery, pumps, propellers, or locomotive wheels.

A simple explanation might suggest that steam should be admitted to the cylinder during the entire piston stroke. In practice, however, the most efficient engines admit steam for only part of the stroke. After the piston has traveled a fraction of its distance, typically between one-quarter and one-third of the stroke, the admission valve closes. The trapped steam continues to expand and pushes the piston to the end of the stroke without requiring additional steam from the boiler.

This process is known as **expansive working**. By allowing steam to expand after admission has stopped, the engine obtains more useful work from the same quantity of steam. Less steam is required for a given power output, reducing fuel and water consumption. Understanding expansive working is essential to understanding both simple and compound steam engines.

The operation of a steam engine can be studied using a **steam indicator**, an instrument that records cylinder pressure throughout the piston cycle. The resulting indicator diagram provides a graphical record of the engine's operation and identifies the principal events of the cycle:

- Steam admission
- Steam cut-off
- Expansion
- Exhaust release
- Compression

These events reveal how steam pressure changes during the stroke and how efficiently the engine uses the energy supplied by the boiler.

As engineers sought greater economy, they looked for ways to extract even more work from the steam before exhausting it. The solution was to divide the expansion process between two or more cylinders. Steam first expanded in a high-pressure cylinder and then passed through one or more larger cylinders, where additional expansion occurred. This development led to the compound, triple-expansion, and quadruple-expansion engines that became common in marine and stationary service during the late nineteenth and early twentieth centuries.

This chapter begins with the operation of the double-acting simple steam engine and the use of the steam indicator to study the events occurring within the cylinder. It then follows the development of compound, triple-expansion, and quadruple-expansion engines as engineers sought to improve the economy of steam power.

22.2 The Aeolipile



Fig. 72 Aeolipile

One of the earliest known steam-powered devices was the **Aeolipile**, described by Hero (Heron) of Alexandria during the first century AD. The device consisted of a hollow sphere mounted so that it could rotate freely. Steam produced in a boiler passed into the sphere and escaped through bent nozzles. The reaction force of the escaping steam caused the sphere to spin.

Although the Aeolipile demonstrated that steam could produce motion, it was not a practical engine. It could not perform useful work beyond its own rotation and was not connected to machinery. Nevertheless, it is historically significant because it illustrates an understanding of steam power nearly two thousand years before the Industrial Revolution.

The development of practical steam engines required a different approach. Instead of producing rotary motion directly from escaping steam, engineers learned to use steam pressure to move a piston within a cylinder. This arrangement made it possible to perform useful work and led to the development of the reciprocating steam engine.

22.3 Operation of a Double-Acting Simple Steam Engine

The double-acting simple steam engine is the basic form of reciprocating steam engine from which many later designs were developed. In a double-acting engine, steam acts alternately on both sides of the piston, producing power during both the outward and return strokes.

The principal components of the engine ([Fig. 73](#)) are the cylinder, piston, piston rod, connecting rod, crankshaft, flywheel, and steam valve. Steam from the boiler enters the cylinder through ports controlled by the valve mechanism. As steam pressure acts on one side of the piston, the piston moves through the cylinder and turns the crankshaft. At the same time, spent steam on the opposite side of the piston is released through the exhaust port.

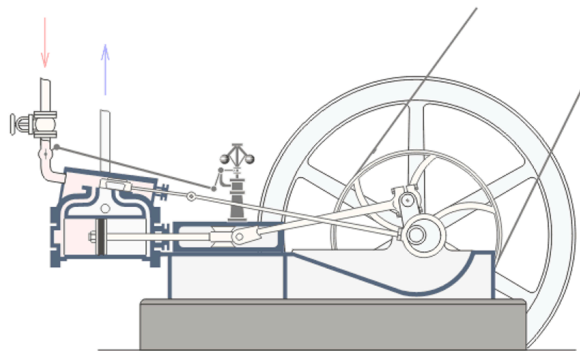


Fig. 73 Double Acting Simple

Near the end of the stroke, the valve mechanism changes position. Steam is then admitted to the opposite side of the piston while the first side is opened to exhaust. The piston reverses direction and the process repeats. As long as steam is supplied from the boiler, the engine continues to produce rotary motion.

Because power is developed during both strokes, a double-acting engine produces a smoother turning effort than a single-acting engine. The flywheel stores energy during the stronger portions of the cycle and releases it during the weaker portions, helping to maintain a more uniform rotational speed.

The pressure acting on the piston is not constant throughout the stroke. Steam is admitted, expanded, exhausted, and compressed in a carefully controlled sequence. These pressure changes determine both the power produced by the engine and its efficiency. To study these changes, engineers use an instrument known as a **steam indicator**, which produces a graphical record of cylinder pressure during each piston cycle.

22.3.1 Comparison with Internal-Combustion Engines

Students familiar with gasoline or diesel engines may find it useful to compare the frequency of power strokes in different engine types.

In a four-stroke (Otto-cycle) engine, each cylinder produces one power stroke for every two revolutions of the crankshaft. The remaining strokes are required for intake, compression, and exhaust.

A two-stroke engine produces one power stroke for every revolution of the crankshaft.

A double-acting steam engine is different. Steam pressure acts alternately on both sides of the piston, producing power during both the outward and return strokes. Since each piston stroke corresponds to one-half revolution of the crankshaft, the engine delivers a power stroke every half revolution.

For a single cylinder, the comparison is:

- Four-stroke internal-combustion engine: 1 power stroke per 2 revolutions
- Two-stroke internal-combustion engine: 1 power stroke per revolution
- Double-acting steam engine: 1 power stroke per 1/2 revolution

This frequent application of power helps explain the smooth operation of steam engines and reduces the size of the flywheel needed to carry the engine through non-power-producing portions of the cycle.

22.3.2 The Steam Indicator

The operation of a steam engine cannot be fully understood by observing the motion of the piston and valve gear alone. Engineers must also know how the steam pressure changes throughout the piston stroke. To measure these pressure changes, early engineers developed an instrument known as the **steam indicator**.

Instruments like these date back to the days of James Watt in the late 18th century. The illustration in [Fig. 74](#) is of a steam indicator developed by Charles Richards a hundred years later.

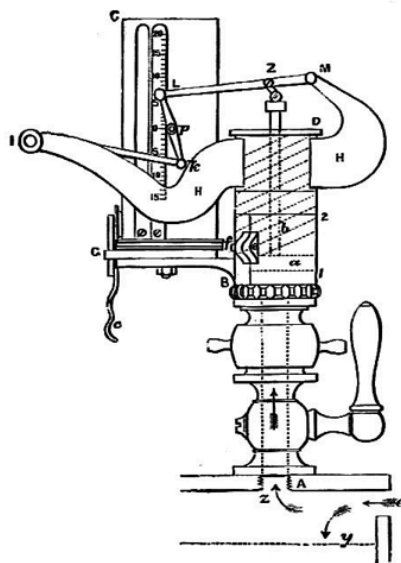


Fig. 74 Steam Indicator c. 1875

22.3.2.1 The Intuition

The purpose of a steam indicator is to record what is happening inside the cylinder while the engine is running. It produces a graphical record of cylinder pressure throughout the piston stroke.

A simple way to visualize the instrument is to imagine a sheet of paper wrapped around a tin can. The can oscillates back and forth in step with the engine piston. A pencil rests against the paper and moves up and down in response to the steam pressure inside the cylinder.

As the piston travels through its stroke, the paper moves horizontally. As the cylinder pressure rises and falls, the pencil moves vertically. The combined motions trace a closed loop on the paper known as an **indicator diagram** or **indicator card**.

The horizontal direction of the diagram represents piston position within the cylinder, while the vertical direction represents steam pressure. The shape of the loop reveals the events occurring during the piston cycle and provides valuable information about engine operation.

Engineers used indicator diagrams to evaluate performance, adjust valve settings, diagnose operating problems, and compare the efficiency of different engine designs. For the steam engineer, the indicator diagram became one of the most important tools for understanding what was happening inside the cylinder.

By examining the indicator diagram, it is possible to identify the principal events of the steam-engine cycle:

- Steam admission
- Steam cut-off
- Expansion
- Exhaust release
- Compression

These events explain how a steam engine obtains useful work from expanding steam and form the foundation for understanding compound and multiple-expansion engines.

22.3.3 The Implementation

A steam indicator is connected to the engine cylinder by a small pipe. Inside the instrument, a spring-loaded piston moves in response to changes in cylinder pressure. At the same time, a mechanism driven from the engine crosshead moves a pencil horizontally in proportion to piston position. The resulting diagram records cylinder pressure against piston travel.

The diagram produced by the instrument is known as an **indicator diagram** or **indicator card**. It provides a graphical record of the events occurring within the cylinder during each cycle.

For steam engineers, the indicator diagram serves much the same purpose that diagnostic instruments serve for modern internal-combustion engines. It reveals how effectively the engine is operating and can identify problems such as incorrect valve timing, excessive back pressure, steam leakage, or restricted exhaust flow.

The indicator was one of the most important tools available to steam engineers because it transformed the operation of the engine from guesswork into a measurable engineering process. By studying the indicator diagram, engineers could evaluate engine performance, adjust valve settings, and compare the effectiveness of different engine designs.

The indicator diagram also provides a convenient way to visualize the principal events of the steam-engine cycle. These events include steam admission, steam cut-off, expansion, exhaust release, and compression. Understanding these events is essential to understanding why compound and multiple-expansion engines achieve greater efficiency than simple engines.

22.3.4 Events of the Piston Cycle

The indicator diagram records the changing pressure within the cylinder as the piston moves through its stroke. By following the diagram clockwise, the principal events of the steam-engine cycle can be identified.

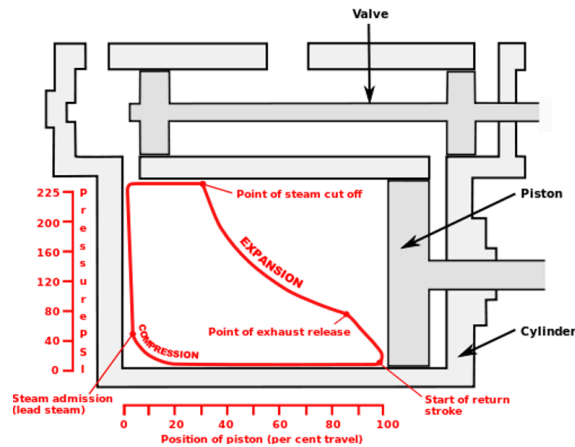


Fig. 75 Schematic Indicator Diagram

Unlike a stand-alone indicator card, Figure [Fig. 75](#) places the indicator diagram directly on the engine cylinder. This allows the reader to associate events on the diagram with the physical position of the piston and the operation of the valves.

22.3.4.1 Steam Admission

At the beginning of the stroke, the admission valve opens and high-pressure steam enters the cylinder. Pressure rises rapidly and acts on the piston, producing the force required to move the piston and turn the crankshaft.

On the indicator diagram, steam admission appears as the near-vertical rise at the left side of the loop.

22.3.4.2 Steam Cut-Off

After the piston has traveled a portion of its stroke, the admission valve closes. No additional steam enters the cylinder.

Rather than ending the power stroke, the trapped steam continues to push on the piston. This is known as **cut-off**, and it marks the beginning of expansive working.

The position of cut-off is one of the most important adjustments affecting engine performance and economy.

22.3.4.3 Expansion

Following cut-off, the steam expands as the piston continues its travel toward the end of the cylinder. As the steam expands, both pressure and temperature decrease. Even though the pressure falls, the steam continues to exert force on the piston and produce useful work.

The curved upper portion of the indicator diagram represents the expansion of the steam.

The ability of expanding steam to continue performing work after admission has stopped is the key to the efficiency of the steam engine.

22.3.4.4 Exhaust Release

Near the end of the stroke, the exhaust valve opens. The remaining steam is released from the cylinder, causing a sudden drop in pressure.

This event is known as **release**. By opening slightly before the piston reaches the end of the stroke, the engine reduces the pressure that would otherwise oppose the return movement of the piston.

On the indicator diagram, release appears as the steep drop on the right side of the loop.

22.3.4.5 Compression

As the piston begins its return stroke, the exhaust valve closes before the piston reaches the end of its travel. A small quantity of steam remains trapped within the cylinder.

This trapped steam is compressed during the final portion of the return stroke, causing cylinder pressure to rise again before fresh steam is admitted.

Compression cushions the motion of the piston, reduces mechanical shock, and prepares the cylinder for the next admission of steam.

The lower portion of the indicator diagram represents this compression process.

22.3.4.6 The Complete Cycle

Together, steam admission, cut-off, expansion, release, and compression form a complete piston cycle. The indicator diagram provides a convenient way to visualize these events and to understand how the engine converts the energy contained in steam into useful mechanical work.

Of these events, cut-off and expansion are particularly important. They allow the engine to continue producing work after steam admission has stopped, reducing steam consumption and improving operating economy.

22.4 Expansion and Thermal Efficiency

One of the most important questions in steam-engine design is why steam admission is cut off before the piston reaches the end of its stroke.

A simple solution would be to keep the admission valve open throughout the entire stroke. While this would produce a large force on the piston, it would also consume a large quantity of steam. Steam engineers discovered that a more economical approach was possible.

High-pressure steam enters the cylinder through the admission valve and begins pushing the piston. After the piston has travelled approximately 25% to 33% of its stroke, the valve closes. No additional steam enters the cylinder, but the trapped steam continues to expand as the piston moves toward the end of its stroke.

Although the pressure of the steam falls during expansion, it continues to exert force on the piston and perform useful work. In this way, the engine extracts additional work from steam that has already been admitted to the cylinder.

Near the end of the stroke, the exhaust valve opens and the remaining steam is released. Depending on the type of engine, the exhaust steam may be discharged directly to the atmosphere or passed into a condenser.

The ability of expanding steam to continue performing work after admission has stopped is known as **expansive working**. This is one of the fundamental principles of efficient steam-engine operation.

22.4.1 Temperature Changes During Expansion

As steam expands in the cylinder, its pressure decreases. Its temperature also decreases as energy is transferred to the piston in the form of mechanical work.

Ideally, very little heat is exchanged between the steam and its surroundings during the brief period of expansion. Engineers describe this process as **adiabatic expansion**, meaning that the steam performs work while losing little or no heat to the outside environment.

As a result, steam enters the cylinder at a relatively high temperature and leaves at a lower temperature after expansion.

22.4.2 A Source of Inefficiency

The changing temperature of the steam creates a problem. During admission, the hot incoming steam heats the cylinder walls. During expansion and exhaust, the cooler steam allows those same walls to cool.

This continual cycle of heating and cooling occurs with every stroke of the engine. Energy is repeatedly transferred into and out of the metal cylinder rather than being converted into useful work.

The heating and cooling of the cylinder is one of the principal sources of inefficiency in a simple steam engine.

22.4.3 The Trade-Off

Early cut-off improves economy because more work is obtained from each pound of steam admitted to the cylinder. However, there is a disadvantage.

Because steam pressure falls during expansion, the force acting on the piston becomes progressively smaller during the stroke. The turning moment, or torque, applied to the crankshaft therefore becomes less uniform.

To smooth out these variations, steam engines rely on a flywheel. The flywheel stores energy during the stronger portions of the cycle and releases it during the weaker portions. Engines employing very early cut-off generally require larger flywheels to maintain a steady speed.

Steam engineers therefore faced a compromise. Early cut-off improved economy by reducing steam consumption, but it also increased the variation in turning effort. Much of the history of steam-engine development can be viewed as an attempt to achieve both good economy and smooth operation.

22.5 The Uniflow Engine

The compound and multiple-expansion engines improved efficiency by dividing the expansion of steam among several cylinders. This reduced the temperature range experienced by any one cylinder and allowed more work to be extracted from the steam before it was exhausted.

Engineers eventually recognized another source of inefficiency. In conventional steam engines, steam enters and leaves through ports located at the ends of the cylinder. Hot incoming steam and cooler exhaust steam therefore pass through the same regions of the cylinder. As a result, the cylinder walls are repeatedly heated and cooled during each cycle.

This continual temperature cycling wastes energy and promotes condensation of steam within the cylinder.

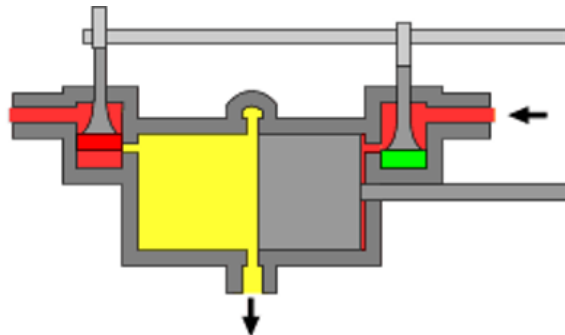


Fig. 76 Uniflow Engine

The **uniflow engine** was developed to reduce this problem. A useful way to visualize a uniflow engine is as two half-cylinders sharing a common exhaust region at the center of the cylinder. Steam enters through inlet valves located near the ends of the cylinder but exhausts through ports near the center. Near the end of the stroke, the piston uncovers exhaust ports located close to the center of the cylinder, allowing the steam to escape.

Unlike a conventional double-acting engine, where admission and exhaust occur alternately at both ends of the cylinder, steam in a uniflow engine always travels in the same general direction: from the hot ends of the cylinder toward the cooler central exhaust ports.

Because the ends of the cylinder remain relatively hot while the central exhaust region remains relatively cool, temperature variations within the cylinder are reduced. This decreases condensation losses and improves thermal efficiency.

The uniflow engine represented one of the final major developments in reciprocating steam-engine design. Although it arrived after compound and triple-expansion engines had become well established, it demonstrated that significant improvements in efficiency were still possible through careful management of heat flow within the cylinder.

The history of steam-engine development can be viewed as a continual effort to extract more useful work from each pound of steam. Early cut-off, expansive working, compound expansion, and the uniflow principle were all important steps toward that goal.

22.5.1 Historical Note: Steam-Engine Catechisms

Many nineteenth- and early twentieth-century engineering manuals were written in the form of a catechism: a series of questions and answers intended for memorization and discussion. This format reflected the apprenticeship system through which many engineers, mechanics, and engine operators learned their trade.

The goal was not merely to provide information but to establish a shared technical vocabulary. By repeatedly reviewing questions and answers, apprentices learned both the terminology and the principles needed to operate and maintain steam machinery.

Nehemiah Hawkins's *Steam Engine Catechism* and *Steam Indicator Catechism* were among the best-known examples of this style of technical instruction.

22.6 Engine Configurations

The double-acting simple engine uses a single cylinder in which steam is admitted, expanded, and exhausted. While this arrangement is mechanically simple and reliable, engineers soon recognized that additional work could be obtained from the steam before it was exhausted.

As steam expands, its pressure and temperature decrease. In a simple engine, a large temperature range exists between admission and exhaust, causing repeated heating and cooling of the cylinder walls. Steam engineers therefore sought methods of dividing the expansion process into stages.

The solution was the **compound engine**. Instead of exhausting steam after a single expansion, the steam is passed from one cylinder to another, expanding progressively as its pressure decreases. Each cylinder handles only a portion of the total expansion.

In a compound engine, high-pressure steam first enters a relatively small **high-pressure (HP) cylinder**. After doing work there, the partially expanded steam passes to a larger **low-pressure (LP) cylinder**, where additional expansion takes place before the steam is exhausted to the atmosphere or to a condenser.

The purpose of compounding is not simply to add cylinders. The purpose is to obtain more useful work from the steam, reduce cylinder temperature variations, and improve the overall economy of the engine.

Several arrangements were developed to achieve these goals. The principal configurations are described in the following sections.

22.6.1 Cross Compound

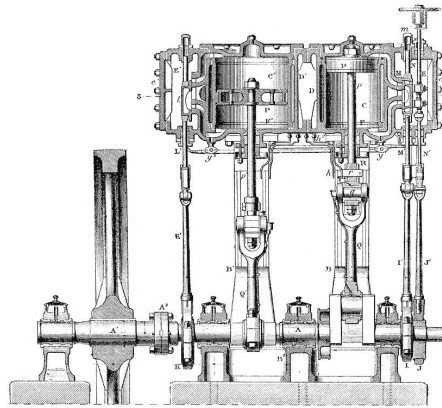


Fig. 77 Cross Compound

In the cross-compound arrangement, the high-pressure and low-pressure cylinders are mounted side by side and drive separate crank throws on a common crankshaft. Steam first enters the smaller high-pressure cylinder and performs part of its expansion. It then passes to the larger low-pressure cylinder, where expansion continues before the steam is exhausted.

The low-pressure cylinder must be larger than the high-pressure cylinder because the steam occupies a greater volume after it has expanded.

A cross-compound engine can be recognized by its two separate cylinders and connecting rods acting on different crank throws. This arrangement distributes the turning effort more evenly around the crankshaft and provides smoother operation than would be obtained from a single-cylinder engine.

The steam follows the path:

Boiler → High-Pressure Cylinder → Low-Pressure Cylinder → Exhaust

The cross-compound engine became a popular arrangement for stationary and marine service because it combined improved economy with relatively straightforward mechanical construction.

22.6.2 Triple-Expansion Engine

As boiler pressures increased during the nineteenth century, engineers found that even greater economy could be achieved by expanding steam in three stages instead of two. This led to the development of the **triple-expansion engine**, one of the most successful steam-engine designs ever built.

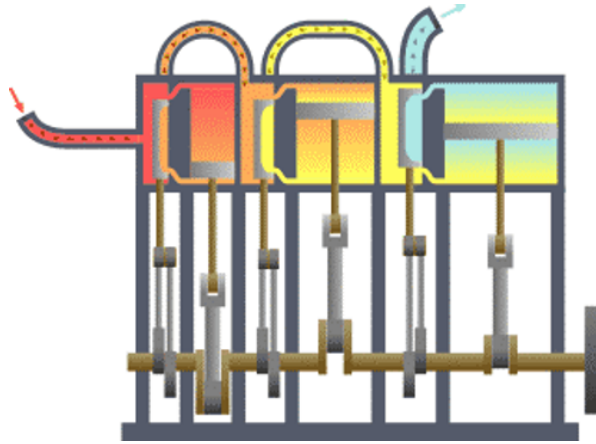


Fig. 78 Triple-expansion Engine

In a triple-expansion engine, steam passes through three cylinders of progressively increasing size:

- High-Pressure (HP) Cylinder
- Intermediate-Pressure (IP) Cylinder
- Low-Pressure (LP) Cylinder

High-pressure steam from the boiler first enters the HP cylinder, where it performs part of its work. The partially expanded steam then passes to the IP cylinder, where further expansion occurs. Finally, the steam enters the LP cylinder, where the last stage of expansion takes place before the steam is exhausted to a condenser or, in some cases, directly to the atmosphere.

The steam path is therefore:

Boiler → HP Cylinder → IP Cylinder → LP Cylinder → Exhaust

Because steam expands as its pressure falls, each successive cylinder must be larger than the one before it. The low-pressure cylinder is often several times larger than the high-pressure cylinder.

Dividing the expansion process among three cylinders reduces the temperature range experienced by each cylinder. This decreases condensation losses and allows more useful work to be extracted from the steam before it is exhausted.

Triple-expansion engines became the preferred choice for many marine applications during the late nineteenth and early twentieth centuries. Their improved economy allowed ships to travel greater distances while carrying less coal, increasing both operating range and cargo capacity.

The triple-expansion engine represents the logical extension of the compound principle. Rather than extracting energy from the steam in one or two stages, the process is divided into three successive expansions, allowing the engine to make more complete use of the energy supplied by the boiler.

22.6.3 Tandem Compound

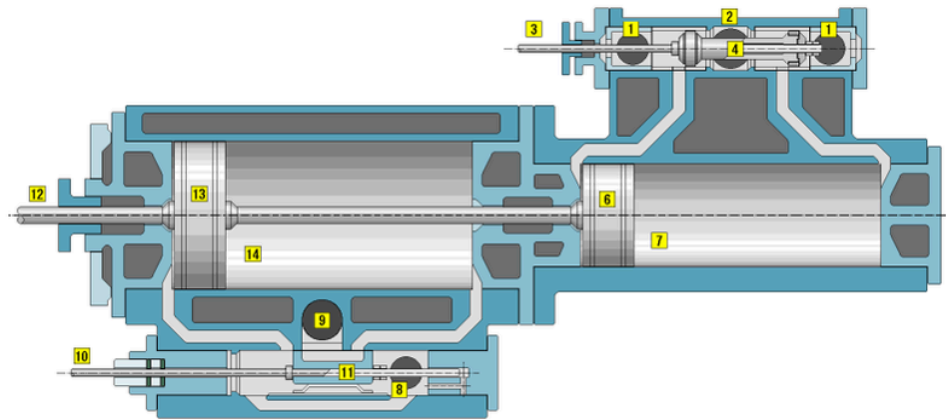


Fig. 79 Tandem Compound

In a tandem compound engine, the high-pressure (HP) and low-pressure (LP) cylinders are arranged in line and share a common piston rod. Both pistons drive the same connecting rod and crankshaft.

High-pressure steam first enters the smaller HP cylinder, where it performs part of its work. The partially expanded steam then passes directly into the larger LP cylinder, where expansion continues before the steam is exhausted.

The steam path is:

Boiler → HP Cylinder → LP Cylinder → Exhaust

Unlike the cross-compound engine, which uses separate connecting rods and crank throws, the tandem compound places both cylinders on the same centerline. This results in a more compact engine with fewer moving parts.

Because both cylinders act on a common piston rod, the forces produced by the HP and LP pistons combine before reaching the crankshaft. This simplifies the mechanical arrangement while retaining the economic advantages of compounding.

The tandem arrangement was widely used on stationary engines, traction engines, and other applications where a compact layout was desirable. Many agricultural and portable steam engines employed tandem compounds to obtain improved fuel economy without greatly increasing the overall size of the machine.

The tandem compound demonstrates that steam engineers could achieve the benefits of compound expansion through different mechanical arrangements. While the cross-compound and tandem-compound engines operate on the same thermodynamic principle, they differ significantly in the way their cylinders are connected to the crankshaft.

22.6.4 Vauclain Compound

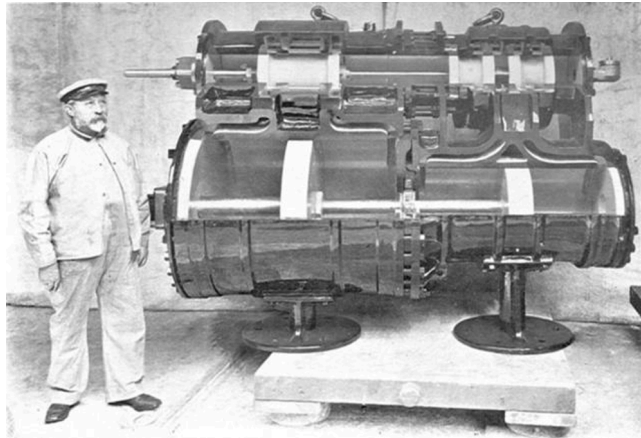


Fig. 80 Vauclain Compound

The Vauclain compound was developed by the Baldwin Locomotive Works as a compact method of applying compound expansion to railway locomotives.

Unlike a conventional cross-compound engine, the Vauclain arrangement places the high-pressure (HP) and low-pressure (LP) cylinders above one another on each side of the locomotive. The two pistons share a common crosshead and drive a single connecting rod.

High-pressure steam first enters the smaller HP cylinder. After partially expanding, the steam is directed to the larger LP cylinder where additional expansion takes place before exhaust.

The steam path is:

Boiler → HP Cylinder → LP Cylinder → Exhaust

The arrangement combines some of the advantages of both tandem and cross-compound engines. The cylinders are closely grouped, producing a compact installation suitable for locomotive service where space between the frame rails is limited.

The Vauclain compound was widely used during the late nineteenth century, particularly by railways seeking improved fuel economy. Although mechanically ingenious, the design was eventually displaced by simpler locomotive arrangements that were easier to maintain.

The Vauclain compound demonstrates how steam engineers adapted the compound principle to the unique requirements of locomotive operation.

22.6.5 Quadruple-Expansion Engine

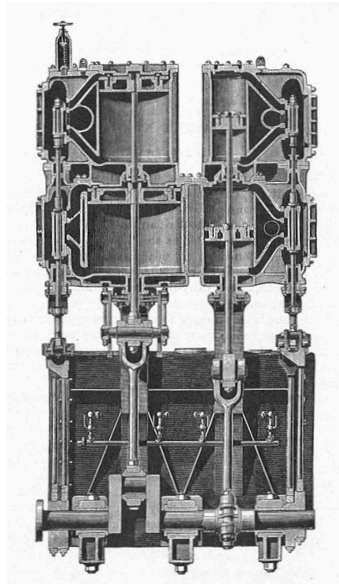


Fig. 81 Quadruple-Expansion Engine

As steam pressures continued to increase, some engineers sought even greater economy by dividing the expansion process into four stages. The result was the **quadruple-expansion engine**, the most highly developed form of the reciprocating compound steam engine.

Steam passes successively through four cylinders:

- High-Pressure (HP)
- First Intermediate-Pressure (IP)
- Second Intermediate-Pressure (IP)
- Low-Pressure (LP)

The steam path is therefore:

Boiler → HP → IP → IP → LP → Exhaust

Each cylinder is larger than the one before it because the steam occupies an increasingly greater volume as its pressure decreases.

The engine shown in Figure [Fig. 81](#) was built by Fleming & Ferguson of Paisley and illustrates a typical quadruple-expansion arrangement. The cylinder diameters are:

- HP: 10¼ in.
- 1st IP: 14 in.
- 2nd IP: 20 in.
- LP: 28 in.

with a common stroke of 20 inches.

Operating with a boiler pressure of 200 psi, the engine developed approximately 360 indicated horsepower.

By dividing expansion among four cylinders, the temperature range within each cylinder is reduced even further than in a triple-expansion engine. This minimizes condensation losses and extracts more useful work from the steam before it reaches the condenser.

Quadruple-expansion engines represented the pinnacle of marine reciprocating steam-engine development. While the gain in efficiency over a triple-expansion engine was relatively modest, the arrangement could be justified in applications where fuel economy was of great importance, particularly in long-distance marine service.

22.7 Summary

From the Aeolipile of Hero to the highly refined uniflow engine, the history of the steam engine is largely the history of improving the use of steam expansion. Engineers progressively learned how to obtain more work from each pound of steam while reducing fuel consumption and mechanical losses.

Although steam engines appeared in many configurations, the underlying objective remained the same: to convert as much of the steam's heat energy as possible into useful mechanical work before the steam was exhausted.

Chapter 23 Measurement of Power

23.1 Introduction

Power is the rate at which work is performed. In the steam age, power measurements allowed engineers to compare engines, evaluate operating performance, and determine whether a machine was producing the work expected of it.

Today power is commonly measured in watts or kilowatts, but during the development of the steam engine a more practical unit was required. Early engines were intended to replace horses in mines, mills, and pumping stations. As a result, engineers naturally compared the work produced by an engine to the work that could be performed by a horse.

One of the earliest references to this comparison appears in the writings of Thomas Savery, who promoted his early steam-powered pumping engine as a replacement for teams of horses.

“So that an engine which will raise as much water as two horses, working together at one time in such a work, can do, and for which there must be constantly kept ten or twelve horses for doing the same. Then I say, such an engine may be made large enough to do the work required in employing eight, ten, fifteen, or twenty horses to be constantly maintained and kept for doing such a work.”

— Thomas Savery, 1702

The concept was later refined by James Watt, who sought a practical and consistent way of comparing steam engines with the horses they replaced. His work eventually led to the unit known as horsepower, which remained the standard measure of engine output for more than a century.

The comparison was not accidental. Both Savery and Watt were concerned with the problem of removing water from coal mines, where horses were widely used to power pumps and other machinery. The "horses" being replaced were often the pit ponies and draft animals that worked in and around the mines. Mine owners understood the cost of feeding and maintaining a team of horses, so describing an engine in terms of the number of horses it could replace provided a practical and easily understood measure of its value.

When Watt began marketing his engines, he formalized this comparison by defining a standard unit of power based on the work that could be performed by a horse. This became known as the horsepower.

Watt defined one mechanical horsepower as the ability to perform 33,000 foot-pounds of work per minute, or 550 foot-pounds of work per second.

A 1-horsepower engine can therefore:

- Raise 33,000 pounds through a height of one foot in one minute.
- Raise 330 pounds through a height of 100 feet in one minute.
- Perform any equivalent amount of work at the same rate.

Mathematically:

$$1 \text{ hp} = 550 \frac{\text{ft}\cdot\text{lb}}{\text{s}}$$

or

$$1 \text{ hp} = 33000 \frac{\text{ft}\cdot\text{lb}}{\text{min}}$$

23.2 When is a Horsepower not a Horse

The term *horsepower* is often used as though it were a single, precisely defined quantity. In practice, several different definitions have been used depending upon what is being measured.

Steam engineers therefore need to be careful when discussing horsepower ratings, since two machines with the same horsepower figure may not be referring to the same measurement.

Other horsepower definitions include:

- **Electric horsepower:** equivalent to 746 watts of electrical power.
- **Boiler horsepower:** a rating of a boiler's ability to generate steam.
- **Indicated horsepower (IHP):** power developed within the engine cylinders.
- **Brake horsepower (BHP):** power available at the engine shaft.
- **Drawbar horsepower (DBHP):** useful pulling power available at the drawbar of a locomotive or traction engine.

The horsepower defined by Watt is now known as **mechanical horsepower**. Over time, engineers developed additional horsepower ratings for specific purposes, each measuring a different aspect of engine or boiler performance.

23.2.1 How Much Power Is a Horsepower?

The term *horsepower* suggests the power produced by a single horse, but the reality is more complicated.

Field experience showed that tasks such as plowing often required teams of several horses. The actual power available from a horse depends upon its size, conditioning, duration of work, ground conditions, and many other factors.

For this reason, James Watt's horsepower should not be regarded as the measured output of a particular horse. Rather, it is a standard unit of power that allows machines and animals to be compared using a common scale.

In practice, the useful measure is often not the number of horses, but the amount of work that can be performed. A farmer might ask how many plow bottoms can be pulled through a field, while a locomotive engineer might ask how many tons can be hauled up a grade. Such questions lead naturally to the concept of drawbar horsepower.

"The four-horse team and Talkington evenner ... have the line of draft about right for a single sulky plow or a two-bottom gang. The horses are spread well apart, wagon double-trees being used for the leaders. They have plenty of air and keep cooler than when crowded together. The team in Fig. 2 is pulling a 16-inch sulky plow in old alfalfa sod. Such an outfit is very good also for plowing under sweet clover in the spring." - M. L. Wilson, *Big Teams in Montana*, 1925.

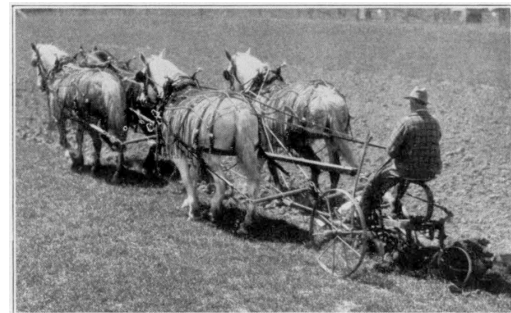


FIG. 2.—FOUR HORSES WITH A TALKINGTON HITCH ON A SULKY PLOW

23.3 Drawbar and Pulley Horsepower

For traction engines, tractors, and locomotives, the most important measure of performance is often not the power developed inside the cylinders, but the power available to perform useful work.

When pulling a load, the useful power is delivered through the drawbar and is known as **drawbar horsepower (DBHP)**.

Drawbar horsepower is determined by measuring two quantities:

- The pulling force at the drawbar.
- The speed at which the load is moved.

Power is simply the product of force and velocity.

For measurements expressed in pounds force and miles per hour:

$$hp_d = \frac{Fv}{375}$$

where

- F = drawbar pull (lb)
- v = speed (mph)

The constant 375 is derived from Watt's definition of horsepower:

$$375 = \frac{33000 \cdot 60}{5280}$$

23.3.1 Example

A tractor produces a drawbar pull of 2,025 pounds while travelling at 5 miles per hour.

The drawbar horsepower is:

$$hp_d = \frac{2025 \cdot 5}{375} = 27hp$$

23.3.2 Measurement

Historically, drawbar horsepower was determined by pulling a known load while measuring both force and speed.

A simple modern method uses a hydraulic cylinder placed between the vehicle and the load. The hydraulic pressure within the cylinder is proportional to the pulling force. By measuring pressure and vehicle speed, drawbar horsepower can be calculated directly.

Traction engines often performed a second role as stationary power plants. When operating a threshing machine, sawmill, elevator, or water pump, power was delivered through the belt pulley. This useful output is known as **pulley horsepower**.

Because power is lost in gears, bearings, wheels, wheel slip, and rolling resistance, drawbar horsepower is always less than the power available at the engine shaft. As a result, the same machine may have different ratings for pulley horsepower and drawbar horsepower depending on how the power is used.

23.4 Marketing Power Designations

The transition from animal power to mechanical power created an immediate need for simple and easily understood power ratings.

Farmers were accustomed to judging machinery by the number of horses required to perform a task. Steam-engine manufacturers therefore adopted horsepower ratings that allowed prospective customers to compare a machine's performance with that of horse-drawn equipment.

Unfortunately, horsepower could be measured in several different ways. As a result, the horsepower advertised by a manufacturer was not always the same quantity that an engineer would measure in a test.

Traction engines commonly carried two power ratings. Examples include:

- Case 18–50
- Case 22–65
- Case 28–80

The first number represented **boiler horsepower**, a measure of the boiler's steam-generating capacity. The second number represented **belt (pulley) horsepower**, the useful power available for driving stationary machinery.

Early gasoline tractors adopted a different convention. Machines were often advertised using **drawbar horsepower** and **belt horsepower**.

For example:

- Case 20–40

indicated approximately 20 drawbar horsepower and 40 belt horsepower.

These ratings reflected the two principal jobs expected of a farm power unit: pulling implements in the field and operating stationary machinery through a belt pulley.

Horsepower ratings found in advertisements, sales literature, and even on engine nameplates should therefore be interpreted carefully. Depending on the manufacturer and the period, the numbers may refer to boiler horsepower, indicated horsepower, brake horsepower, pulley horsepower, or drawbar horsepower.

23.5 Measuring Torque

As steam engines and gasoline tractors became common, manufacturers naturally wished to advertise the capabilities of their machines. Farmers, however, wanted more than claims and sales literature. They wanted objective measurements that allowed one machine to be compared fairly against another.

One response was the Winnipeg Tractor Trials, held between 1908 and 1913. The event was originally conceived as an industrial exhibition. At the time, Winnipeg was the principal railhead serving the recently settled prairie provinces of Saskatchewan and Alberta, and manufacturers were eager to demonstrate their machinery to western farmers.

The character of the event changed when agricultural researchers became involved. Professors from the Manitoba Agricultural College, later incorporated into the University of Manitoba, introduced scientific testing methods and standardized measurements. What began as a machinery exhibition evolved into a controlled engineering experiment in which competing tractors and engines could be compared under identical conditions.

The Winnipeg Trials became a forerunner of the better-known Nebraska Tractor Tests established after the First World War. Manufacturers quickly realized that independently verified performance figures carried far more weight than advertising claims alone.

To compare machines fairly, the judges needed a way to measure the power delivered at the engine shaft. This required the measurement of **torque**.

23.5.1 Gaspard de Prony

The solution had been developed nearly a century earlier by the French engineer Gaspard Clair François Marie Riche de Prony.

In 1826, de Prony described a simple device capable of measuring the torque produced by a rotating shaft. The device became known as the **de Prony brake** and remained one of the most widely used methods of determining engine power throughout the nineteenth and early twentieth centuries.

23.5.2 The De Prony Brake

The de Prony brake consists of a friction brake wrapped around a rotating drum or flywheel. Friction between the brake and the rotating surface attempts to carry the brake assembly around with the shaft.

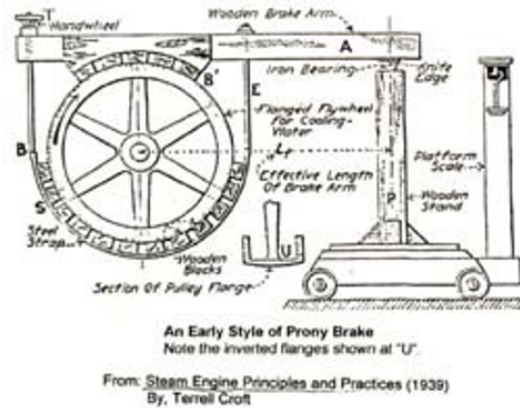


Fig. 82 De Prony Brake

A lever arm attached to the brake resists this motion. The force acting at the end of the lever can be measured using a scale or other force-measuring device.

The arrangement converts the engine's torque into two directly measurable quantities:

- Force
- Distance

Since torque is simply force multiplied by distance,

$$T = F \cdot L$$

where:

- T = torque
- F = measured force
- L = length of the brake arm

Once torque is known, the engine power can be determined if the rotational speed is also known.

Each revolution causes the measured force to travel a distance equal to the circumference of a circle having radius L . Therefore the distance travelled in one revolution is:

$$2 \cdot \pi L$$

If the shaft rotates at r revolutions per minute, the work performed each minute is:

unexpected symbol F

Dividing by Watt's definition of horsepower gives:

unexpected symbol F

where:

- L = brake-arm length (ft)
- r = rotational speed (rpm)
- F = measured force (lb)

This remarkably simple equation allowed engineers to determine brake horsepower using only a scale, a lever arm, and a tachometer.

23.5.3 A Convenient Shortcut

Practical engineers are rarely content with complicated arithmetic.

If the brake-arm length is chosen so that:

$$2 \cdot \pi L$$

is a convenient multiple of 33,000, the horsepower equation simplifies considerably.

A commonly used arm length of approximately 63 inches (5.25 ft) produces the convenient relationship:

$$hp = \frac{r \cdot F}{1000}$$

At 250 rpm, each 4 pounds indicated on the scale corresponds to approximately 1 horsepower.

This simple rule allowed engineers and test officials to determine engine power quickly without extensive calculation, making the de Prony brake particularly useful at field tests such as the Winnipeg Tractor Trials.

The de Prony brake transformed horsepower from a manufacturer's claim into a measurable quantity. For perhaps the first time, competing machines could be compared using objective engineering data rather than reputation or advertising.

23.5.4 Horsepower and Torque

Torque and horsepower are related, but they are not the same thing.

Torque is a twisting force. If a wrench is placed on a bolt and a force is applied at the end of the wrench, a torque is produced.

Horsepower is the rate at which work is performed.

A steam engine may produce a large torque while turning slowly. Another engine may produce a smaller torque but turn much faster. Both may produce the same horsepower.

A useful analogy is a water wheel.

- Torque answers the question: "How hard is it pushing?"
- Horsepower answers the question: "How fast is work being done?"

An engine producing torque but not rotating is doing no work. Since power is the rate of doing work, the horsepower at zero speed is zero regardless of the torque being produced.

23.5.5 A Practical Note on de Prony Brakes

Textbook descriptions of a de Prony brake often show a simple friction band wrapped around a rotating drum. In practice, large horsepower measurements generate enormous quantities of heat and require both lubrication and cooling.

Historically, beef tallow was commonly used as a lubricant for the brake band. The tallow reduced wear, prevented chatter, and helped provide a reasonably consistent coefficient of friction during testing.

Many modern Prony brakes use a hollow brake wheel resembling a steel tire. Cooling water is continuously introduced into the wheel while the brake is operating. Centrifugal force distributes the water around the inside of the rotating wheel, where it absorbs heat generated by friction.

An internal pickup located near the outer circumference collects the water and carries it away for disposal. This simple arrangement allows substantial amounts of power to be absorbed continuously without overheating the brake.

These practical details remind us that a Prony brake is actually a power-absorbing device. A 100-horsepower engine delivers approximately 255,000 BTU per hour to the brake, nearly all of which must

ultimately be removed as heat.

23.6 Indicated Horsepower

The de Prony brake determines power by measuring torque at the engine shaft. A steam engineer, however, has another option.

Because the pressure within the cylinder can be measured using a steam indicator, it is possible to estimate the power produced directly by the piston. This measurement is known as **indicated horsepower (IHP)**.

The indicator diagram introduced in the previous chapter provides the information needed to estimate the average pressure acting on the piston throughout its stroke.

Once the average pressure is known, the force acting on the piston can be calculated from:

$$\text{Force} = \text{Pressure} \times \text{Area}$$

The work performed during one stroke is then:

$$\text{Work} = \text{Force} \times \text{Distance}$$

Multiplying by the number of strokes per minute gives the horsepower produced within the cylinder.

23.6.1 Boiler Pressure vs. Cylinder Pressure

A boiler pressure gauge measures the pressure available within the boiler. This is not necessarily the same pressure acting on the piston.

Before reaching the cylinder, steam must pass through the dry pipe, throttle, governor, steam chest, valve passages, and finally the admission port. Each restriction causes a pressure drop. Steam engineers refer to these losses collectively as **wire drawing**.

As a result, the pressure available to perform work within the cylinder is generally lower than the pressure indicated by the boiler gauge.

The indicator card records the pressure actually acting on the piston and is therefore a more useful tool for determining engine power. In the following example, the pressure term represents the effective cylinder pressure rather than the boiler pressure.

The boiler gauge tells the engineer what pressure is available.

The indicator card tells the engineer what pressure the piston actually receives.

23.6.2 A Simple Approximation

A complete analysis would require determining the exact area enclosed by the indicator diagram. In practice, a useful estimate can often be obtained by replacing the curved expansion line with simple geometric shapes and applying the familiar **PLAN** formula:

$$HP = \frac{PLAN}{33000}$$

where:

- P = Effective cylinder pressure (psi)
- L = stroke length (ft)
- A = piston area (in²)
- N = power strokes per minute

Consider an engine modeled on the Case 22-65 operating with:

- Cylinder pressure: 100 psi

- Cutoff: 33% of the stroke
- Stroke: 11 in
- Bore: 10 in
- Speed: 225 rpm

Assume that full cylinder pressure acts during the first one-third of the stroke and then falls linearly to zero during the remaining two-thirds.

The entire calculation can then be written as:

$$HP = \frac{P \cdot L \cdot A \cdot N}{33000} \text{ where } \begin{cases} P \rightarrow \frac{1}{3}P_c + \frac{2}{3}\frac{P_c}{2} \\ L \rightarrow \frac{S}{12} \\ A \rightarrow \pi\left(\frac{B}{2}\right)^2 \\ N \rightarrow rpm \end{cases} \text{ where } \begin{cases} P_c \rightarrow 100 \\ S \rightarrow 11 \\ B \rightarrow 10 \\ rpm \rightarrow 2 \cdot 225 \end{cases}$$

$$= 65.450$$

The individual terms are easy to identify.

23.6.2.1 Pressure

The mean effective pressure is approximated by a rectangle plus a triangle on the indicator card:

$$P = \frac{1}{3}P_c + \frac{2}{3}\left(\frac{P_c}{2}\right)$$

Substituting:

$$P = \frac{1}{3}(100) + \frac{2}{3}(50)$$

$$P \approx 67psi$$

Notice that this simplifies to:

$$P = \frac{2}{3}P_c$$

for the assumed cutoff and linear expansion.

23.6.2.2 Length

The 11-inch stroke becomes:

$$L = \frac{11}{12} = 0.917ft$$

23.6.2.3 Area

For a 10-inch bore:

$$A = \frac{\pi \cdot 10^2}{4}$$

$$A = 78.500in^2$$

23.6.2.4 Number of Power Strokes

A double-acting engine produces two power strokes per revolution:

$$N = 2rpm$$

$$N = 2(225) = 450 \frac{strokes}{min}$$

23.6.2.5 Applying PLAN

Substituting these values into:

$$HP = \frac{PLAN}{33000}$$

gives:

$$HP = \frac{67 \cdot 0.917 \cdot 78.500 \cdot 450}{33000}$$

$$HP \approx 65.500hp$$

23.6.3 Discussion

Using only a simple approximation of the indicator diagram, the estimated output is approximately 65 horsepower, remarkably close to the rated output of a Case 22-65.

The result illustrates the power of the indicator diagram. By estimating the mean effective pressure and applying the PLAN formula, a steam engineer can obtain a surprisingly accurate estimate of engine output using only a few dimensions and some straightforward arithmetic.

23.7 Summary

The various methods of measuring power discussed in this chapter approach the same question from different directions.

- Drawbar horsepower measures power delivered to the load.
- Brake horsepower measures power delivered at the shaft.
- Indicated horsepower measures power produced within the cylinder.

Each method tells part of the story.

Perhaps the most remarkable result is that a simple indicator diagram and a few engine dimensions allow the steam engineer to estimate engine power with surprising accuracy. Long before electronic sensors and computerized data acquisition, steam engineers were able to analyze engine performance using little more than pressure measurements, geometry, and arithmetic.

Chapter 24 Valve Maintenance

A globe valve is a linear-motion valve used to start, stop, and regulate the flow of fluids. As shown in the cross-sectional diagram in [Fig. 83](#), the main components are the body, bonnet, stem, and plug (often called the disc in steam plant terminology). The handwheel turns the stem, causing the disc to move toward or away from the valve seat. This design allows precise flow control and reliable shutoff, making globe valves common in steam, condensate, and process systems.

The bonnet contains the stem threads and packing assembly. The packing seals around the stem to prevent leakage while still allowing the stem to move during valve operation.

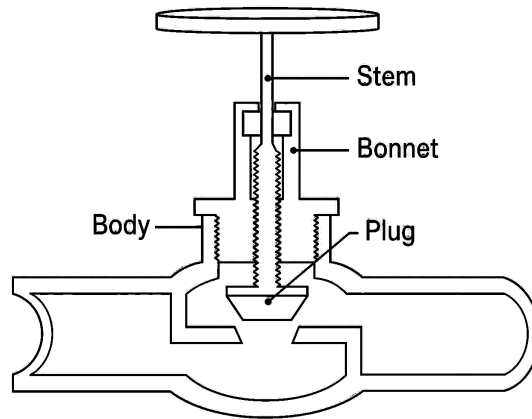


Fig. 83 Globe Valve

24.1 Disc (Plug) Materials

The disc is the primary sealing component of the valve and is selected according to the pressure, temperature, and service conditions of the system. In low- and medium-pressure steam systems operating at pressures below approximately 300 psi, replaceable discs with **PTFE (Teflon) seating surfaces** are used almost exclusively because they provide excellent shutoff performance and can be replaced easily during routine maintenance.

Common disc materials include:

- **PTFE (Teflon) Disc**
 - The most common choice for steam-rated globe valves below 300 psi.
 - Provides excellent shutoff performance in low- and medium-pressure steam service.
 - Simple and inexpensive to replace when worn.
 - Resistant to corrosion and many process fluids.
- **Bronze Disc**
 - Typically used in water service and older low-pressure valve designs.
 - Offers good corrosion resistance but does not seal as effectively as PTFE-seated discs.
- **Stainless Steel Disc**
 - Used where temperatures exceed the limits of PTFE.
 - Common in high-temperature steam and process applications.
 - Provides durability but generally requires metal-to-metal seating.
- **Hardened Stainless Steel Disc**
 - Used in valves that experience frequent operation or abrasive service.
 - Provides improved wear resistance compared to standard stainless steel.
- **Stellite-Faced Disc**
 - Used in high-pressure and high-temperature steam service.
 - The hard-facing alloy resists erosion, wire drawing, and seat damage.
 - Commonly found in power plant and severe-service applications.

A disc should be replaced when it becomes worn, scored, cracked, distorted, or when the valve leaks through the seat while fully closed.

24.2 Stem Packing Materials

Packing forms a pressure-tight seal between the stem and bonnet while allowing stem movement.

Common packing materials include:

24.2.1 Graphite Packing

- Most common for steam service.
- Excellent high-temperature performance.
- Low friction and long service life.

24.2.2 PTFE (Teflon) Packing

- Excellent chemical resistance.
- Common in water and chemical service.
- Limited for high-temperature steam applications.

24.2.3 Graphite/PTFE Combination Packing

- Combines chemical resistance with improved temperature capability.

Packing material must always be selected to match the operating temperature, pressure, and fluid being controlled.

24.3 Adjusting the Packing

If steam, water, or condensate is leaking from around the stem, the packing may not require replacement. In many cases, normal packing wear can be compensated for by tightening the gland nut slightly.

1. Tighten the gland nut a small amount.
2. Operate the valve several times.
3. Check whether leakage has stopped.
4. If leakage persists, repeat the adjustment as necessary.

If the gland nut can no longer be tightened sufficiently to stop the leak, or if leakage continues after adjustment, inspect and replace the packing.

24.4 Repacking the Bonnet-Stem Interface

The bonnet-stem interface consists of the stuffing box, packing, gland follower, and gland nut(s). The stuffing box is the annular space between the valve stem and the bonnet that is filled with packing material. The gland follower compresses the packing, while the gland nut or gland nuts provide the force required to maintain a tight seal around the stem.

Depending on the valve design, the packing may be installed as preformed rings or as continuous packing cord.

Step 1: Isolate the Valve

1. Close and isolate the valve from the system.
2. Apply lockout/tagout procedures.
3. Depressurize and drain the valve.
4. Verify that pressure has been removed before beginning work.

Step 2: Loosen the Gland Assembly

1. Loosen the gland nut evenly.
2. Lift off or withdraw the gland follower.
3. Expose the stuffing box.

Step 3: Remove Old Packing

1. Use a packing puller to remove all old packing material.
2. Remove packing completely from the stuffing box.
3. Clean the stuffing box thoroughly.

Step 4: Inspect Components

Inspect:

- Stem for scoring or wear
- Stuffing box for corrosion or damage
- Gland follower for distortion

Replace damaged components before installing new packing.

Step 5: Prepare New Packing

1. Select the correct packing material for the service.
2. Determine whether the packing is supplied as:
 - Preformed rings, or
 - Continuous packing cord (rope packing).

For Preformed Rings

1. Verify that the rings are the correct size for the valve stem and stuffing box.
2. Inspect rings for damage before installation.

For Rope Packing

1. Clean the stem thoroughly.
2. Wind the packing around the stem in the stuffing-box area.
3. Apply enough turns that the packing will fill the stuffing box when compressed by the gland follower.
4. Ensure the packing is wrapped evenly and without twists.

Step 6: Install the Packing

Using Preformed Rings

1. Install one ring at a time.
2. Seat each ring firmly in the stuffing box.
3. Stagger ring joints approximately 90° to 120° apart.
4. Continue until the stuffing box is filled to the original packing height.

Using Rope Packing

1. Position the wound packing around the stem.
2. Install the gland follower.
3. Tighten the gland nut evenly.
4. As the gland follower moves downward, it compresses the packing into the stuffing box.
5. Continue tightening until the packing is firmly seated but the stem still moves freely.

Step 7: Adjust the Packing

1. Verify the gland follower is seated correctly.
2. Tighten gland nut evenly.
3. Apply only enough compression to seat the packing.
4. Ensure the stem still operates smoothly.

Step 8: Return the Valve to Service

1. Slowly restore system pressure.
2. Cycle the valve several times.

3. Check for stem leakage.
4. Tighten the gland slightly if leakage occurs.
5. Avoid overtightening, as excessive packing pressure can increase operating torque and accelerate stem wear.

24.5 Key Point

Leakage around the stem does not necessarily indicate failed packing. First attempt to stop the leak by tightening the gland nut slightly. If adjustment is ineffective, inspect and replace the packing. If the valve leaks through the seat while fully closed, the disc (plug) and seat should be inspected for wear or damage.

24.6 Valve Seat Reconditioning

Occasionally, a globe valve may continue to leak after the disc has been replaced. In this case, the valve seat should be inspected for scoring, pitting, or erosion.

Minor seat damage can often be repaired by reconditioning the seating surface.

Step 1: Disassemble the Valve

1. Isolate and depressurize the valve.
2. Remove the bonnet and disc assembly.
3. Inspect the seat for wear, scoring, or pitting.

Step 2: Dress the Seat

1. Mount a suitable seat-grinding stone in a power drill.
2. Position the stone so that it remains square with the valve seat throughout the grinding operation.
3. Grind lightly using moderate speed and pressure.
4. Remove only enough material to restore a smooth, continuous seating surface.
5. Periodically inspect the seat to avoid excessive material removal.

Step 3: Clean and Inspect

1. Remove all grinding residue.
2. Inspect the seating surface.
3. Verify that all scoring and surface defects have been removed.

Step 4: Reassemble and Test

1. Reinstall the disc and bonnet assembly.
2. Return the valve to service.
3. Check for leakage when the valve is fully closed.

If a satisfactory seat surface cannot be restored, the seat or valve should be replaced.

Chapter 25

Cold Walk-up Checklist

25.1 Approach & Situational Awareness

- Verify engine is **cold** (no pressure on gauge, no warmth at fittings).
- Ensure the engine is on stable ground with brakes set or wheels chocked.
- Check surroundings for hazards: loose tools, fuel containers, bystanders.

25.2 Boiler Exterior & Shell Inspection

- Inspect boiler barrel, firebox wrapper, and smokebox for:
 - Cracks, bulges, fresh rust streaks, or weeping seams.
 - Loose or missing stays, rivets, or fasteners.
- Check smokebox door fit and hinge condition.
- Confirm stack is clear of obstructions (birds, debris).

25.3 Water Level & Feedwater System

- Verify gauge glass is intact, valves open, and drains functional.
- Blow down gauge glass to confirm:
 - Water level responds correctly.
 - Top and bottom cocks are clear.
- Test try cocks (if fitted) for correct water/steam response.
- Inspect injector(s):
 - Check overflow pipe clear.
 - Confirm water supply valve moves freely.
- Inspect mechanical pump or crosshead pump for free movement.

25.4 Fittings & Valves

- Safety valve: ensure free movement of easing lever.
- Blowdown valve: verify closed and threads sound.
- Check throttle for full travel and smooth operation.
- Inspect whistle valve, blower valve, and cylinder cocks for free motion.
- Confirm pressure gauge glass is unbroken and pointer at zero.

25.5 Lubrication — Before Any Motion

- Fill displacement lubricator(s) with correct cylinder oil.
- Check mechanical lubricators for:
 - Oil level
 - Ratchet/pawl engagement
 - Free rotation
- Oil all motion points:
 - Crossheads
 - Slide bars
 - Valve gear joints
 - Eccentrics
 - Crank pins
 - Main bearings
- Check all drip cups and wicks for proper feed.

25.6 Motion Work & Running Gear

- Turn flywheel slightly by hand (if safe) to feel for:
 - Binding
 - Unusual resistance
 - Loose components
- Inspect:
 - Connecting rods
 - Valve rods
 - Eccentric straps
 - Steering gear
 - Differential and final drive
- Check wheel hubs and axle bearings for oil and tightness.

25.7 Firebox, Grate & Ashpan

- Open firedoor and inspect:
 - Grate condition
 - No clinker buildup
 - No foreign objects
- Check ashpan:
 - Empty
 - No smoldering material
 - Damper moves freely
- Confirm fusible plug is present and not weeping.

25.8 Draft Path & Tubes

- Verify smokebox is not packed with soot or ash.
- **Clean boiler tubes** as required:
 - Use appropriate tube brush or cleaner.
 - Ensure all tubes are clear of soot and obstructions.
- Check blower ring for blockage.
- Ensure damper and ashpan air controls operate smoothly.

25.9 Fuel & Water Readiness

- Confirm adequate water supply for:
 - Raising steam
 - Operating period
- Confirm adequate fuel (coal/wood) staged safely.
- Ensure fire tools are present and in good condition.

25.10 Pre-Light-Off Final Checks

- Water level at proper starting height.
- All lubrication points serviced.
- All valves in correct starting positions:
 - Cylinder cocks **open**
 - Throttle **closed**
 - Blower **closed**
- Firebox and ashpan clear.
- No loose tools on footplate or running boards.
- Operator has PPE: gloves, eye protection, hearing protection.

Engine is now ready for light-off.

Chapter 26 Control of Motion

26.1 Throttle

- Identify the throttle and its direction of travel.
- Understand that the throttle controls *steam admission*, not speed directly.
- Practice smooth, progressive opening — never snap it open.
- Recognize that the throttle is the primary control for starting, modulating, and stopping motion.

26.2 Governor

- Understand that the governor limits maximum engine speed.
- Note that the governor does *not* start the engine — it only trims speed once running.
- Observe how the governor responds to load changes.
- Learn that the governor cannot prevent overspeed if the throttle is opened too far.

26.3 Dead Centres

- Define front dead centre and back dead centre.
- Learn why the engine cannot start when the crank is on dead centre.
- Practice identifying dead centre by crank position.
- Understand how to “rock” the engine off dead centre using the clutch or bar.

26.4 Cylinder Drains

- Locate the cylinder drain cocks and their handles.
- Learn why drains must be opened before starting:
 - to clear condensate
 - to prevent water hammer
- Keep drains open until the engine is turning freely and dry steam appears.
- Use drains when stopping and when maneuvering at low speed.

26.5 Predicting Motion

- Predict which way the engine will move before opening the throttle.
- Review crank position, valve gear setting, and direction of rotation.
- Understand that the engine may move unexpectedly if the throttle is cracked too quickly.
- Practice visualizing the first quarter-turn of motion.

26.6 Clutch

- Identify the clutch lever and its travel.
- Understand that the clutch connects the crankshaft to the traction gearing.
- Ensure the clutch is fully engaged before applying power.
- Know when to disengage:
 - maneuvering
 - stopping
 - rocking off dead centre
- Avoid slipping the clutch except when absolutely necessary.

26.7 Hooking Up (Valve Gear Adjustment)

- Understand the purpose of hooking up:
 - reduced steam consumption
 - finer control at speed
- Identify the reach rod or quadrant lever and its direction of travel.
- Hook up only when the engine is running smoothly.
- Recognize that hooking up changes valve events and affects starting torque.

26.8 Stopping Procedure

- Close the throttle smoothly — never snap it shut.
- Open cylinder drains as the engine slows to clear condensate.
- Disengage the clutch once the engine is nearly stopped.
- Avoid leaving the crank on dead centre if a restart is expected.
- Secure the engine:
 - throttle closed
 - drains open
 - clutch disengaged
 - wheels chocked if on grade