EMISSIONS SOURCES

From Boilers to Bulldozers

Redefining possible.

SOURCES: BROAD DEFINITIONS

Everyone loves definitions

Sources: Broad Definitions

A source is simply the location at which a contaminant is released into the atmosphere, defined by:

Geometry:

- Point sources, such as a stack or vent;
- Area sources, such as a pool, landfill, or open tank; or,
- Volume sources, such as parking garages or material handling.

Mobility:

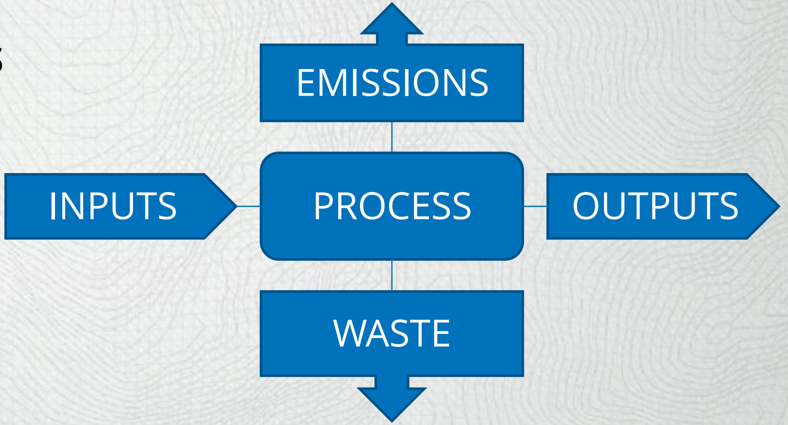
- Stationary sources, such as industrial sites, institutional facilities landfills and wastewater treatment plants; or
- Mobile sources, such as planes, trains and automobiles, but <u>not</u> airports, railway lines or roads, which are actually stationary.

Sources: Broad Definitions

Sources can also be thought of as processes, each with potential inputs, outputs, emissions and waste streams.

This becomes critical as we estimate emissions.

Ideally, we can estimate emissions by doing a full mass balance of all streams (even if we don't know the process details).



Sources: Broad Definitions

For other sources, a mass balance is more difficult. In these cases, we turn to:

- Emission factors, which use the inputs or outputs to estimate emissions for a given process;
- Engineering calculations, looking at evaporation rates, for example; or,
- Direct measurements, from one-off samples to continuous monitors.

EMISSION SOURCES

Enough definitions
Bring on the Bulldozers

Emission Sources





Emission Sources

1

Stationary Combustion

- External
- Internal

2

Mobile Combustion

- Planes
- Trains
- Automobiles

3

Fugitive Dust

- Vehicle Traffic
- Aggregates, Mining and Construction

4

Surface Coating Operations

- Painting
- Plating

5

Evaporative Loss Sources

- Fume Hoods
- Storage Tanks

Stationary Combustion

Stationary Combustion

Stationary combustion equipment falls into two broad categories, essentially defined by the desired product of the combustion process:

- External combustion sources:
  - Include boilers, furnaces, woodstoves and ovens;
  - Burn almost anything including coal, oil, natural gas, landfill gas, digester gas, wood, or wood waste; and,
  - Produce heat to generate steam, to heat water or air, or for cooking.
- Internal combustion sources:
  - Include engines (spark or compression-ignited) and turbines;
  - Burn only liquid or gaseous fuels; and,
  - Produce pressure to create mechanical power.
  - Heat is essentially a by-product (although it can also be harnessed).

Stationary Combustion - External

Generally operated under low pressure, these sources are ubiquitous:

- Woodstoves in rural residences or cottages;
- Natural gas furnace in a home;
- Air handling units on the roof of a hospital;
- Infrared tube heaters in a warehouse;
- Natural gas-fired steam boilers for heating at a university;
- Large natural gas-fired ovens at commercial bakeries;
- Natural-gas fired dryer at an asphalt plant;
- Oil-fired steam boiler at a refinery or paper mill;
- Coal fired boilers once used to generate electricity in Ontario.

https://s3.amazonaws.com/pastperfectonline/images/museum_460/028/ph5793.jpg

http://www.blodgett.com/xr8

https://watmfg.com/products/flx-flexible-watertube-steam-boiler/

Stationary Combustion - External

As the list suggests, boilers are pretty common!

This technology essentially ushered in the industrial revolution, and yet remains as one of our primary sources of heat and power.

Not many homes still have boilers and radiators, but in many multi-residential buildings and institutional facilities, boilers are still the norm.

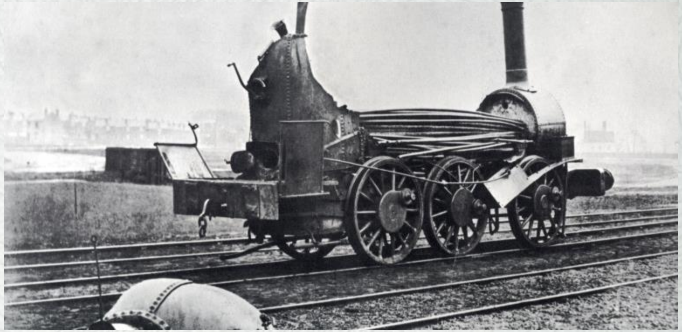
Boilers also provide steam used to generate mechanical power, which in turn provide electrical power at power plants throughout the world.

We generally now see two main types of boilers.

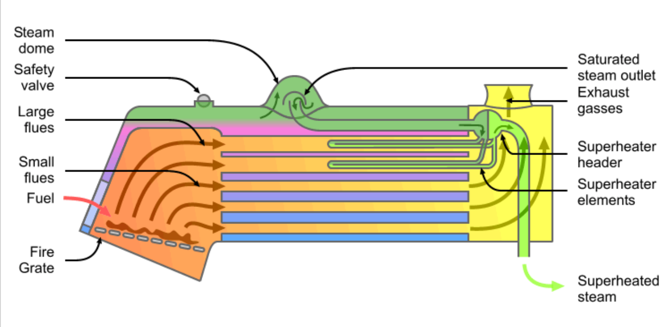
Stationary Combustion - External

Fire-Tube boilers:

- Consist of a tank of water perforated with pipes, through which hot gases pass to boil the water.
- These often exploded.
- Dramatically.
- Stories of boiler explosions are a staple in history books.



http://en.wikipedia.org/wiki/Image:Boiler_explosion_1850.jpg

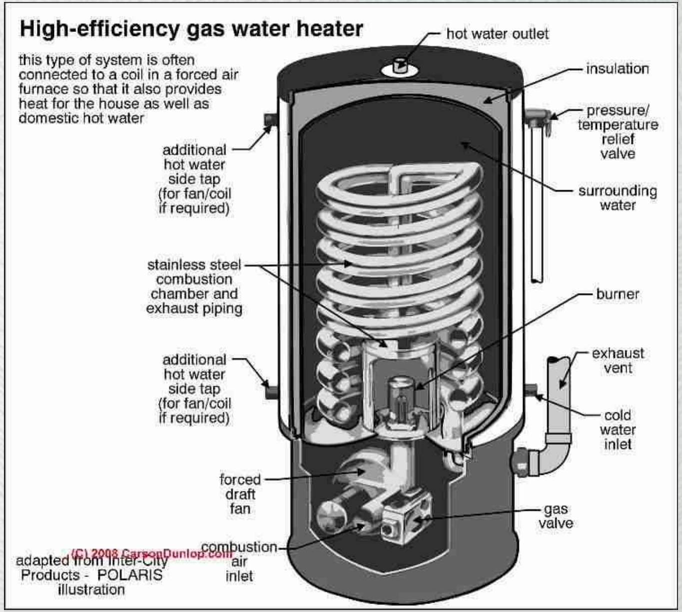


https://commons.wikimedia.org/w/index.php?curid=565965

Stationary Combustion - External

Fire-Tube boilers:

- Nowadays, most of us have something similar in our homes, in the form of hot water tanks.
- Operated at lower pressure and temperature (ideally no boiling happens).
- Things can still go wrong, hence the pressure relief valve, but hot water tank explosions aren't something you tend to hear about.

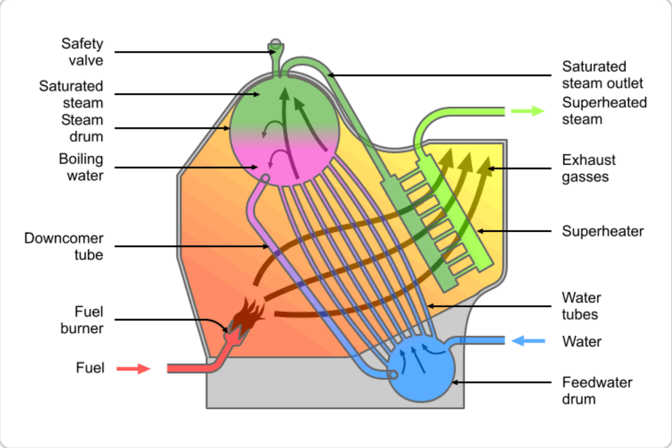


http://inspectapedia.com/heat/1607s.jpg

Stationary Combustion - External

Water-tube Boilers:

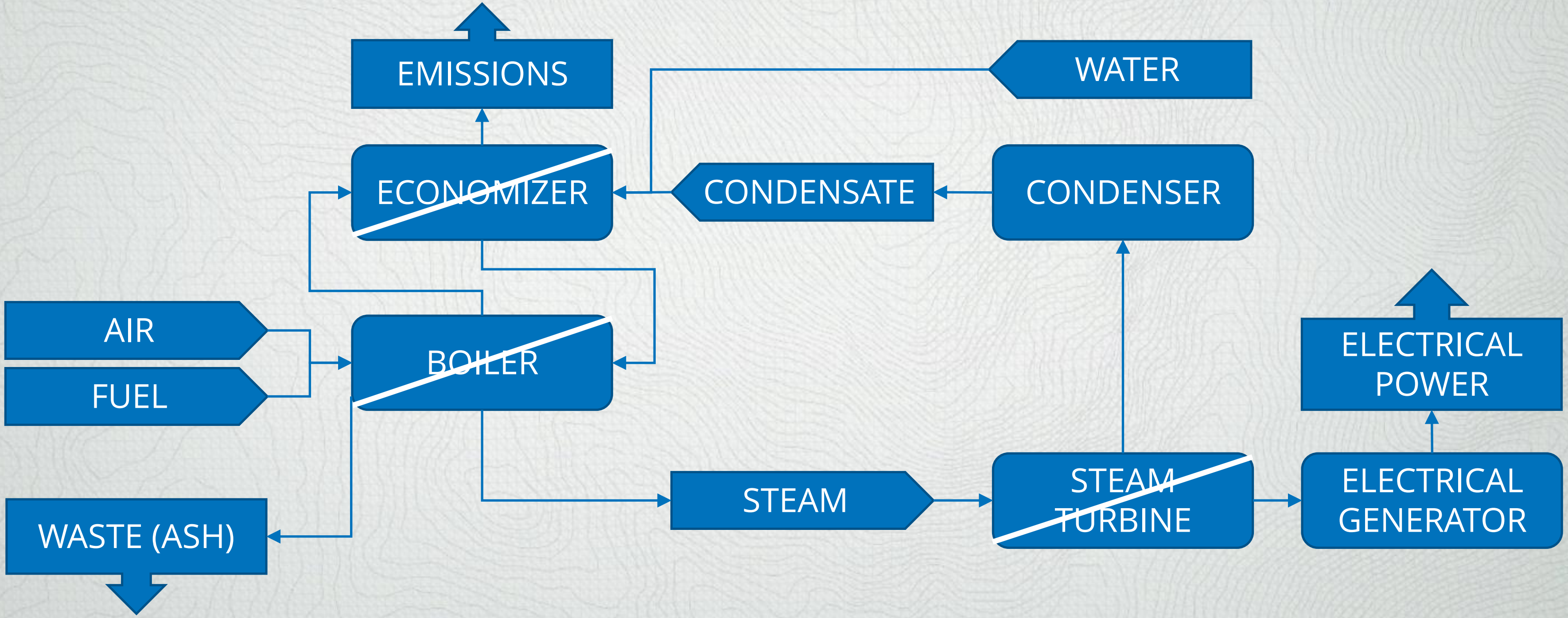
- Essentially the reverse of fire-tube boilers, the water runs through a rack of tubes that are positioned in the hot gases from the fire.
- Due to the design, they can be operated at far higher pressure, and also don't tend to explode.
- Used at power plants, refineries, chemical plants and pulp and paper mills.



https://commons.wikimedia.org/w/index.php?curid=565528

Stationary Combustion - External

"Simplified" Process Flow for a Power Boiler



Stationary Combustion - External

Emissions from these sources are highly variable, given the range of possible configurations and fuels.

Thankfully, there is a large amount of literature available, covering almost all of these.

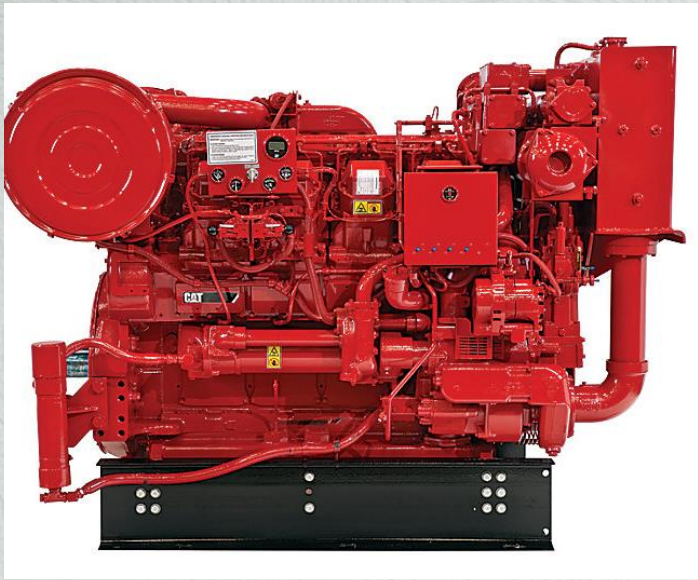
As an example, the U.S. EPA's AP-42 Emission Factors provides 11 separate chapters devoted to different fuels and processes.

Beyond this, industry associations and manufacturers are a tremendous source of information, and are often happy to provide details on how low emissions have become.

Stationary Combustion - Internal

Operated primarily to generate mechanical power, these sources are also ubiquitous:

- Gasoline (spark-ignition) internal combustion engines used for generators, pumps, and compressors (2 stroke or 4-stroke);
- Diesel (compression-ignition) internal combustion engines, used for generators, pumps, and compressors (2 stroke or 4-stroke).
- Combustion turbines used for power generation;
- Combustion turbines on compressors in the oil & gas industry;
- Not all "engines" are internal combustion processes however:
  - Steam engines use steam produced by a boiler;
  - Stirling engines are basically witchcraft, as far as I can tell.



https://powerequipment.honda.ca/generators#economy-series

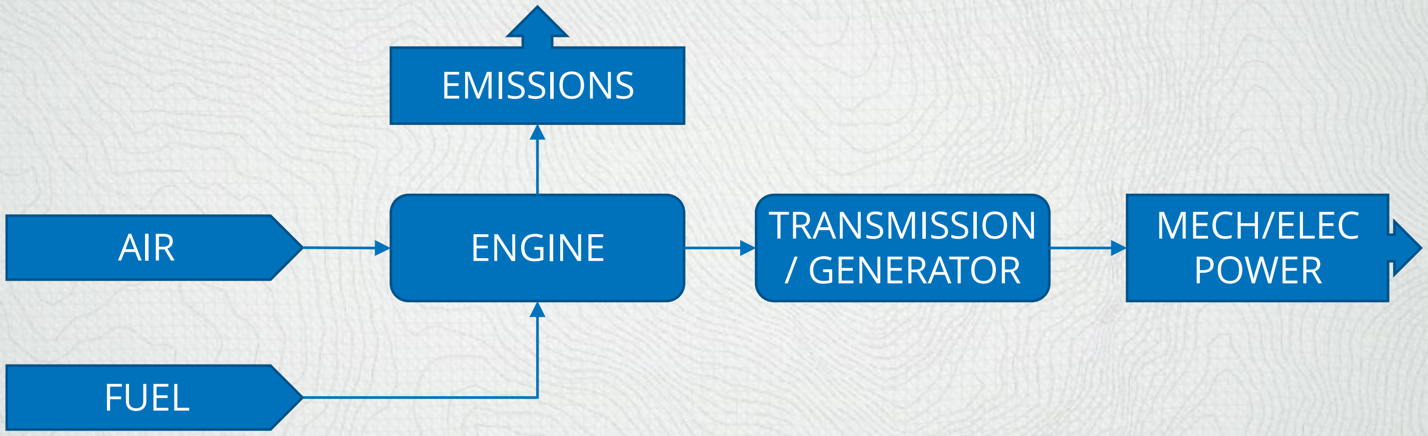
Stationary Combustion - Internal

Internal Combustion Engines

- Gasoline and diesel engines both use a process whereby the explosive combustion of fuel mixed with air creates a pressure that forces a piston to move down a cylinder.
- The moving piston acts against a crankshaft, which provides mechanical power.
- Each cycle creates one full revolution in the shaft, consisting of two strokes (up and down).
- Gasoline engines use a spark plug to ignite the air and fuel mixture (hence “spark-ignition”).
- Diesel engines use adiabatic compression to spontaneously ignite the air and fuel mixture (hence “compression-ignition”).

Stationary Combustion - Internal

Simplified Process Flow for an Internal Combustion Engine



Stationary Combustion - Internal

Internal Combustion Engines

- Air and fuel are introduced through a series of valves as the piston is travelling back up the cylinder.
- Combustion gasses are exhausted through another set of valves, also as the piston is travelling back up the cylinder.
- As you may have guessed, this is where problems occur.
- Newer designs incorporate technologies to improve this issue, at the cost of increased weight and decreased performance.

Stationary Combustion - Internal

In two-stroke engines, ignition occurs once for every revolution of the shaft (i.e., every two “strokes”).

This means air and fuel are introduced at the same time combustion gasses are being exhausted, allowing unburned fuel to escape.

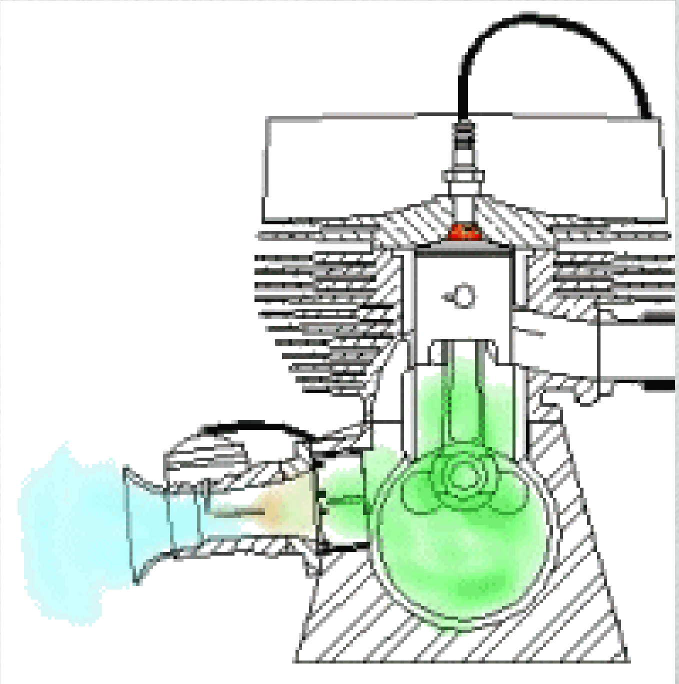


Image source: https://en.wikipedia.org/wiki/Two-stroke_engine#/media/File:2-Stroke_Engine_ani.gif

Stationary Combustion - Internal

In four-stroke engines, ignition occurs once for every 2 revolutions of the shaft (i.e., every 4 strokes).

This provides a separate cycle for air and fuel to be introduced, and a cycle for combustion gasses to be exhausted.

This requires a larger engine to produce the same power.

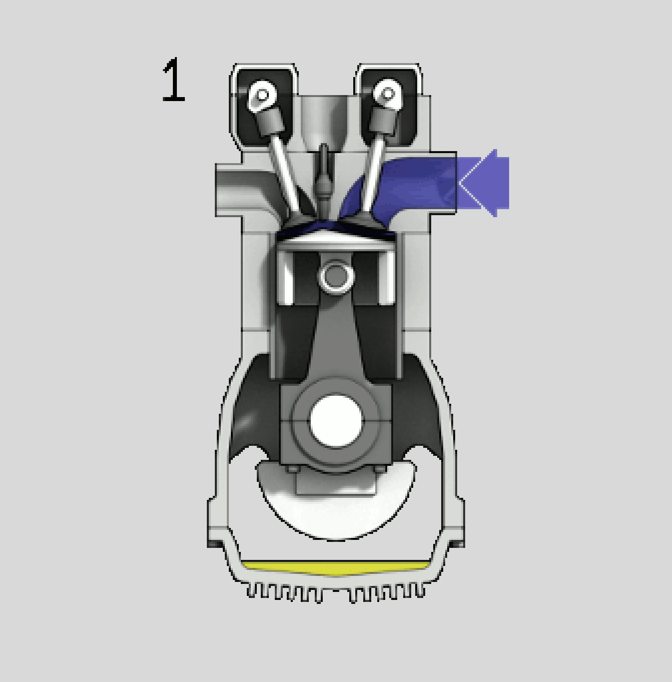


Image source: https://en.wikipedia.org/wiki/Four-stroke_engine#/media/File:4StrokeEngine_Ortho_3D_Small.gif

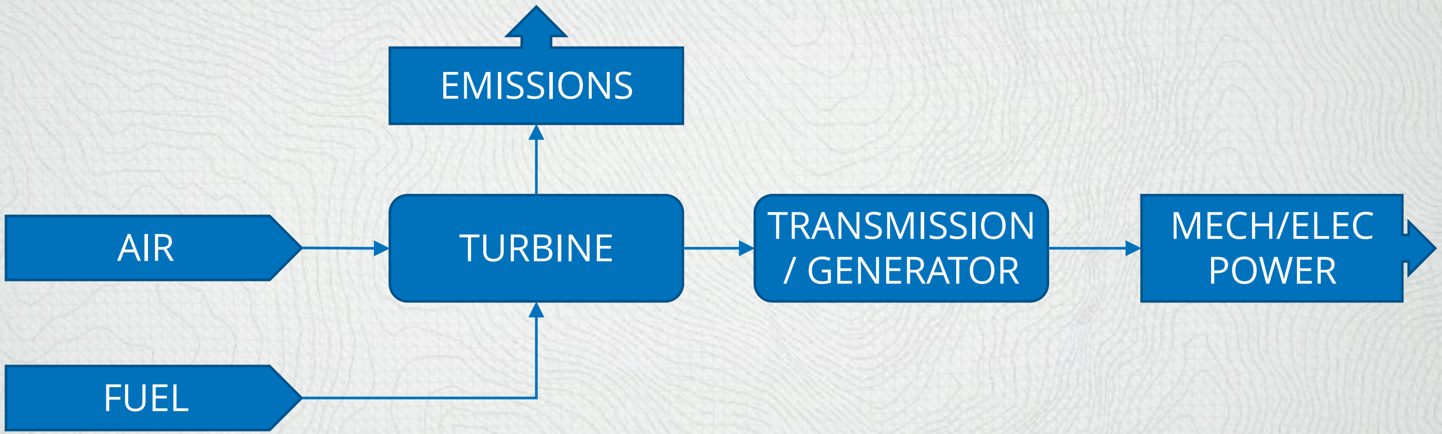
Stationary Combustion - Internal

Combustion Turbines

- Combustion turbines use a high pressure combustion process to drive a turbine instead of a piston.
- Air is drawn into the turbine and compressed through a rotating air compressor.
- Fuel is then injected and ignited, resulting in a high-pressure, high-temperature exhaust stream.
- This stream turns the turbine, generating mechanical power which is used both to compress the incoming air, and to power whatever is connected to the shaft at the other end.
- The hot exhaust gasses are then vented to atmosphere.
- This is referred to as a "simple-cycle" combustion turbine.

Stationary Combustion - Internal

Simplified Process Flow for a Simple Cycle Combustion Turbine



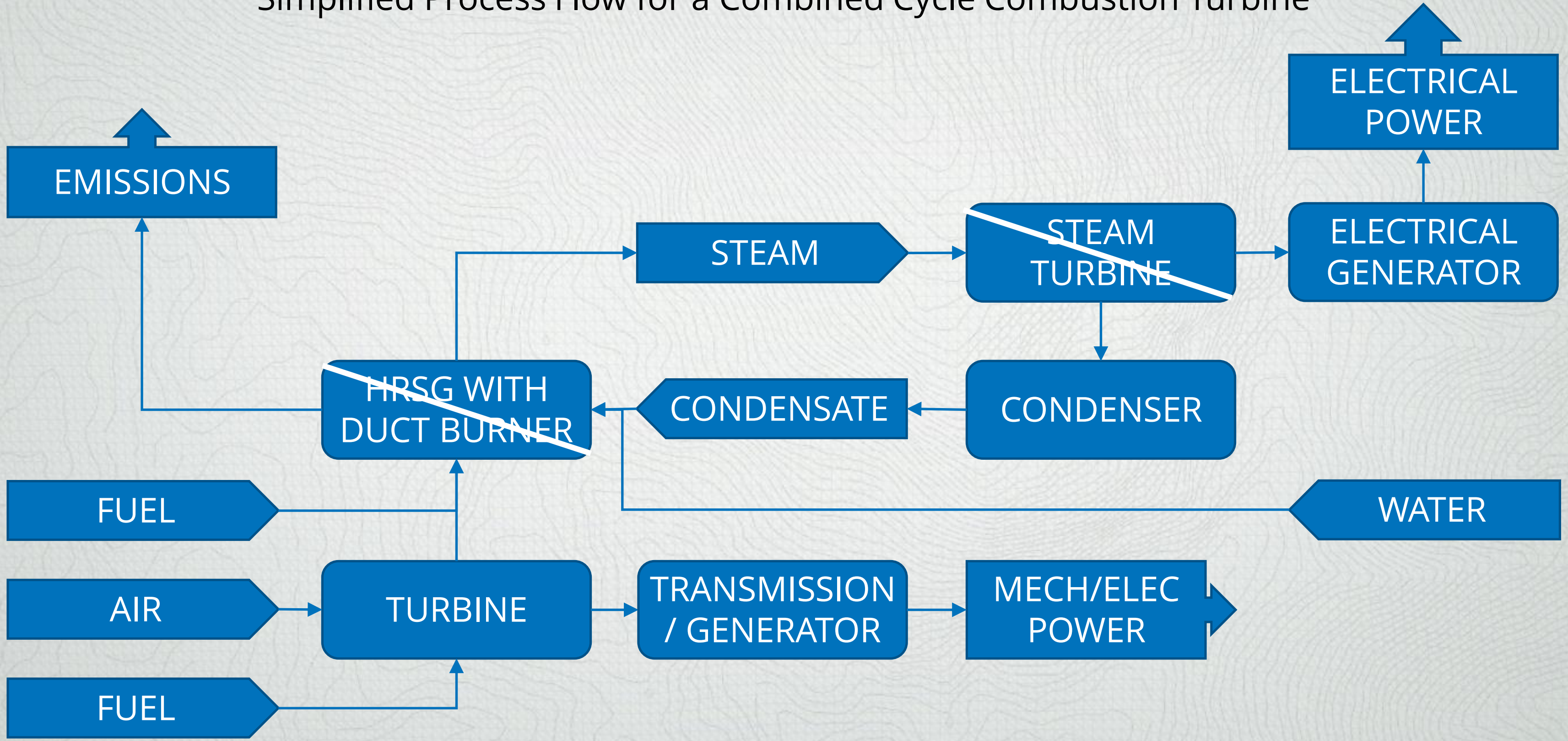
Stationary Combustion - Internal

Combustion Turbines

- In “combined-cycle” systems, the hot exhaust gasses are passed through a heat recovery steam generator, or HRSG (also called a “once-through” steam generator, or OTSG), which uses the heat to generate steam.
- This steam is used to drive an additional steam turbine, which produces more power.
- The HRSG may also include duct burners which provide additional heat energy for steam generation.
- These systems are the heart of the “gas plants” that were once a “hot” topic in Ontario political circles.

Stationary Combustion - Internal

Simplified Process Flow for a Combined Cycle Combustion Turbine



Stationary Combustion - Internal

While burning fewer types of fuel, and consisting essentially of only three basic processes, emissions are no less variable than with external combustion sources.

The U.S. EPA provides 4 chapters, covering natural gas, gasoline and distillate oil-fired versions of the three types, including a separate chapter for large engines.

In addition, there are emission limits on virtually every combination, which can provide an upper bound.

While factors are available and published limits exist, this is where a call to a manufacturer is truly warranted.

Mobile Combustion

Mobile Combustion

2

Operated primarily to generate mechanical power, these sources are also ubiquitous (there's a trend here):

- Gasoline (spark-ignition) engines in cars and light-duty trucks;
- Diesel (compression-ignition) engines in cars, trucks, busses, heavy equipment (finally a bulldozer), trains and ships.
- Piston engines on propeller-driven aircraft;
- Turboprop engines on propeller-driven aircraft;
- Aircraft jet engines (technically called turbofans);

These are all forms of internal combustion.

- External combustion is now rarely used in mobile applications.
- The locomotive or steamship boiler was once the primary way we moved people and goods, these are now museum pieces.

Mobile Combustion

https://commons.wikimedia.org/wiki/File:Beaver_floatplane_at_Comox.jpg

https://www.cat.com/en_US/products/new/equipment/dozers/large-dozers/18332635.html

https://www.flickr.com/photos/147621582@N02/34664824105

Mobile Combustion – Engines

2

Gasoline and Diesel Engines

- In general, engines used on mobile sources are the same as stationary engines.
- While 4-stroke engines are the norm for gasoline engines on cars and light duty trucks, many motorcycles and scooters still have two-stroke engines.
- Two-stroke engines are also the norm on outdoor power tools such as lawnmowers, weed trimmers and chainsaws, and are also still popular for small boats and watercraft.
- Two-stroke engines are still heavily used in large diesel engine applications, whether in trucks, busses, trains or ships.
- The high power-to-weight ratio of two-stroke engines is a major incentive to continue using and improving on these engines.

Mobile Combustion – Engines

2

Piston Engines on Propeller-Driven Aircraft:

- These specialized gasoline engines were once the dominant form of propulsion for aircraft, before turboprop and turbofan engines came into use.
- While now considered an older design, it remains immensely popular – just ask any bush pilot in northern Canada.
- Basically the same as a normal gasoline engine, the unique requirements of aircraft design result in different arrangement of cylinders, best exemplified by the radial piston engine used on planes such as the de Havilland Canada Beaver – a plane as Canadian as maple syrup and Nanaimo bars.
- One key item of note is that the fuel used in these engines still contains tetraethyl lead. Yes, leaded gasoline is still in use.

Mobile Combustion - Engines

2

As noted, engines used on mobile sources are the same as stationary engines, but they typically experience much greater variations in load over time.

This is readily observed in our driving habits, as no two individuals drive the same – from "jack rabbits" and "lead foots" to "Sunday drivers".

Thus we tend to focus on duty cycles, speed profiles or other methods for approximating the load on the engine over a given period of time, whether hourly or daily.

This complicates the emission estimation process.

Mobile Combustion – TurboProps

Turboprop Engines on Propeller-Driven Aircraft:

- The beginning of the “Golden Age of Air Travel” was ushered in by the development of modern turboprop airliners.
- The turboprop-driven Vickers Viscount was the first commercial airliner used in North America, by Trans-Canada Air Lines.
- While eventually replaced for longer flights by jet aircraft, shorter routes are still heavily served by turboprop aircraft such as the Bombardier Q400 flown extensively out of Billy Bishop Airport.
- For shorter flights, where flights can travel at lower altitude, turboprop aircraft are actually more fuel efficient than similar-sized regional jets.
- These engines use jet fuel, essentially a form of kerosene.

2

Mobile Combustion – Jet Engines

2

- The heart of the system is a gas turbine, similar to that discussed under stationary combustion.
- The rotating shaft not only powers the rotating air compressor, it powers the propeller directly through a gearbox.
- Very little thrust is generated by the hot exhaust, unlike turbofan engines, where this is a major source of thrust.

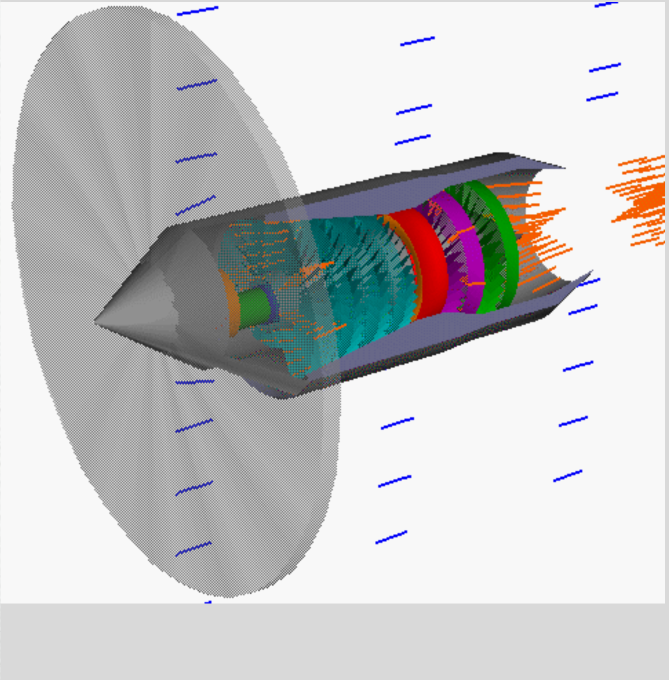


Image source: By US GOV - http://www.grc.nasa.gov/WWW/K-12/airplane/Animation/turbtyp/Images/flowtp.gif

Mobile Combustion – Jet Engines

Aircraft Jet Engines:

- Airports in Ontario face continuing pressure to expand operations, leading to concerns over air quality and noise.
- The most notable is the restriction on jets at Billy Bishop Airport in Toronto – only turboprops are permitted.
- Most modern jet aircraft use an engine known as a turbofan.
- Other forms of air craft propulsion do exist, including ramjets, scramjets, pulsejets and even rockets, but these are generally confined to experimental designs or military applications.
- Basically, if you're on a plane and you don't see propellers, it is being powered by a turbofan.
- On longer flights, the higher speed of jet aircraft is key.
- These engines also use jet fuel.

Mobile Combustion – Jet Engines

- The heart of the system is a gas turbine, similar to that discussed under stationary combustion.
- The key difference is that some of the air compressed by the rotating air compressor bypasses the combustion chamber, such that both the bypass air and the high temperature exhaust provide thrust.

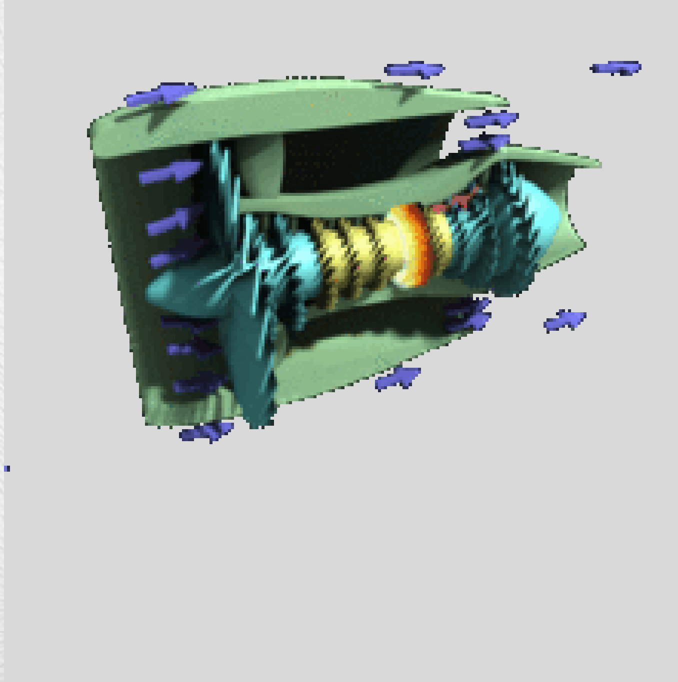


Image source: https://en.wikipedia.org/wiki/Turbofan#/media/File:Turbofan3_Unlabelled.gif

Mobile Combustion – Aircraft

2

Given the vast range of aircraft types, estimating emissions is a considerable challenge.

Thankfully the U.S. Federal Aviation Administration (FAA) has developed a system to help.

The FAA Aviation Environmental Design Tool (AEDT) estimates fuel consumption, emissions, noise, and air quality consequences.

While a U.S. model, the similarities in airports between the U.S. and Canada far exceed any differences.

6

Fugitive Dust

Fugitive Dust

Fugitive dust can be generated by a wide range of both human activity and natural processes.

Natural processes are driven primarily by wind erosion, especially under dry, drought-like conditions.

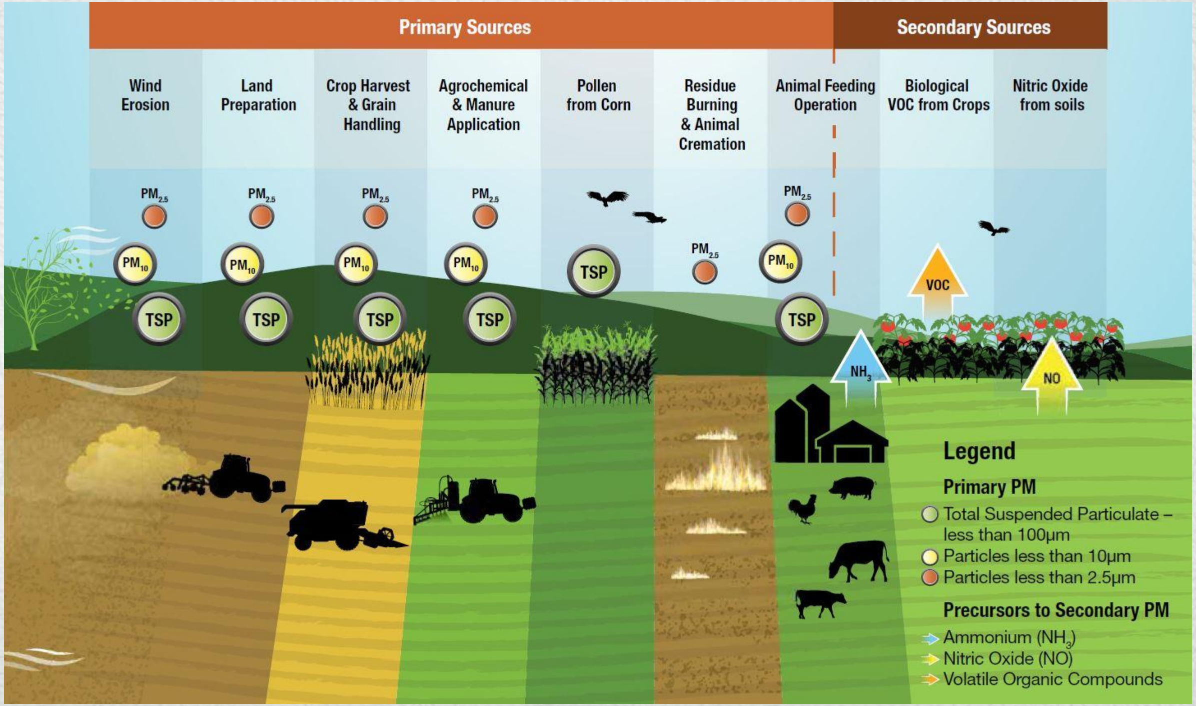
Wind erosion can readily be exacerbated by human activity, when land clearing or agricultural practices provide fresh erodible material.

Beyond this, dust is generated directly by agricultural practices, construction activities, mineral extraction operations (including aggregate extraction), and movement of vehicles on paved and unpaved roads.

Fugitive Dust

https://farmersforum.com/2017/10/

Agriculture



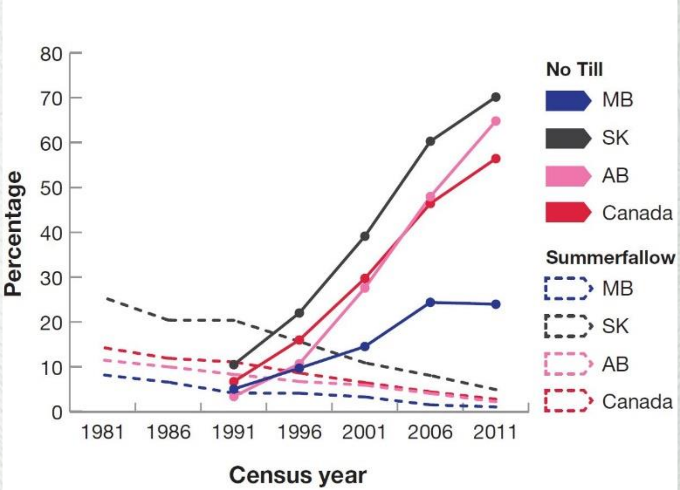
http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/climate-change-and-agriculture/particulate-matter-indicator/?id=1462392213883

Agriculture

3

Certain practices leave soils vulnerable to losses from wind erosion, such as summerfallow and intensive tillage.

These practices have been decreasing in recent years, and the results show, especially in major agricultural areas.



http://www.agr.gc.ca/eng/science-and-innovation/agricultural-practices/climate-change-and-agriculture/particulate-matter-indicator/?id=1462392213883

Construction Activities

Construction activities often lead to nuisance dust complaints, but are often not directly regulated by governments.

Dust emissions originate from:

- Demolition;
- Land clearing;
- Wind erosion;
- Earth moving; and,
- Equipment movement;

Construction Activities

3

Estimating emissions from these operations is not normally part of the typical permitting process, but often comes up on large Environmental Assessments.

While construction-specific emission data for things such as demolition are not abundant, the emissions for most individual operations can be estimated easily enough using emission factors for erosion, vehicle movement and material handling.

Associated industries such as ready-mix concrete and hot-mix asphalt do have detailed emission factors however.

Mineral Extraction

3

Mining and aggregate extraction share similar sources:

- Site preparation / stripping;
- Berm construction;
- Wind erosion;
- Drilling and blasting;
- Excavation and handling;
- Equipment movement;
- Processing;
- Loading for shipment; and,
- Rehabilitation activities.

Mineral Extraction

The U.S. EPA AP-42 Emission Factors lists 31 separate chapters dealing with the mineral products industry.

In addition, there are separate chapters dealing with site preparation, blasting, material handling, erosion, and vehicle movement.

As you can imagine, it is beyond the scope of this course to delve into this in much detail.

For most operations however, the estimation process is based on a simple emission factor, usually based on the mass of material extracted, processed, or handled.

Vehicle Movement

3

Unpaved roads can be a major localized source of fugitive dust – a drive on a gravel road can quickly confirm this statement.

Paved roads are also a significant source, however, especially in late winter / early spring as significant salt and sand residue are present.

Vehicle Movement

In 2011, RWDI conducted an ambient monitoring program along a paved highway and a nearby unpaved road in a rural setting in Ontario.

- For the paved highway, measured concentrations of coarse and fine particulate downwind of the highway were roughly double the values measured upwind of the highway.
- For the unpaved road, the data was less clear, partly due to the lower overall values. Measured concentrations of coarse particulate downwind were just over 10% higher than the values measured upwind, while for fine particulate the difference was approximately 75%.
- The key message remains, however. Roads, even paved roads, can be a significant localized source.

Vehicle Movement

3

Much work has been done by the U.S. EPA and various partner organizations in the U.S. on fugitive dust emissions from roads.

The emission factors in the U.S. EPA AP-42 compilation have several known issues, but do reflect much of this recent research.

For a given mix of vehicles, on a road segment with a given silt and moisture level, dust emissions can be estimated on a gram-per-kilometre travelled basis.

This does not include tailpipe particulate, which must also be included for a full assessment.

Surface Coating Operations

Surface Coating Operations

4

Surface coating covers more than just painting and staining, which most readily come to mind.

The U.S. EPA AP-42 Emission Factors provides 15 separate chapters devoted to different coatings and processes, including:

- Large painting operations at automotive plants;
- Wire coating for electrical cables;
- Electrostatic spraying of metal parts; and,
- Paper coatings.

For now, we'll focus on paint spray booths, as these tend to be most common, such as the neighbourhood autobody repair shop.

Paint Booths

4

Paint spray booths are separately ventilated and generally filtered rooms where paint is applied to parts (steel beams, cars, or anything else).

From model airplanes to real airplanes, there is a paint booth for almost every application.

http://www.tcpglobal.com/MASB420DCK.html#.W-tSPnmGOUk

http://managedairsystems.com/booth/aerospace-spray-booths/

Paint Booths

4

Emissions typically have 2 causes

- Excess paint (overspray) that escapes through the filter.
  - Overspray is defined by the transfer efficiency of the method used to apply the paint.
  - This ranges widely, from as low as 25% for spray cans, to 95% for electrostatic spraying.
- Evaporation of the volatile components in the paint.
  - As a simplification, it is typically assumed that 100% of the volatile components are lost as emissions.
  - This may take time, depending on the volatility.

Dryers may also be used to cure the parts, speeding up the loss of volatile components, as well as potentially introducing combustion contaminants.

Electroplating

4

Electroplating is also a common form of surface coating, although it can also be considered a metallurgical process.

This industry was once a target of the Ontario MECP “Sector Compliance Branch” (also known as the SWAT team), as a possible sector of concern.

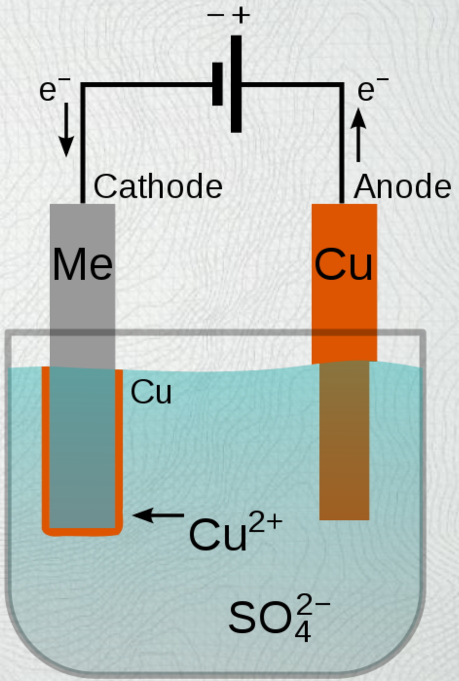
In many cases operating in small industrial plazas, this industry had become a source of concern.

Electroplating

4

The basic process involves placing an electrically-conductive item into a electrolyte bath of the metal to be plated.

An electric current is then passed through the bath, causing the surface of the item, which acts as a cathode, to become plated with the metal in the electrolyte bath.



By Torsten Henning. https://commons.wikimedia.org/w/index.php?curid=1472235

Electroplating

4

This creates a surface coating with properties different than the item being plated, which his often done for corrosion protection, or simply decorative purposes.

Emissions occur because of mists generated by the evolution of hydrogen and oxygen gas on the surface of the anode and / or cathode.

The bubbles are able to carry liquid with them in the form of a fine mist as they break through the surface of the bath.

This liquid contains the metal being plated, which can then escape into the atmosphere if not captured.

Electroplating

4

This is especially concerning when metals such as chromium, nickel or cadmium are involved.

Standard AP-42 emission factors exist for chromium plating, incorporating a wide range of emission control techniques.

Non chromium plating operations can be essentially "scaled" from the chromium plating factors using the electrochemical properties of the metal, current strength and bath properties.

5

Evaporative Loss Sources

Evaporative Loss Sources

5

A fancy term for spilling something in a fume hood.

This term actually covers any process where a volatile material evaporated and is vented to the atmosphere.

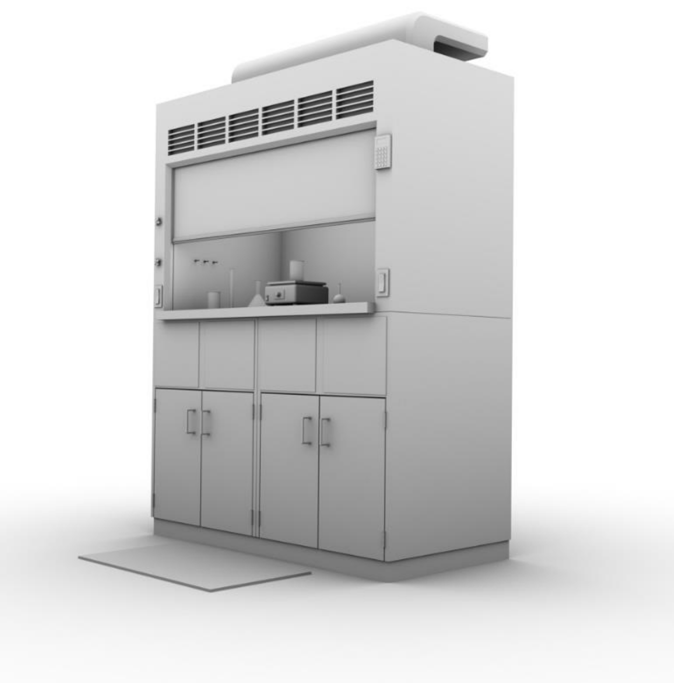
From the aforementioned fume hood spill (or simply working with volatile chemicals in a fume hood), to floating roof tanks at a refinery, these processes are all defined by a mass transfer process, driven mainly by temperature and air flow.

I hated mass transfer in university. Now I'm some sort of resident expert on fume hoods and storage tanks. Fate is a funny thing.

Evaporative Loss Sources

When material is spilled in a fume hood, until that material is cleaned up or covered, it will continue to evaporate.

The same is true for any open surface of volatile material, such as a waste water lagoon, or a chemical spill at a plant.



5

Evaporative Loss Sources

In theory, evaporation will continue until the entire mass of volatile material is gone.

Evaporation is highly dependent on temperature (anyone remember the Antoine Equation?), with higher temperatures accelerating evaporation.

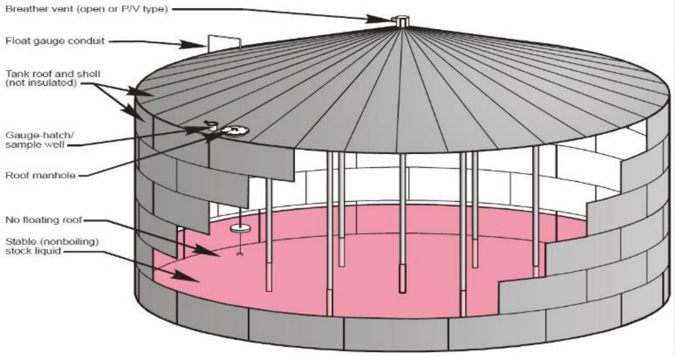
Air moving across the surface exacerbates evaporation even further, as equilibrium above the air-liquid interface is never achieved when fresh air continuously arrives.

5

Evaporative Loss Sources

"Putting a lid on it" reduces evaporation by limiting the movement of air across the surface.

The amount of volatile material in the air above the liquid eventually reaches equilibrium with the liquid below, and evaporation essentially slow down or stops.



https://www3.epa.gov/ttn/chief/ap42/ch07/final/c07s01.pdf

Evaporative Loss Sources

Increased temperature will increase the vapour pressure of the material, resulting in a higher concentration in the air above the liquid, but again, a new equilibrium will be reached.

This also increases the air pressure inside the space however, potentially resulting in venting to the atmosphere. Cooling does the reverse.

Heating and cooling therefore create a potential source of emissions due to thermal expansion and contraction, which we call "breathing".

5

Evaporative Loss Source

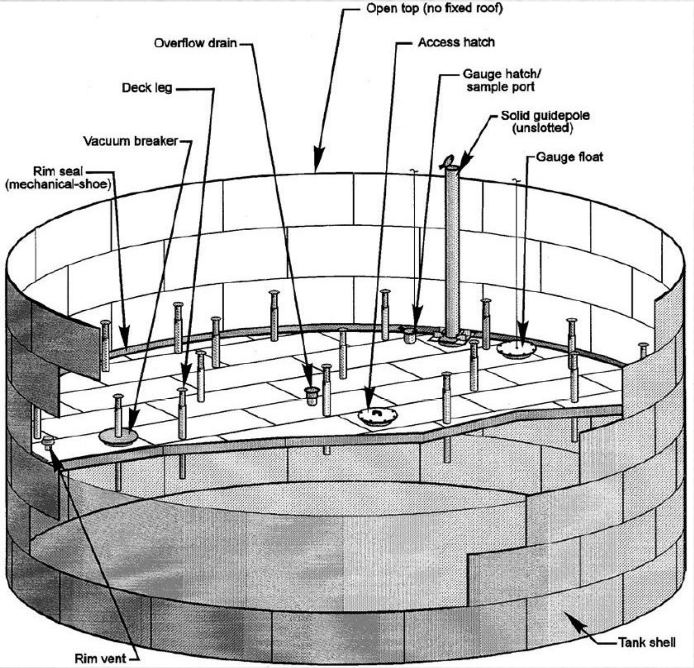
In unheated fixed roof tanks, diurnal heating and cooling can actually lead to emissions.

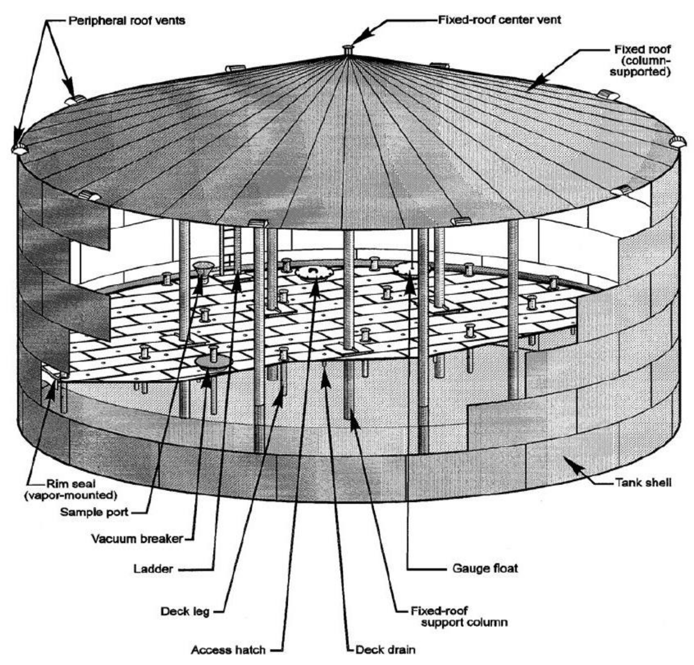
- The temperature of the tank increases during the day, and as a result, vents on the tank release contaminated air.
- As the tank cools at night, the vents allow fresh air to enter the tank, as the air inside the tank contracts.
- While small compared to the emissions that occur when a tank is filled (and the entire vapour space is potentially vented), these breathing losses occur every day.

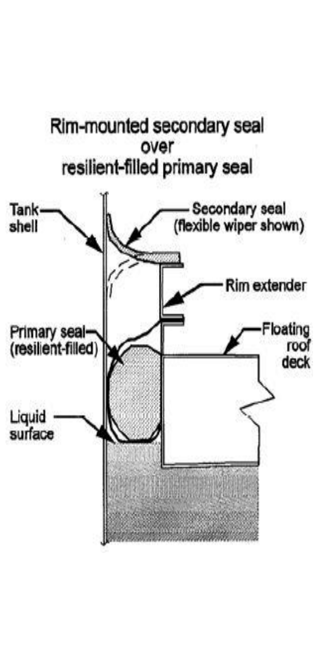
Floating roof tanks reduce this loss, by essentially eliminating the vapour space above the liquid.

There are still working losses, but these are less as well.

Evaporative Loss Source







Evaporative Loss Source

Due to the importance of diurnal heating and cooling, estimating evaporative losses from storage tanks provide one of the more interesting set of variables in the field of air quality.

A review of the U.S. EPA emission factors indicates that to properly assess emissions, the colour and condition of the roof and shell of the tank are critical variables.

For heated tanks, this is less of an issue, but for fixed unheated, fixed roof tanks, it doesn't take much logic to realize that a black-painted tank will heat up quicker than a white-painted one.

Evaporative Loss Source

The U.S. EPA provides a software tool for estimating emissions from storage tanks holding organic liquids (called TANKS, conveniently enough).

While robust, the tool is now well over 15 years old, and has limitations.

Regardless, other than third-party pay-per-use software, this remains the primary means of estimating these emissions.

For inorganic liquids, things get more difficult, forcing one to resort to first-principle calculations, perhaps using air-liquid interface data from literature.

Summary, Questions & Quiz

Summary, Questions & Quiz

Just kidding, there's no quiz.

We have covered a lot of material, hopefully dealing with sources that have direct application to your work.

There are certainly many other types of sources, dealing with processes and equipment not covered here, but this presentation is intended to hit the most common.

At this time, I am happy to discuss other processes and equipment, or delve deeper into any of the material covered previously.

THANK YOU!

Redefining possible.