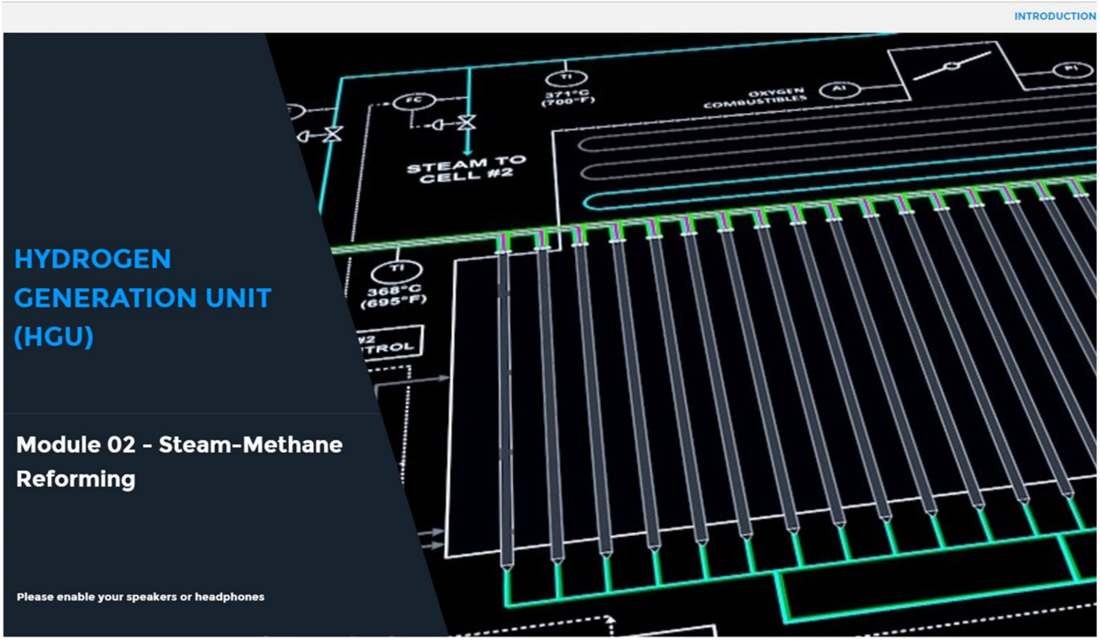
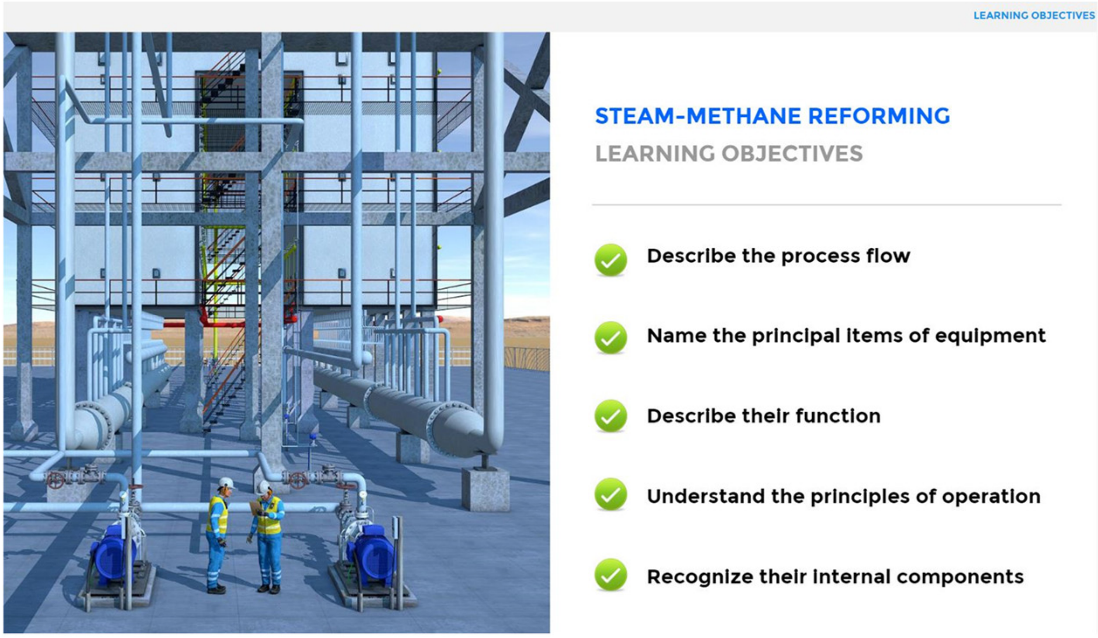
BU MEASUREMENT & ANALYTICS

Refinery Process Units

Hydrogen Generation Unit (HGU) – Module 2: Steam-Methane Reforming



Welcome to Hydrogen Generation Unit Module 2, Steam-Methane Reforming.



For the Steam-Methane Reforming unit operations, upon completion of this module, you should be able to:

Describe the process flow

Name the principal items of equipment

Describe their function

Understand the principles of operation

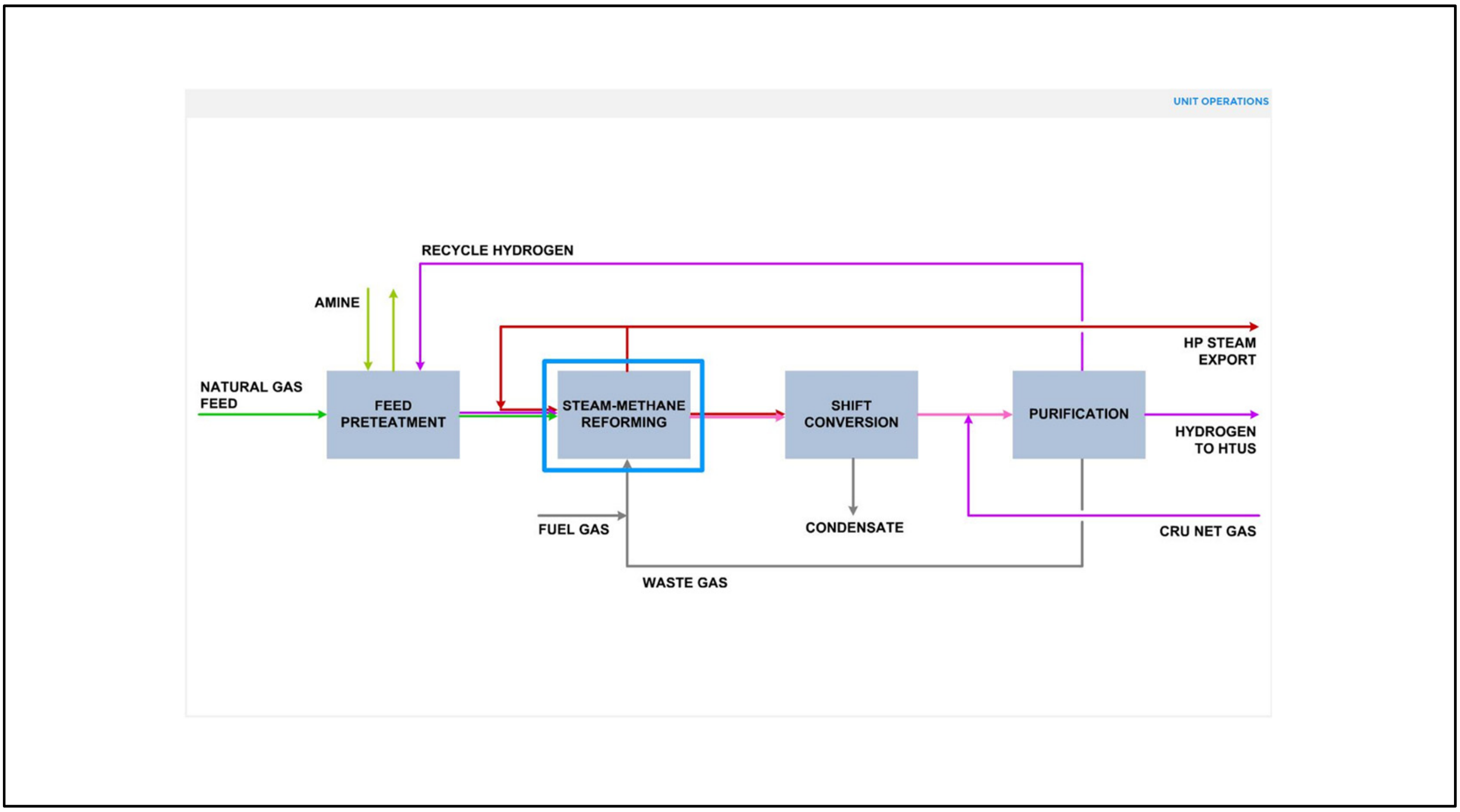
Recognize their internal components

Additionally, you should be able to demonstrate an awareness of:

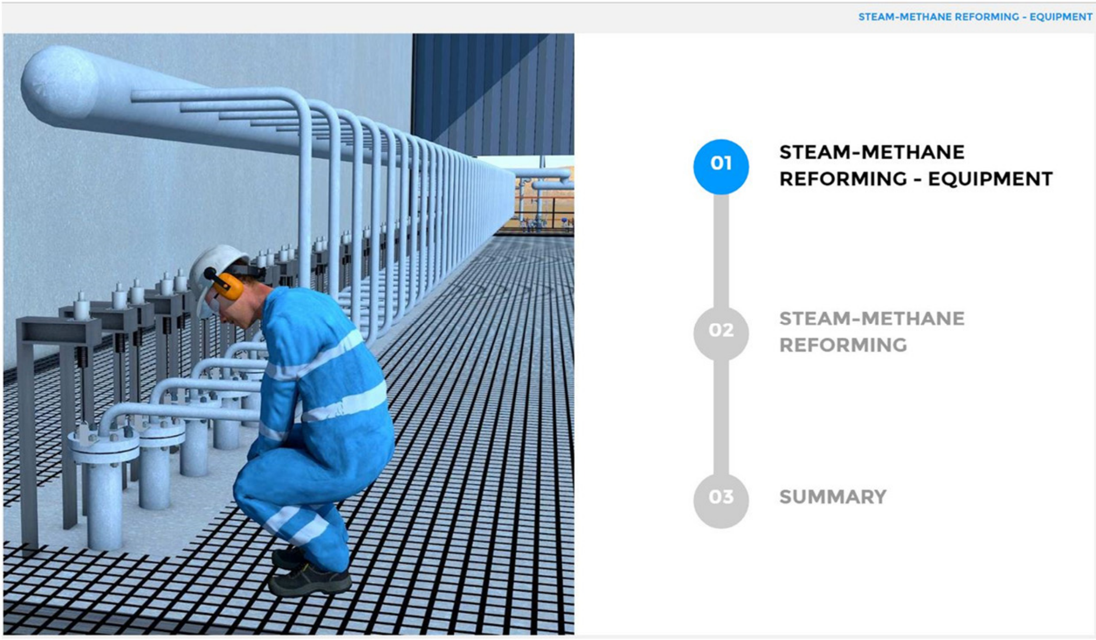
Important process variables and how they're controlled

Major operating constraints

Typical operating problems

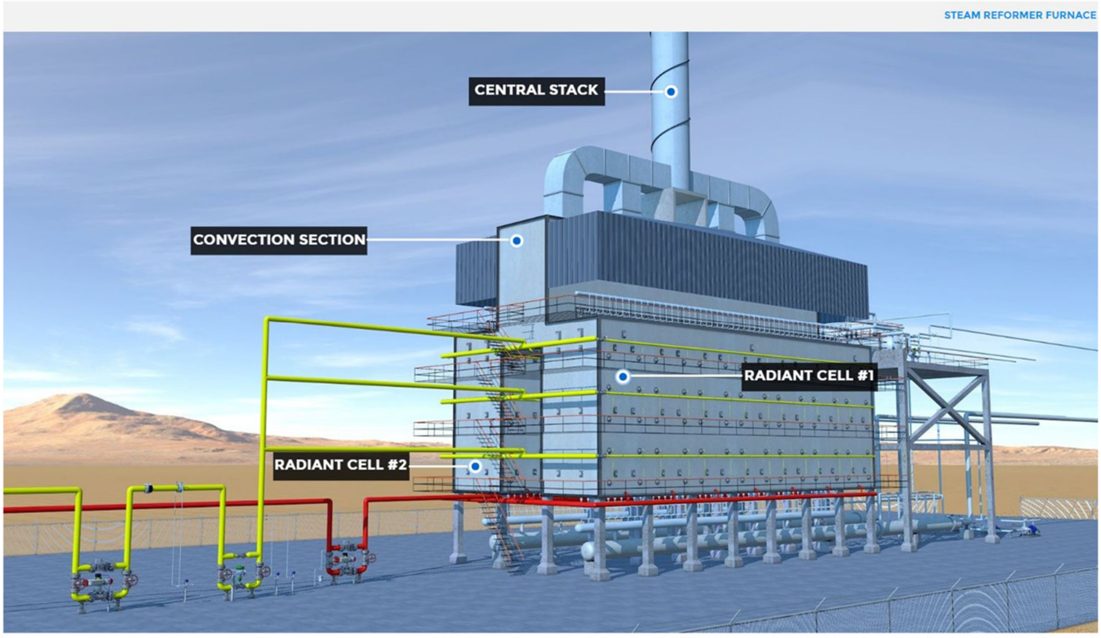


OK, let’s make a start on our second unit operation, Steam-Methane Reforming.



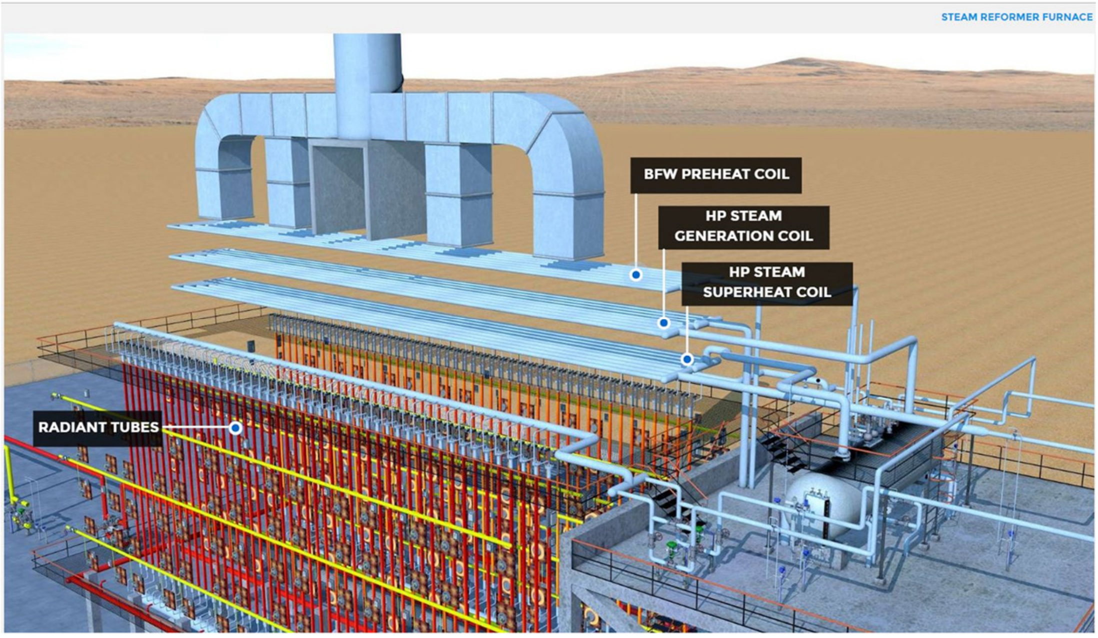
These are our topics.

We’ll start with a brief orientation of the 3D model.



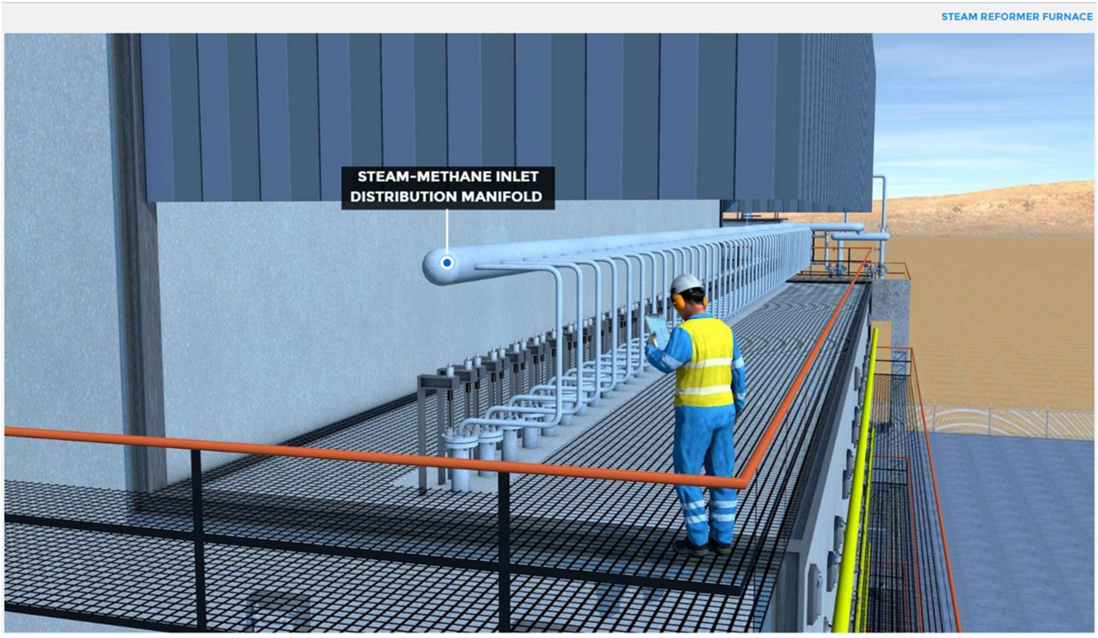
Steam-methane reforming is carried out in a Steam Reformer Furnace.

The one pictured here has two radiant cells, with flue gas exiting into a common convection section and then through ductwork into a central stack.



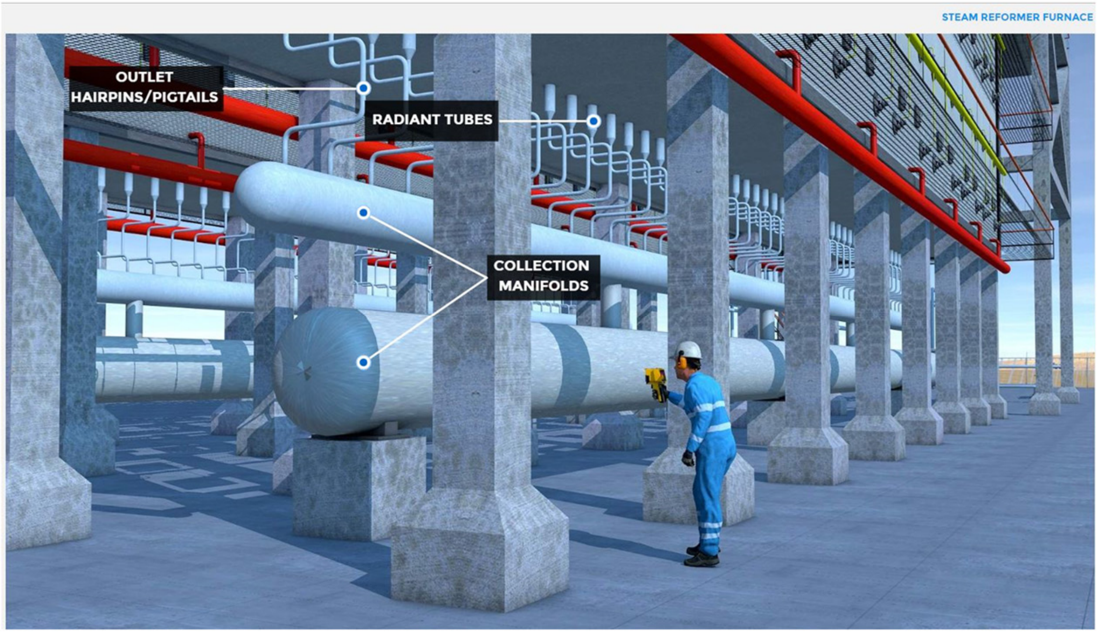
Each radiant cell has a central row of 48 tubes that are packed with catalyst, over which a mixture of steam and methane is passed and chemical reactions take place.

The convection section has three coils for makeup boiler feed water preheating, high pressure steam generation and high pressure steam superheating.

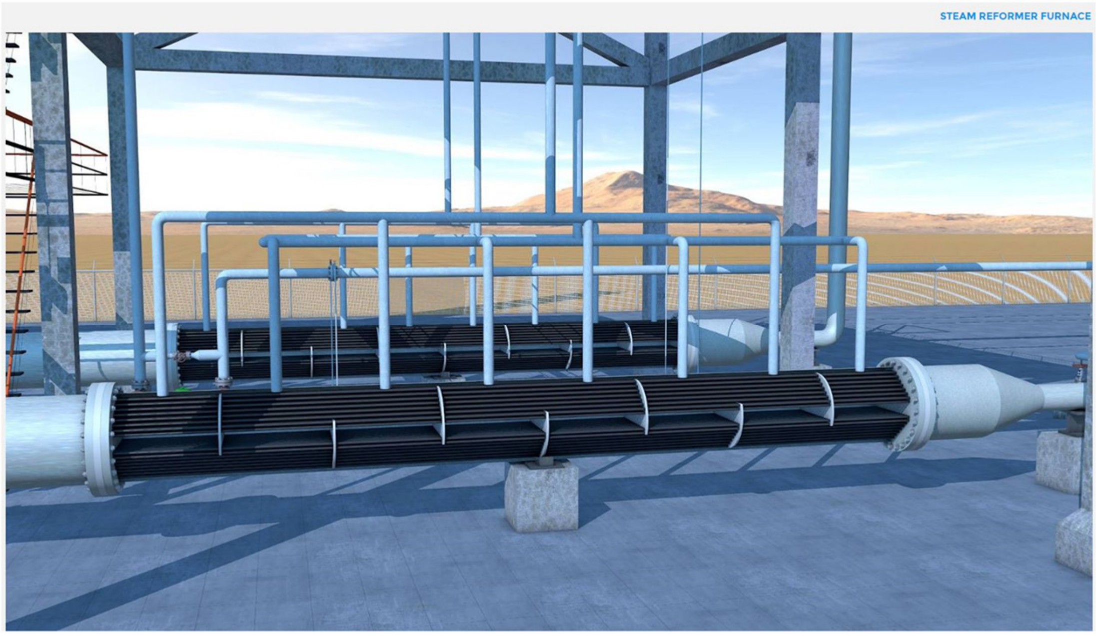


A mixture of steam and methane passes along an inlet manifold that distributes it evenly to the row of 48 radiant tubes.

Small bore pipes (called hairpins or pigtails) connect the inlet distribution manifold with each of the radiant tubes.

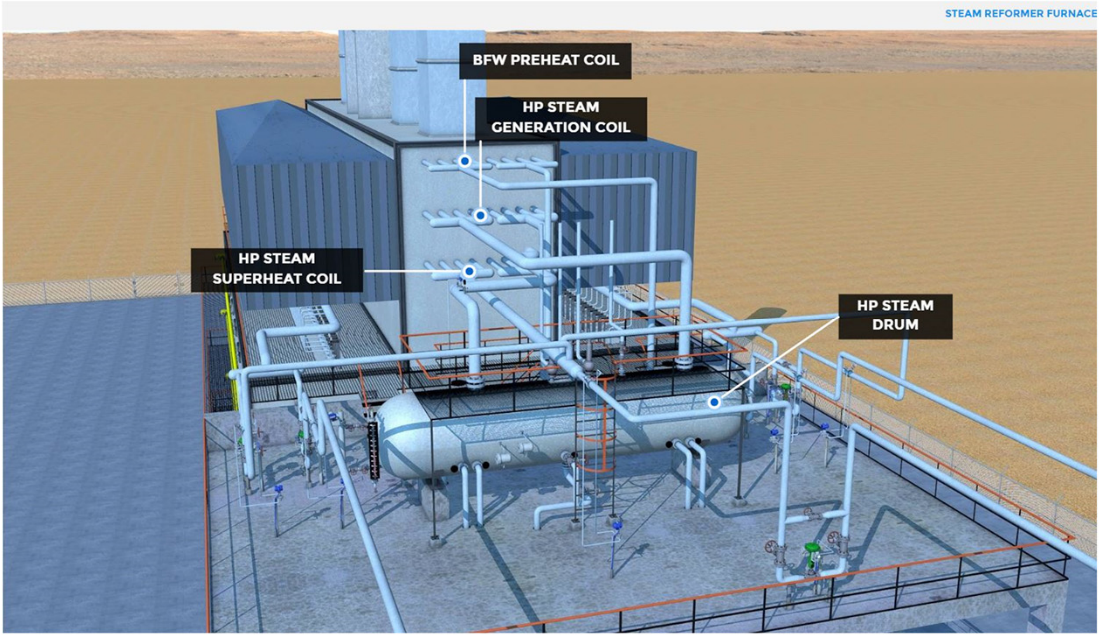


The outlets of the radiant tubes are connected via hairpins to two collection manifolds.

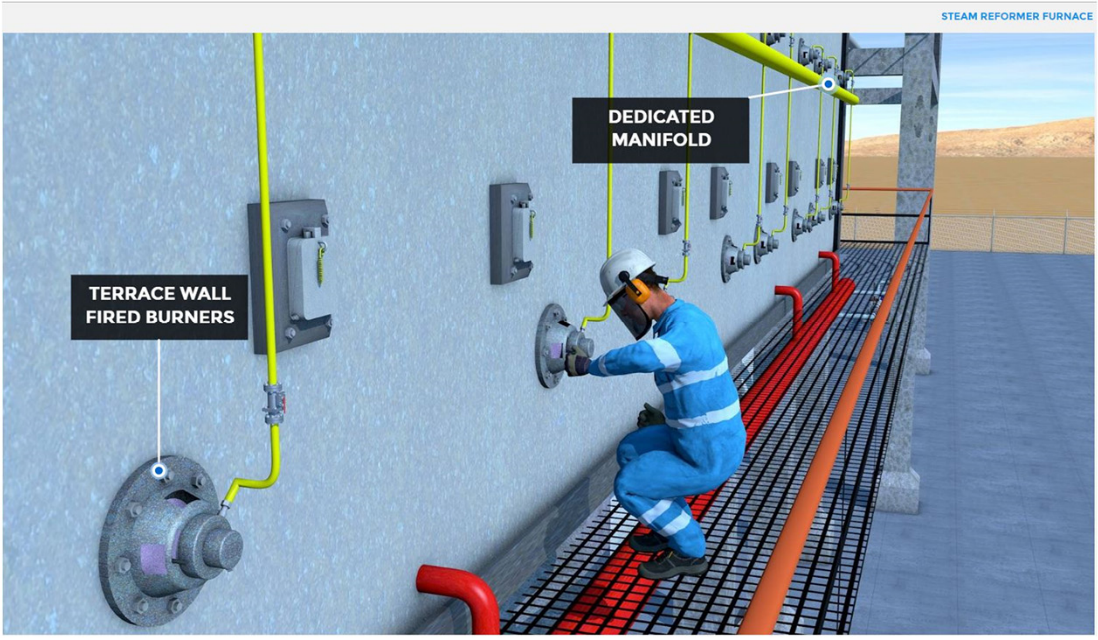


Towards the end of each collector, there’s a tube bundle.

The reaction products, called synthesis gas, pass through the tubes, exchanging heat with boiler water which naturally circulates through the shell from the High Pressure Steam Drum above.



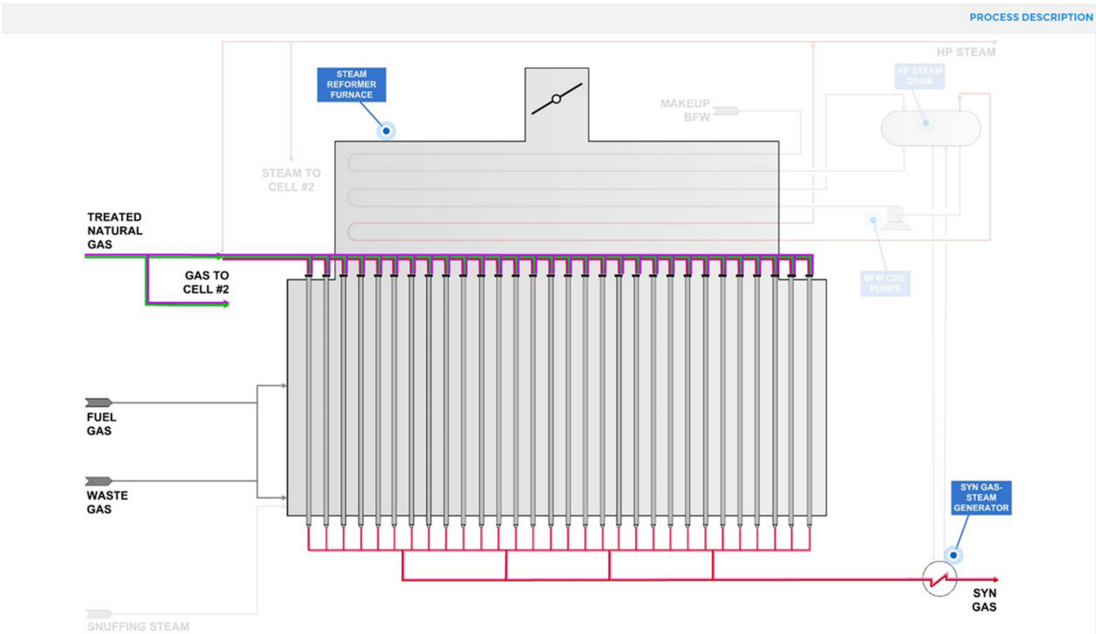
This image shows the High Pressure Steam Drum and its interconnecting pipework to the boiler feed water preheat, steam generation and steam superheat convection coils.



Each radiant cell has terrace-wall fired burners arranged at four levels to provide even heat distribution along the length of the radiant tubes.

There are 56 burners on each wall. Each row of burners is supplied by a dedicated manifold, enabling fuel firing pressures to be staggered.

OK… now that you have a mental image of the Steam Reformer Furnace, let's make a start on the process description.



Process Description

Treated natural gas, free of contaminants, splits and mixes with superheated high pressure steam before entering the steam-methane inlet distribution manifolds supplying the radiant tubes in each of the two radiant cells.

The steam-methane mixture passes down through the radiant tubes, flowing over the catalyst that fills the complete length of each tube.

The steam and methane react to form a mixture of gases that are referred to as synthesis gas.

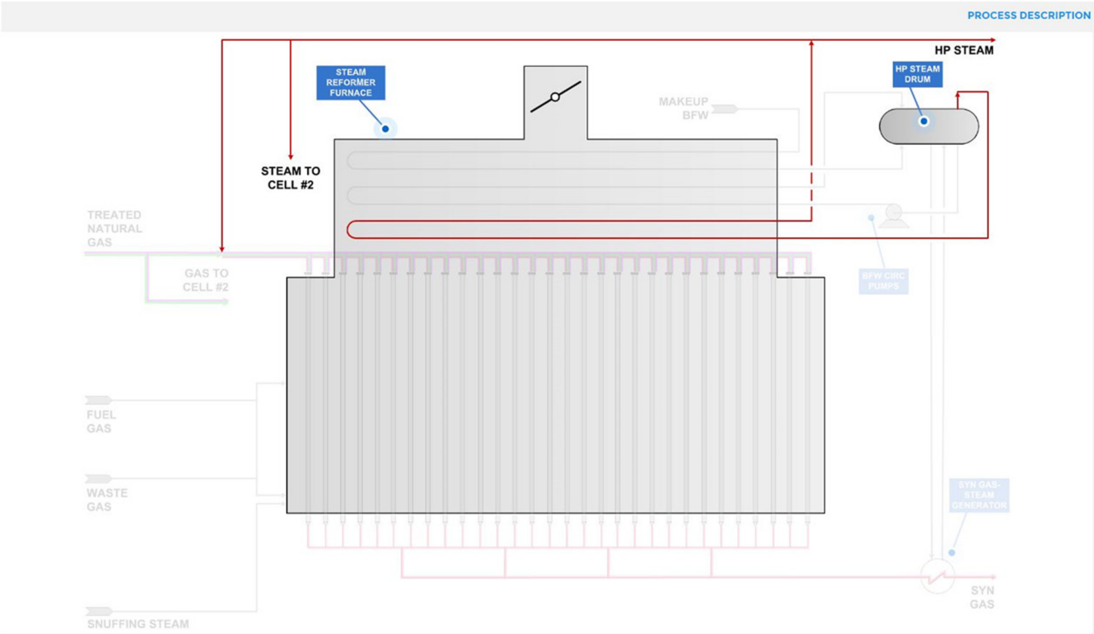
The synthesis gas exits the bottom of the radiant tubes into collectors, passing through the tube-side of two Synthesis Gas Steam Generators at the far end of the furnace.

Boiler water passes through the shell-side under natural circulation from an elevated High Pressure Steam Drum.

Terrace-wall fired burners provide the heat required to initiate and sustain the reactions that take place over the catalyst.

The Reformer Furnace has two fuels - the primary fuel is refinery fuel gas which meets around 30% of the furnace heat duty - the secondary fuel is waste gas from the downstream PSA Unit, which meets the remainder of the furnace heat duty.

The furnace heat duty is the total amount of heat that is required to be released in the firebox.



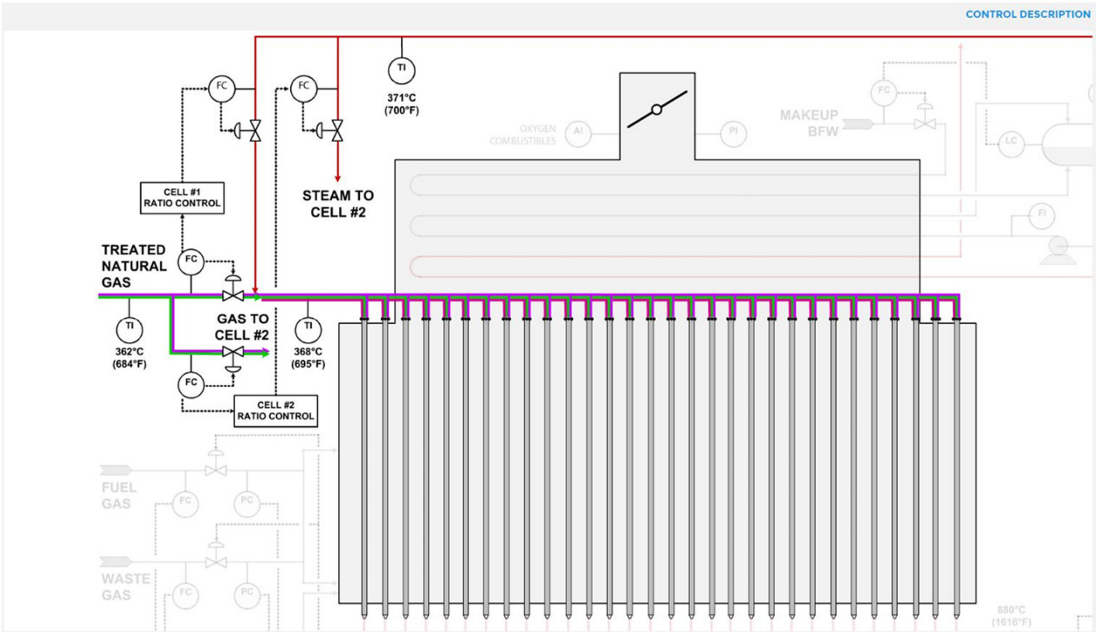
Makeup boiler feed water passes through a preheat coil in the convection section before entering the High Pressure Steam Drum.

The Boiler Feed Water Circulation Pumps provide forced circulation between the High Pressure Steam Drum and a high pressure steam generation coil located below the BFW preheat coil in the convection section.

Saturated steam exits the top of the High Pressure Steam Drum and passes through a high pressure steam superheat coil in the hottest part of the convection section.

Upon exiting the coil, the superheated steam splits - part of it mixes with the natural gas feed - the balance is exported to the refinery HP Steam Main.

If you would like to learn more about steam generation, please refer to the 3D Equipment Glossary, where you will find a more detailed description.



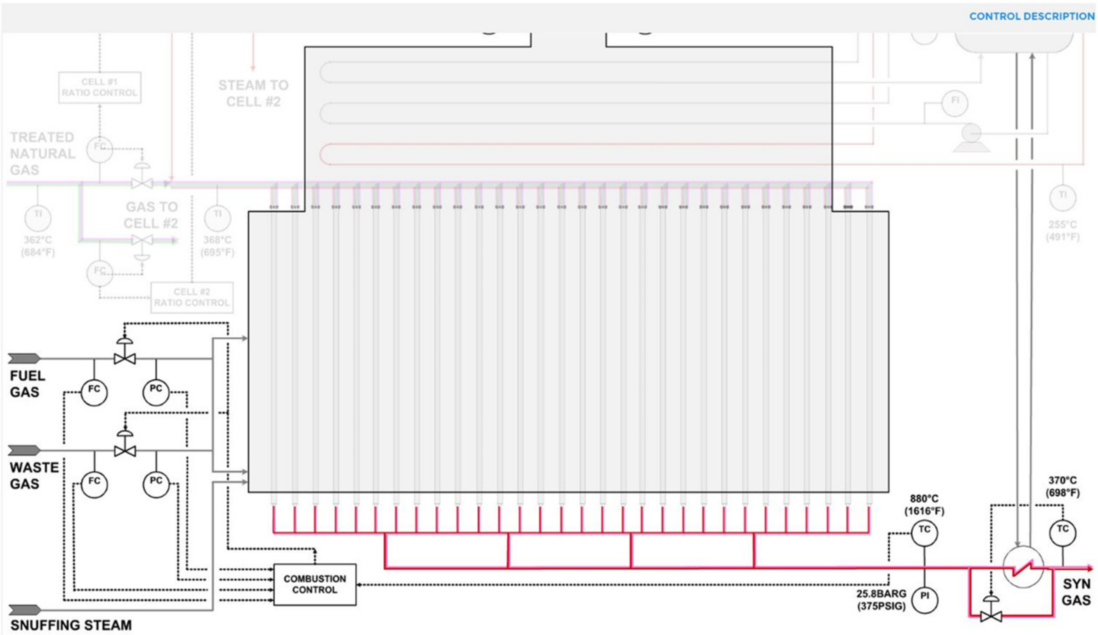
Control Description

For each of the two radiant cells, flow controlled natural gas, at 362ºC (684ºF) mixes with flow controlled superheated steam at 371ºC (700ºF) before entering the steam-methane inlet distribution manifold.

The flows are set by a master ratio controller that maintains a 2:1 molar ratio of steam to gas.

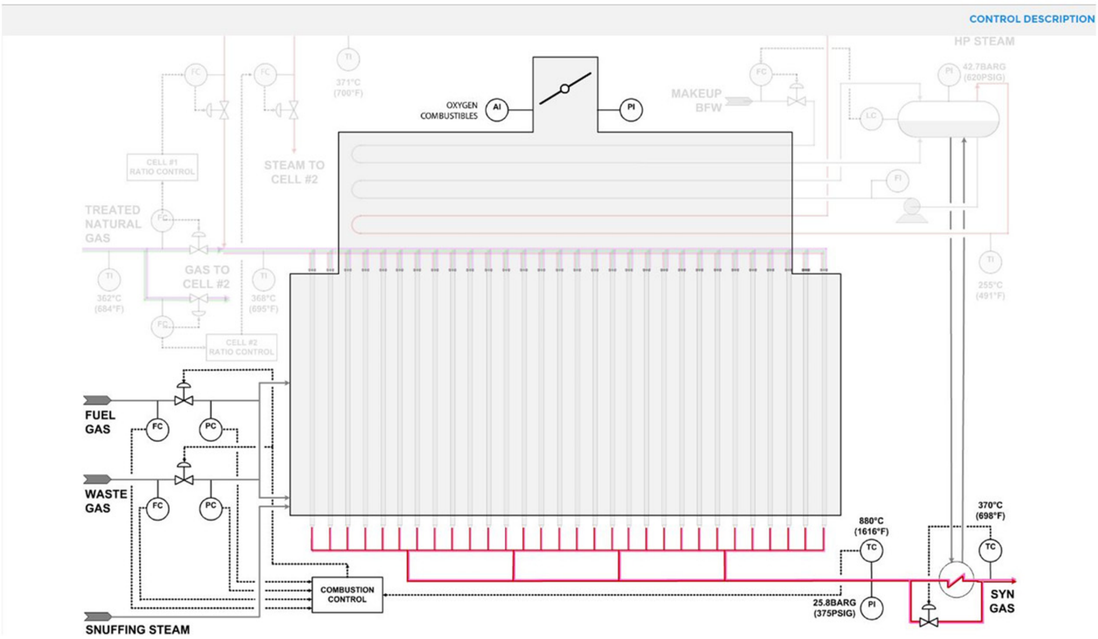
This ratio is critical - too low a ratio can result in coking of the catalyst, while too high a ratio is wasteful of steam and energy inefficient.

The combined steam-methane mixture enters the radiant tubes at 368ºC (695ºF).



A combustion controller maintains the temperatures of the two outlet collectors at 880ºC (1,616ºF) - these two temperatures determine the extent of the reactions that take place in the radiant tubes.

A second pair of temperature controllers, located downstream of the Synthesis Gas Steam Generators, maintain the synthesis gas temperature to the downstream High Temperature Shift Convertor at 370ºC (698ºF), again determining the extent of chemical reactions.



The combustion controller adjusts the refinery fuel gas and waste gas streams in a 30:70 ratio, with refinery fuel gas meeting the baseload.

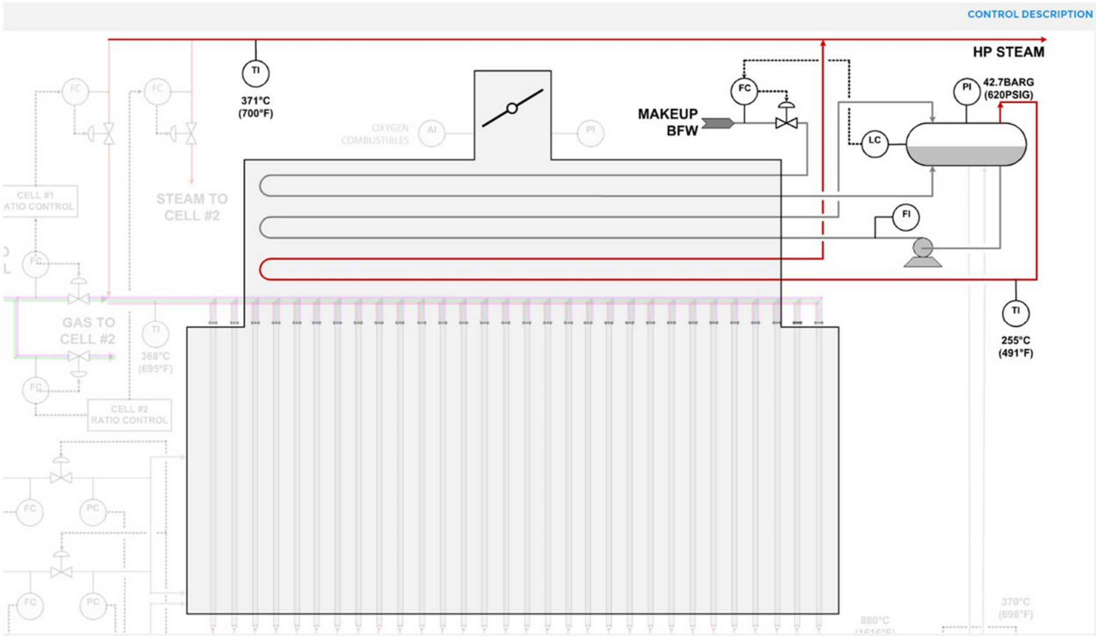
The reason for this is that refinery fuel gas is generally considered to be a more reliable fuel supply while waste gas can be subject to transient fluctuations in quality and quantity.

The combustion controller has inputs from pressure constraint controllers that ensure safe firing pressures are maintained at the burners at all times.

The flue gas oxygen is maintained at around 2-2.5% vol by manual adjustment of the burner air registers.

More modern, higher efficiency Reformer Furnaces have forced draft burners, with combustion air preheated in the convection section and passed to each of the burners via constant velocity ducting that ensures all burners get their fair share of the air.

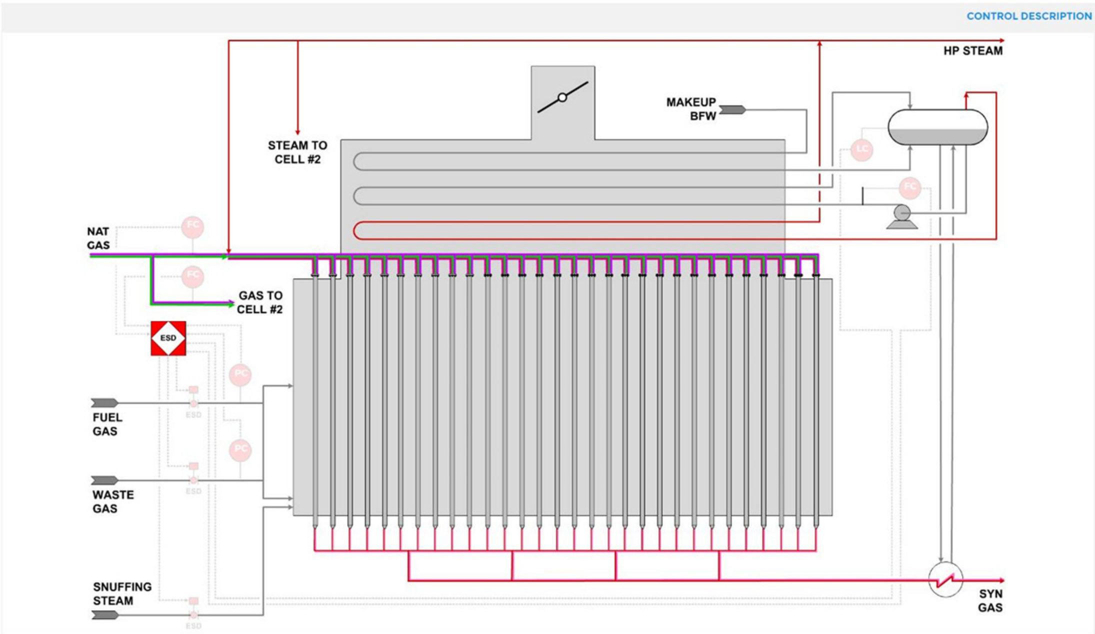
The draft is maintained by adjustment of the stack damper.



The High Pressure Steam Drum has a constant makeup of preheated boiler feed water, maintained by a level to flow cascade control arrangement.

Saturated high pressure steam at 255ºC (491ºF) and 42.7barg (620psig) exits the top of the HP Steam Drum and passes to the steam superheat coil, where its temperature is raised to 371ºC (700ºF).

The pressure of the HP Steam Drum ‘floats’ on the pressure of the refinery HP Steam Main.



The Reformer Furnace and its catalyst are protected by an ESD system, which is activated by:

- Natural gas low flow
- Fuel gas low pressure
- Waste gas low pressure
- Steam drum low level
- BFW circulation low flow

The ESD trip initiators and actuators are shown here.

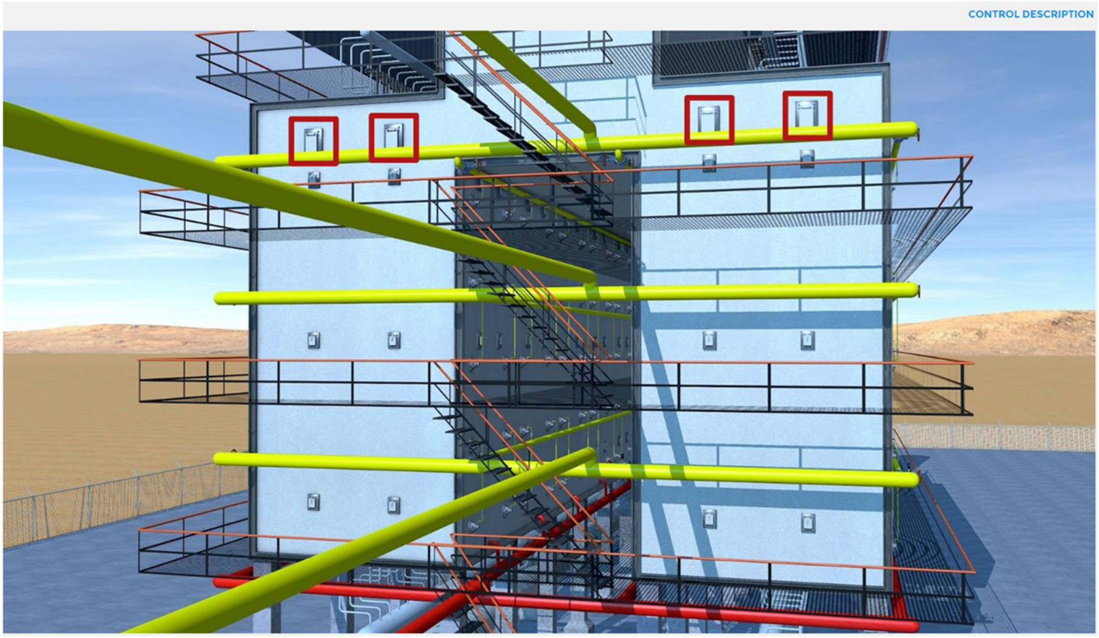
The basic intent of the ESD system is to prevent overheating of the radiant tubes or a firebox explosion.

You may be curious as to why there isn't a low flow trip on the superheated steam to the inlet distribution manifold.

There is a reason for this - when the Reformer Furnace is shut down, the radiant tubes are steam purged for around 20-30 minutes to ensure all traces of hydrocarbons are removed, preventing coking of the catalyst.

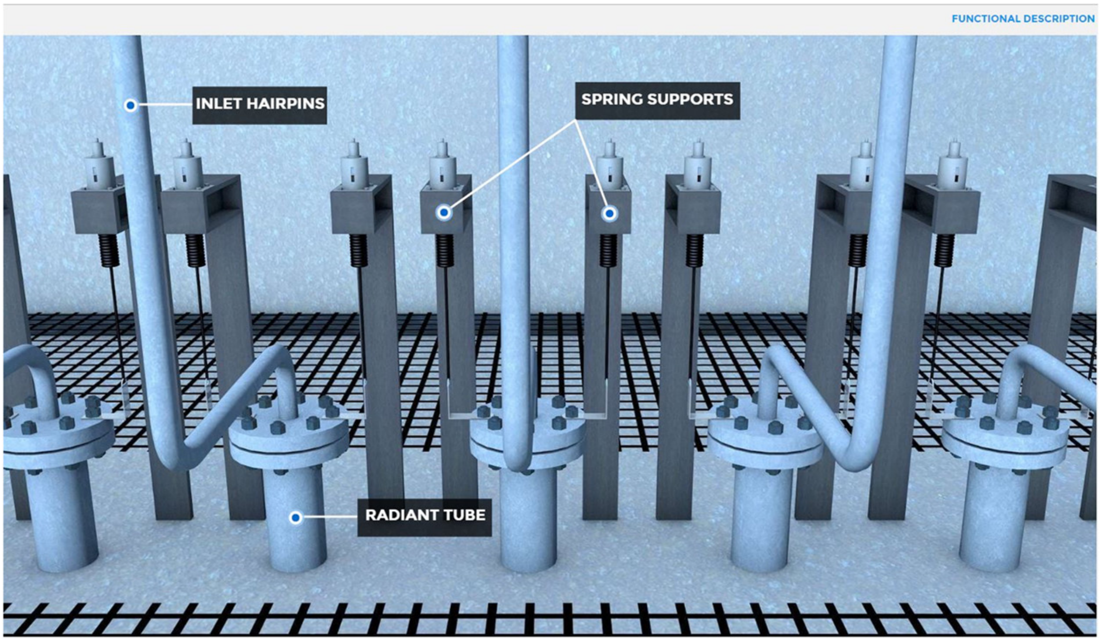
The two superheated steam control valves are fitted with mechanical stops so that they are not able to completely close - manual isolation is required when radiant tube steam-out is complete.

By way of background information, steam flows are notoriously unreliable as trip initiators and shutdown system designers usually avoid their use if at all possible as they tend to generate spurious trips at a frequency that far out-weighs their benefits.



As additional protection against damage, the radiant cells have a number of hinged explosion doors that relieve pressure in the event of a firebox explosion.

This image shows the primary fuel gas ESD and control valves and the snuffing steam ESD valve.

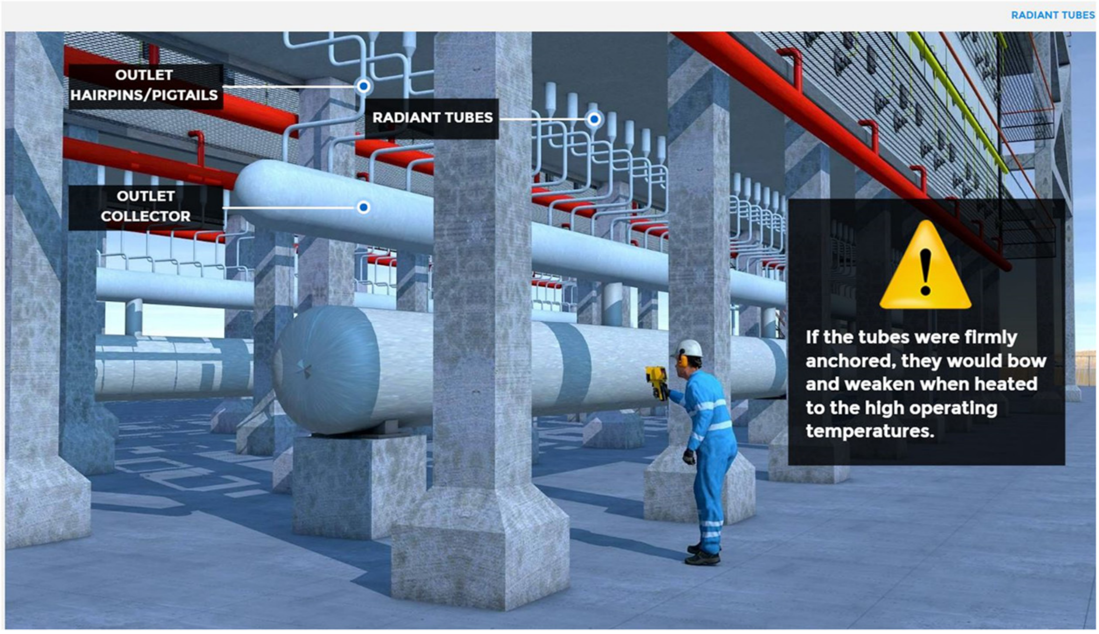


Functional Description

Next, we’re going to talk about some functional issues, first, radiant tube expansion and contraction with respect to operating temperatures and then chemical reactions.

As mentioned earlier, the radiant tubes are connected to the inlet distribution manifold by hairpins (sometimes also called pigtails). The radiant tubes hang from spring supports.

Together, the hairpins and spring supports allow the radiant tubes to expand and contract as they are heated up (at startup) and cooled down (at shut down).



The outlet hairpins also facilitate expansion and contraction of the radiant tubes.

When heated, the radiant tubes ‘grow’ vertically by up to 30cms (1 ft), pushing upwards against the springs, which absorb the movement.

If the tubes were firmly anchored, they would bow and weaken when heated to the high operating temperatures.

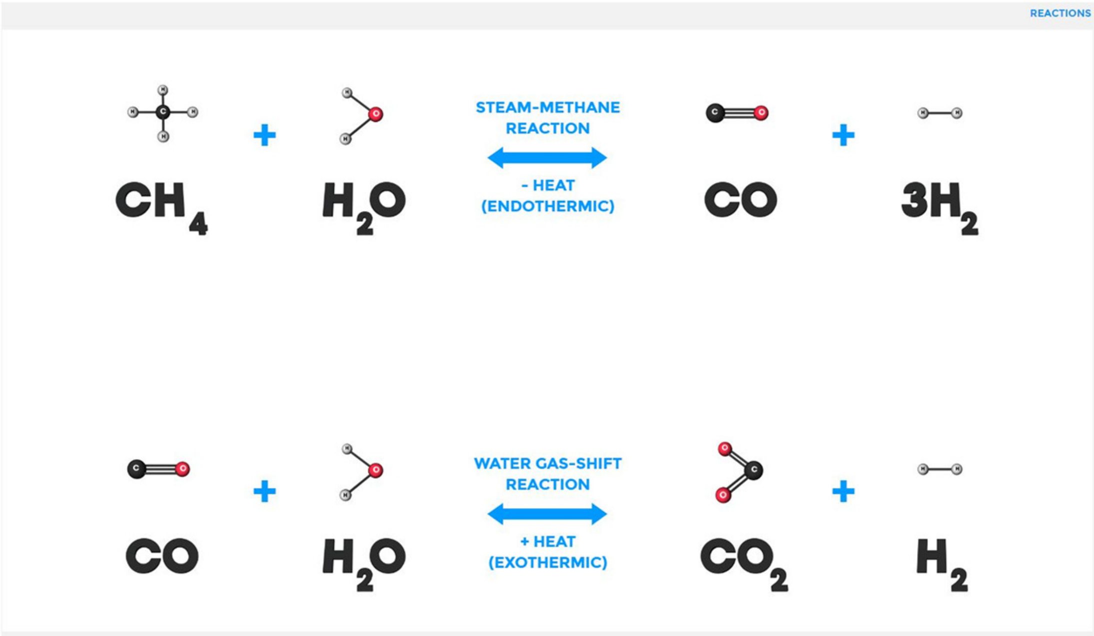
The radiant tubes are subject to a substantial temperature differential from top to bottom.

Most modern, more complex reformer furnaces preheat their natural gas, LPG or naphtha feed, so the radiant tube inlet temperature could be hotter by up to 280ºC (536ºF).

Also, for a heavier feed, such as naphtha, the radiant tube outlet temperature would be of the order of 920ºC (1,688ºF).

The highest temperature in the tube typically occurs around 20% of the way down - this is known as the hotspot.

As skinpoint thermocouples are not very reliable in this type of service, hotspot temperatures are checked regularly using an optical pyrometer or thermal imaging camera (as shown here).



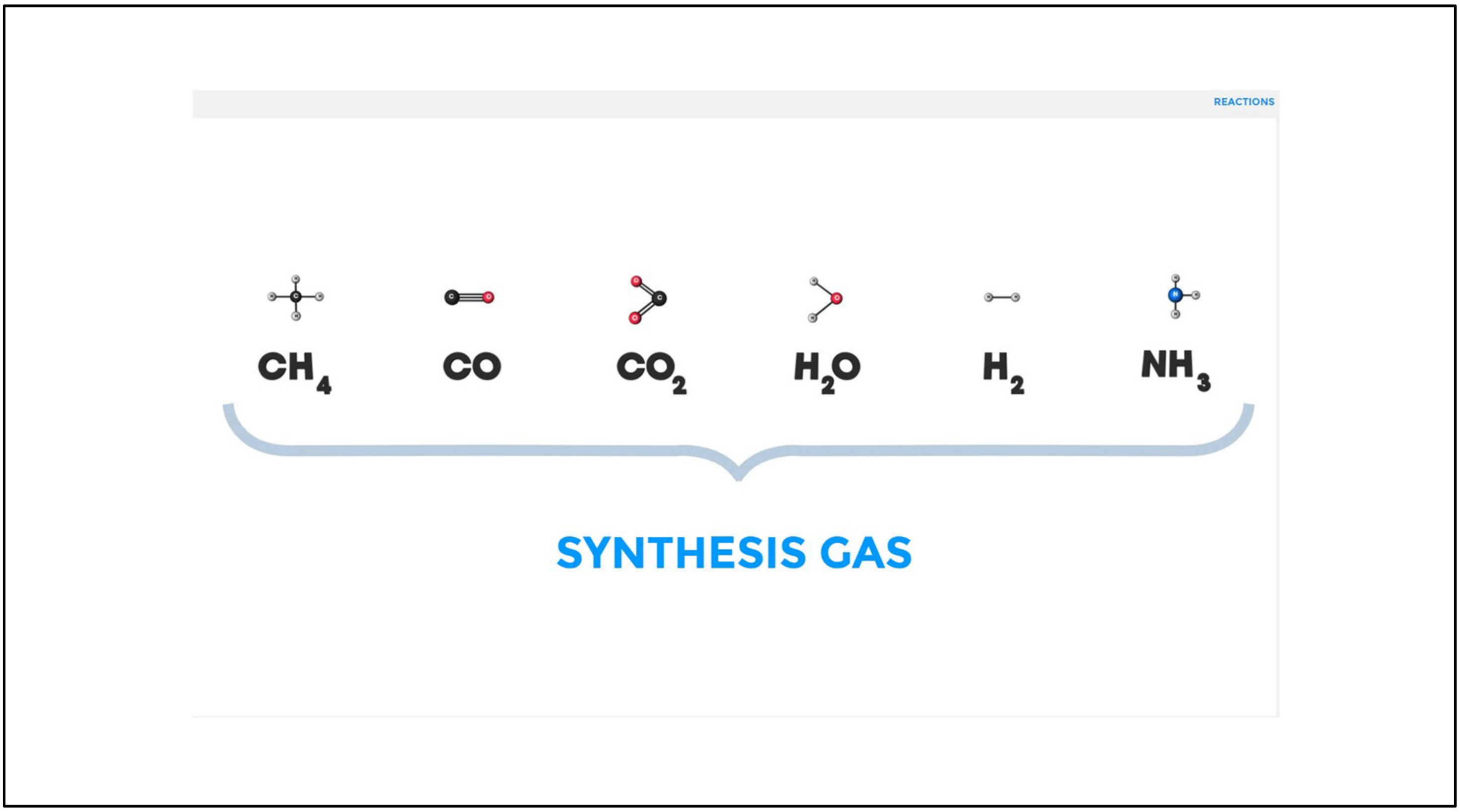
There are two reactions that take place as superheated steam and methane pass across the catalyst in the radiant tubes.

The first reaction that occurs is the steam-methane reaction, which is endothermic - this means it takes in heat, so the temperature must be sustained by the burners as the reaction progresses.

One molecule of methane reacts with one molecule of steam to produce one molecule of carbon monoxide and three molecules of hydrogen.

The second reaction that occurs is the water gas-shift reaction, which is exothermic - this means it gives off heat.

The water gas-shift reaction takes one molecule of carbon monoxide (formed in the first reaction) and reacts it with one molecule of steam to form one molecule of carbon dioxide and one molecule of hydrogen.



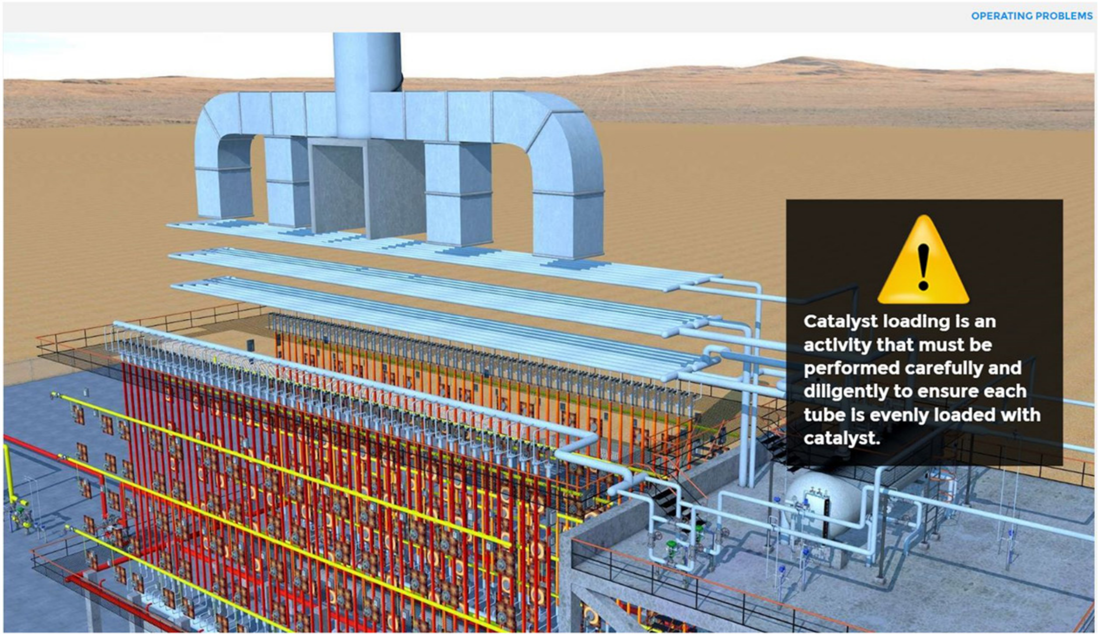
The two reactions produce a mixture of gases, collectively known as synthesis gas.

You'll recall that back in module 1, I mentioned that the natural gas feed contained a small amount of nitrogen that we didn't remove.

The nitrogen reacts with hydrogen to form ammonia.

The reaction has little impact on hydrogen production but the small amount of ammonia can cause problems.

You'll hear more about this in module 3.



Operating Problems

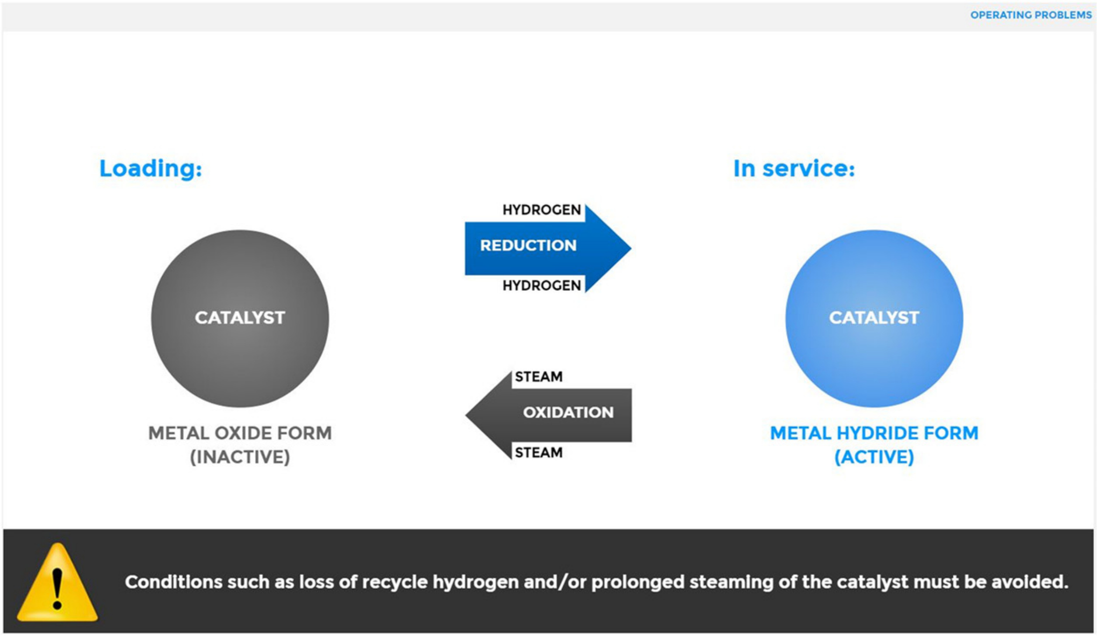
And lastly, operating problems. We've talked quite a bit about catalyst poisons and radiant tube mechanical issues, so I won't go into these again, suffice to say they are problematic if not properly monitored and controlled.

As mentioned previously, the radiant tubes are filled with catalyst.

Catalyst loading is an activity that must be performed carefully and diligently to ensure each tube is evenly loaded with catalyst.

Any breakage of catalyst or over-loading or under-loading will result in more or less resistance to flow in deviant tubes when the plant is started up.

This causes maldistribution problems with the result that some tubes run hotter and some run colder, making it difficult to achieve optimum temperatures without exceeding a mechanical limitation.



The radiant tube catalyst, as loaded, is usually in its metal oxide (inactive) form.

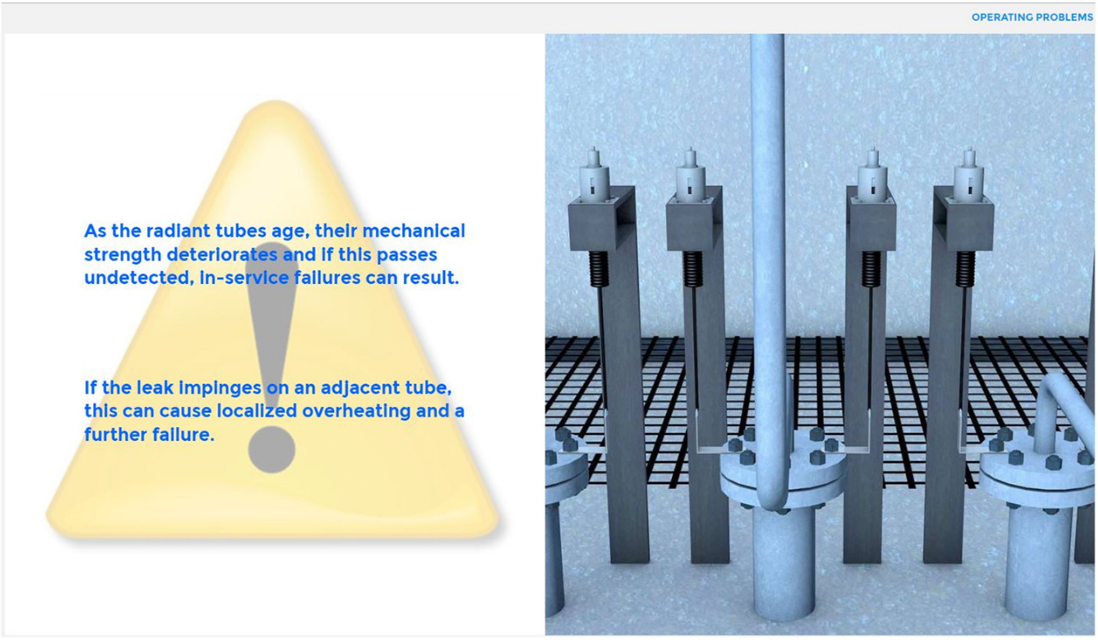
In service, the catalyst is activated by converting it to its metal hydride form.

The mechanism for activating the catalyst is called ‘reduction’ and the mechanism for returning the catalyst to its inactive state is called ‘oxidation’.

Hydrogen is a reducing agent - the presence of recycle hydrogen in the natural gas feed ensures the top 10-20% of the catalyst gets reduced before hydrogen is formed by the steam-methane reaction and reduction is sustained.

Conversely, steam is an oxidizing agent - prolonged contacting of the catalyst with steam and no hydrogen has the effect of returning the catalyst to its inactive metal oxide state.

As the processing objective is to maximize catalyst performance and hence maximize production of hydrogen, conditions such as loss of recycle hydrogen and/or prolonged steaming of the catalyst must be avoided.



With careful operation, the reformer radiant tubes should achieve a life-time of around 100,000 hours (or 10 years).

During that period, there could be two or more catalyst changes.

As the radiant tubes age, their mechanical strength deteriorates and if this passes undetected, in-service failures can result.

This usually starts as a 'pin-hole' leak that ignites and is visible from one of the many firebox view ports.

If the leak impinges on an adjacent tube, this can cause localized overheating and a further failure.

A leaking tube is temporarily handled by 'crimping' the associated inlet hairpin, which stops the flow through the tube.

The tube is then replaced at the next available opportunity.

Generally, leakers are a sign that the tubes are approaching the end of their life and all need to be replaced.

And this completes Module 2, in which we have covered the steam-methane reforming unit operation.

To summarize:

The function of the steam-methane reforming unit operation is to pass a pretreated natural gas-superheated steam mixture across a catalyst at high temperature, initiating steam-methane and water gas-shift reactions to form hydrogen

The reforming process requires a substantial input of heat, most of which is recovered by generating and superheating high pressure steam - some of which is used as a reformer reactant, with the balance exported to other refinery users

For this key unit operation, you should now be familiar with:

Principal items of equipment and their function

Important process variables and associated controls

Principles of operation and the internal components of key items of equipment

Typical operating problems

Your task now is to take the HGU Module 02 Quiz to ensure you have fully understood the material.

If you find the questions challenging, you should consider repeating this module before moving on.

Good luck!

You can now close this module.