IAGT Fall Course

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Delta Toronto Airport West

Steam Generation and Organic Bottoming Cycles

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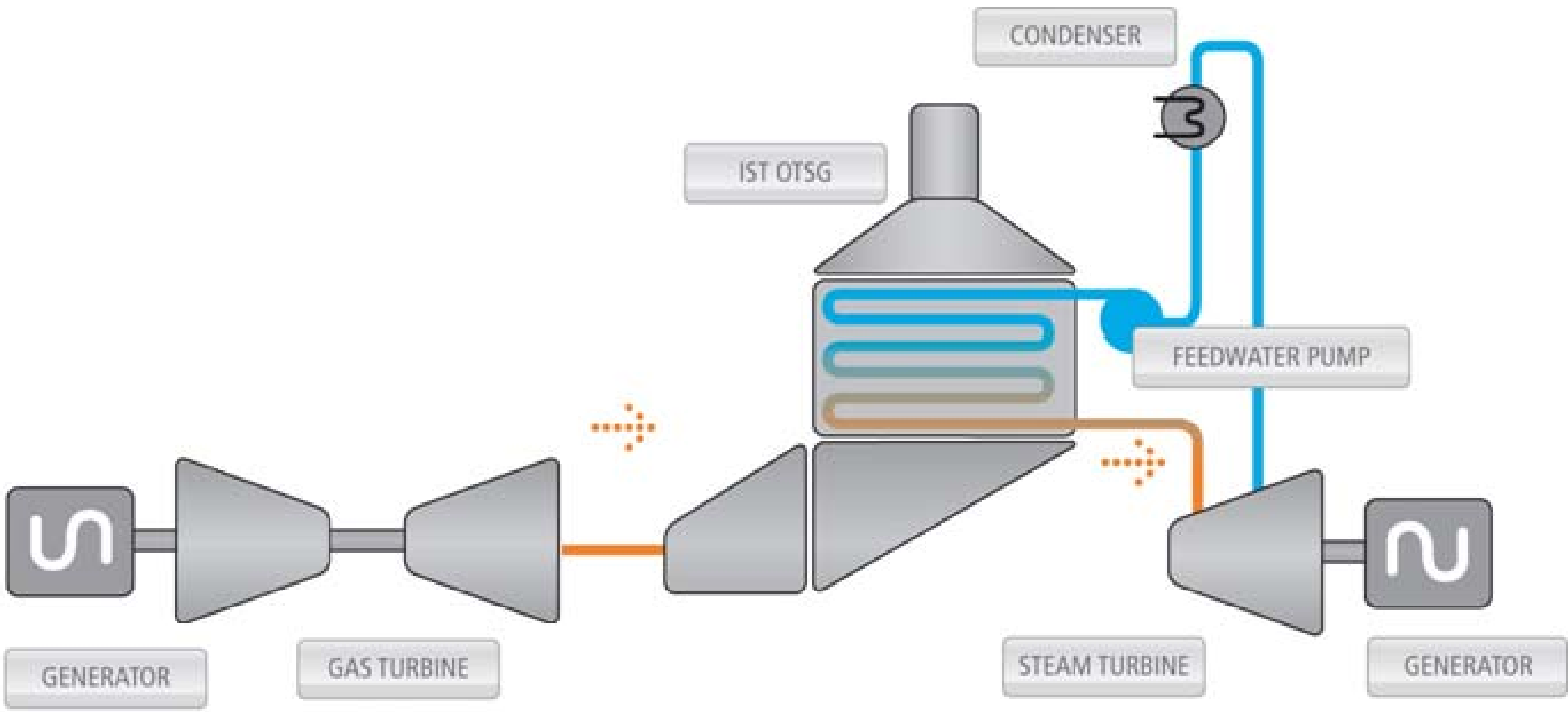
Innovative Steam Technologies

Introduction to HRSGs

Heat Recovery Steam Generator

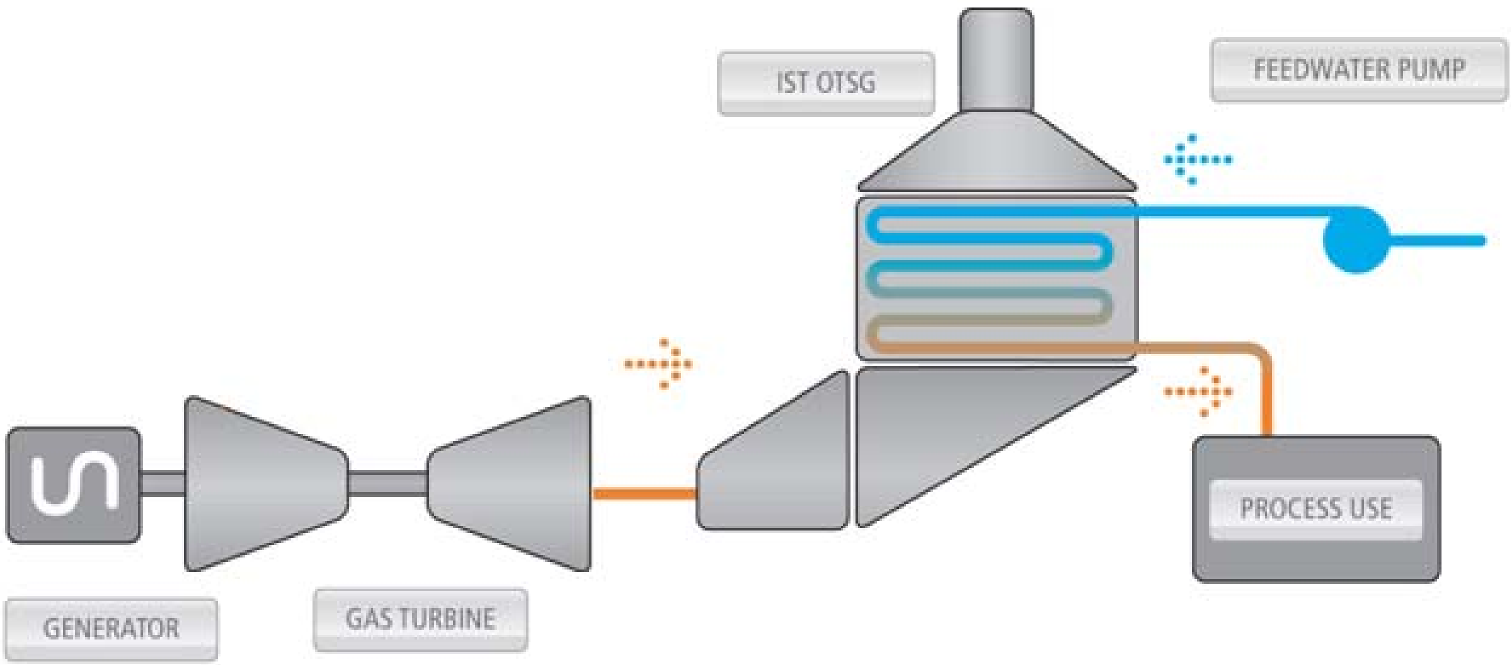
- Also referred to as a waste heat boiler
- Cools hot gasses – most commonly the exhaust of a gas turbine
- Generates steam and regains energy

Combined Cycle Plant



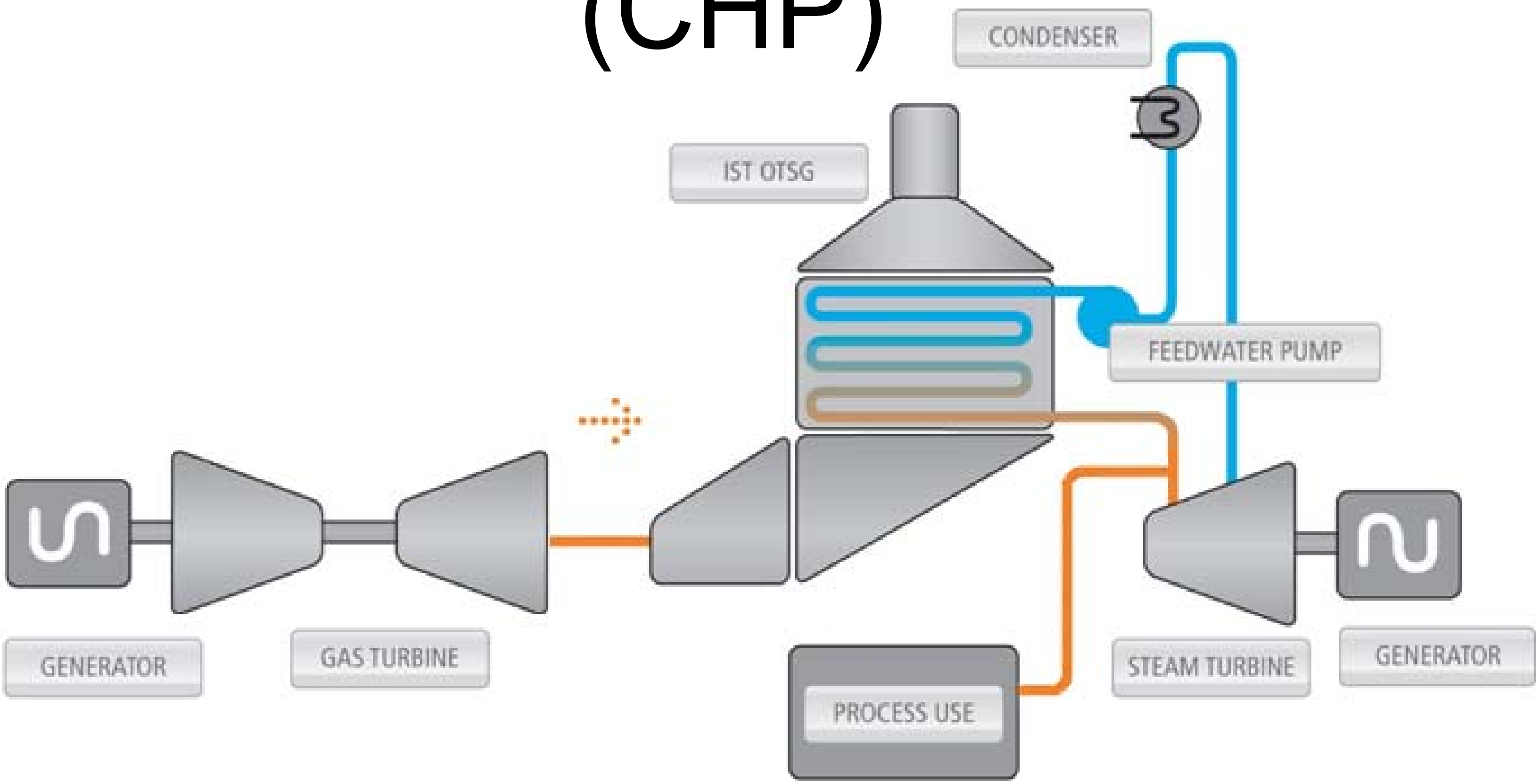
- Key Point: HRSG generates steam using waste heat from the GT and this steam is used to generate electrical power

Cogeneration



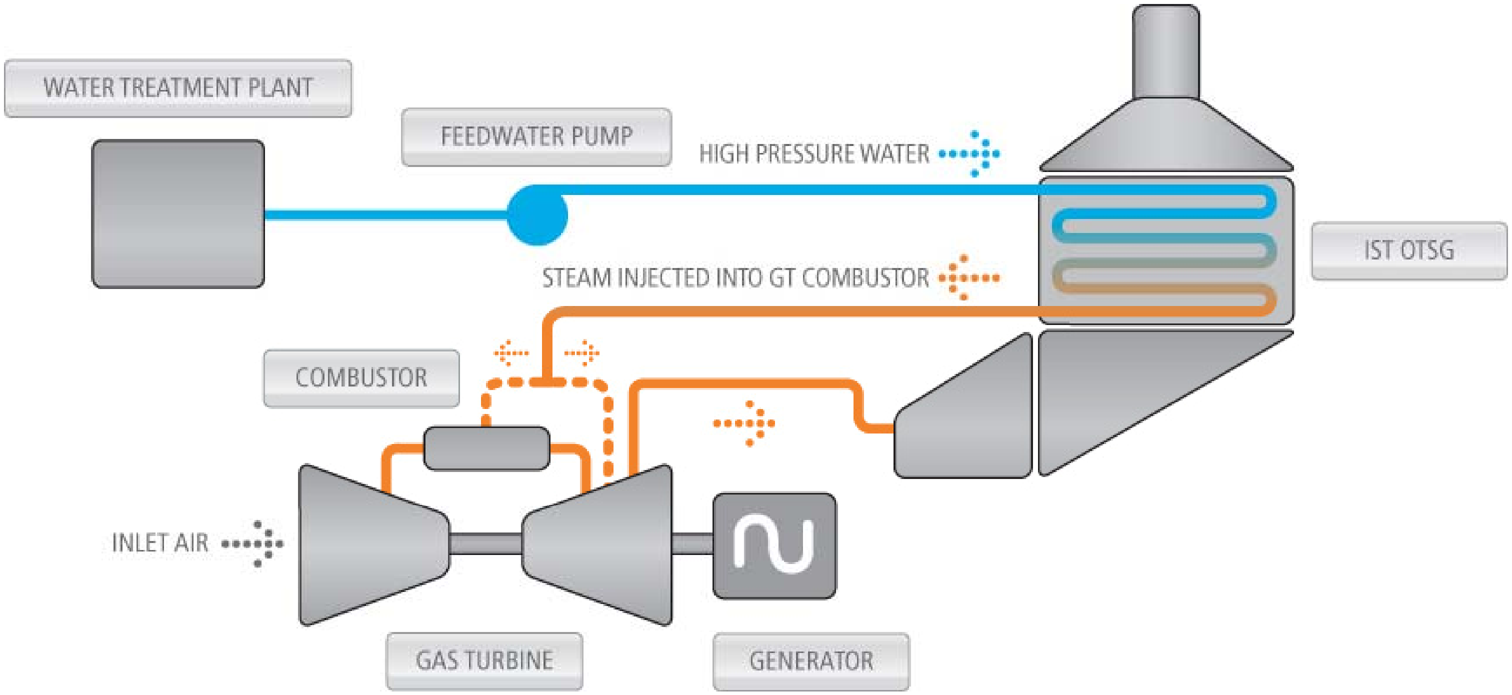
- Key Point: HRSG generates steam using waste heat from the GT and this steam is used in an industrial process

Combined Heat & Power Plant (CHP)



- Key Point: HRSG generates steam using waste heat from the GT and this steam is used in an industrial process and to generate electrical power

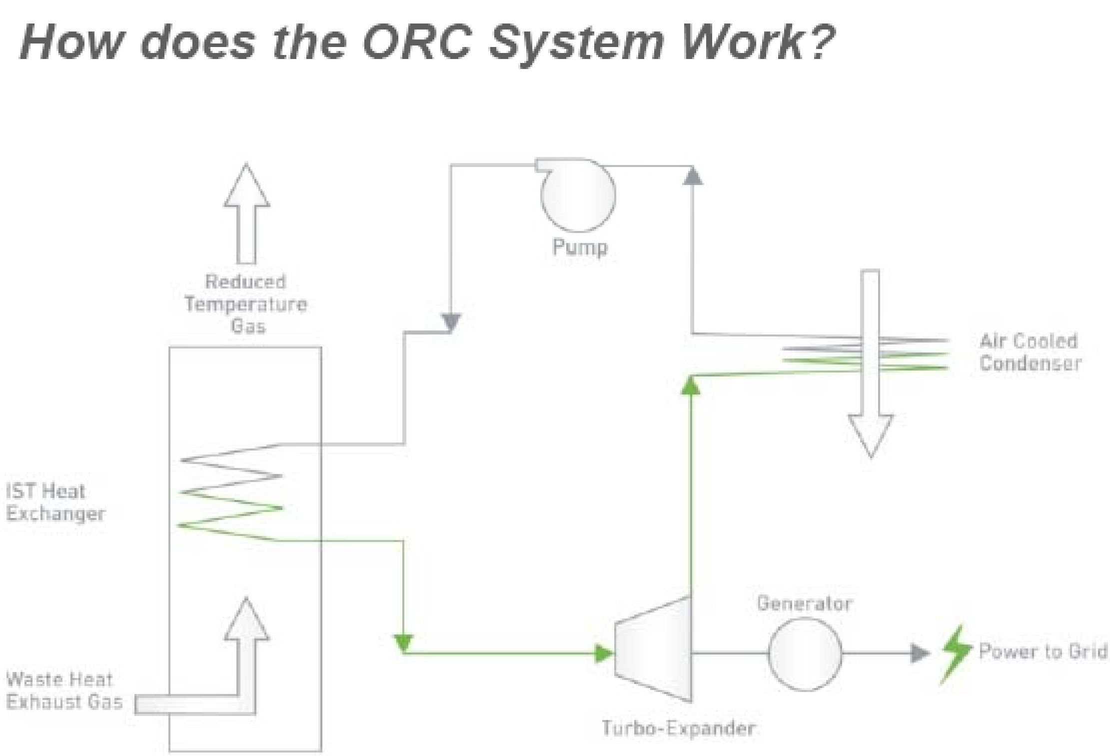
The GTI Cycle



- Key Point: HRSG generates steam using waste heat from the GT and this steam is injected into the GT to augment power and/or reduce emissions

Aside – Organic Rankine Cycle

- Focus on low grade heat applications often use ORC technology

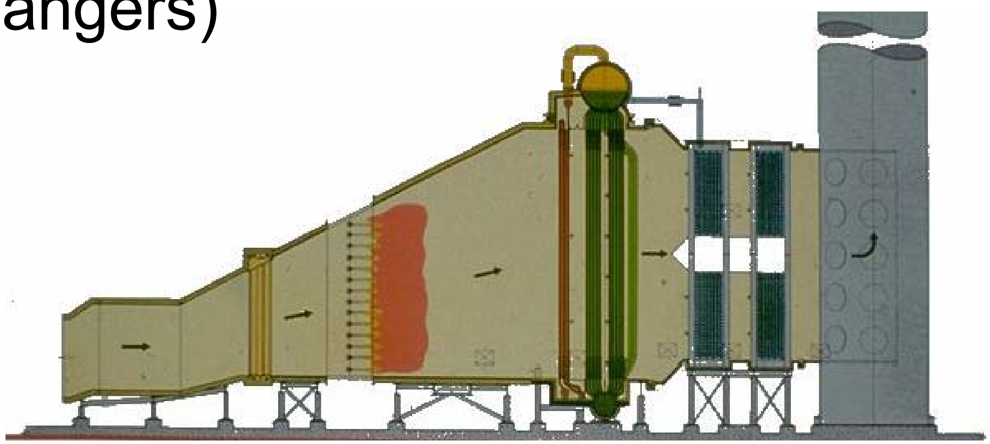


simply generates more profit

HRSG Design Philosophy

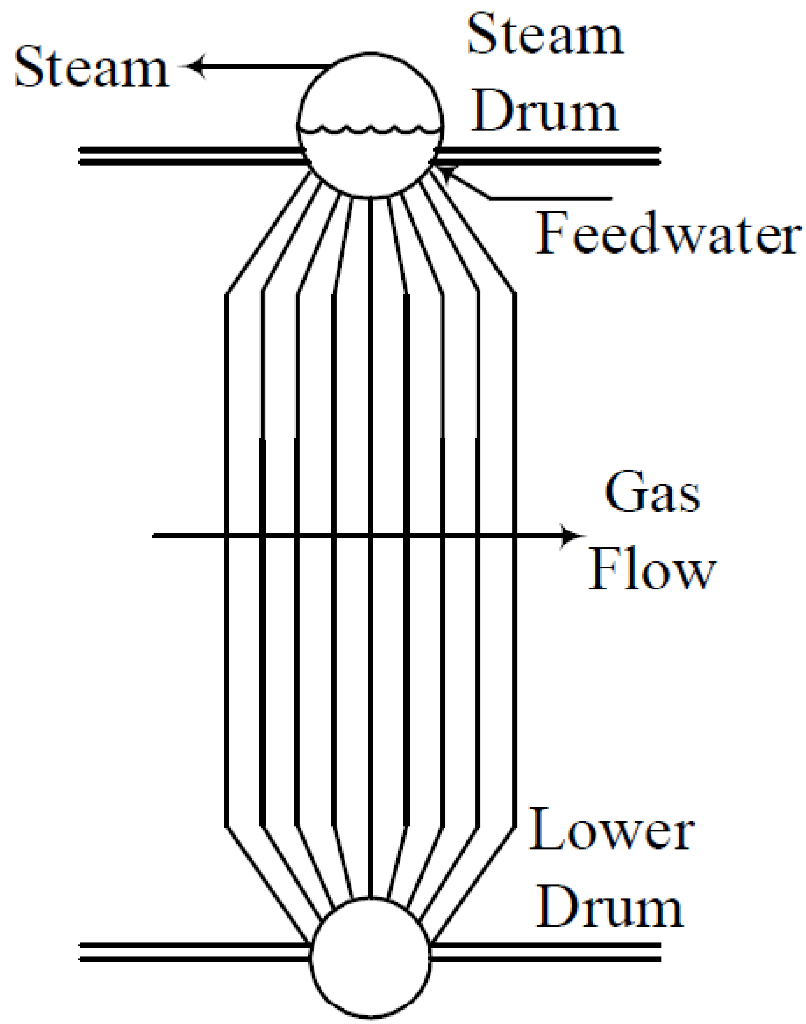
Fundamental Parts of a HRSG

- Four Basic HRSG Components
  - Evaporators (flue gas to wet steam exchangers)
  - Economizers (flue gas to water heat exchangers
  - Superheaters/Reheaters (flue gas to dry steam heat exchangers)
  - Preheaters (flue gas to water/glycol/air etc. heat exchangers)



Evaporator

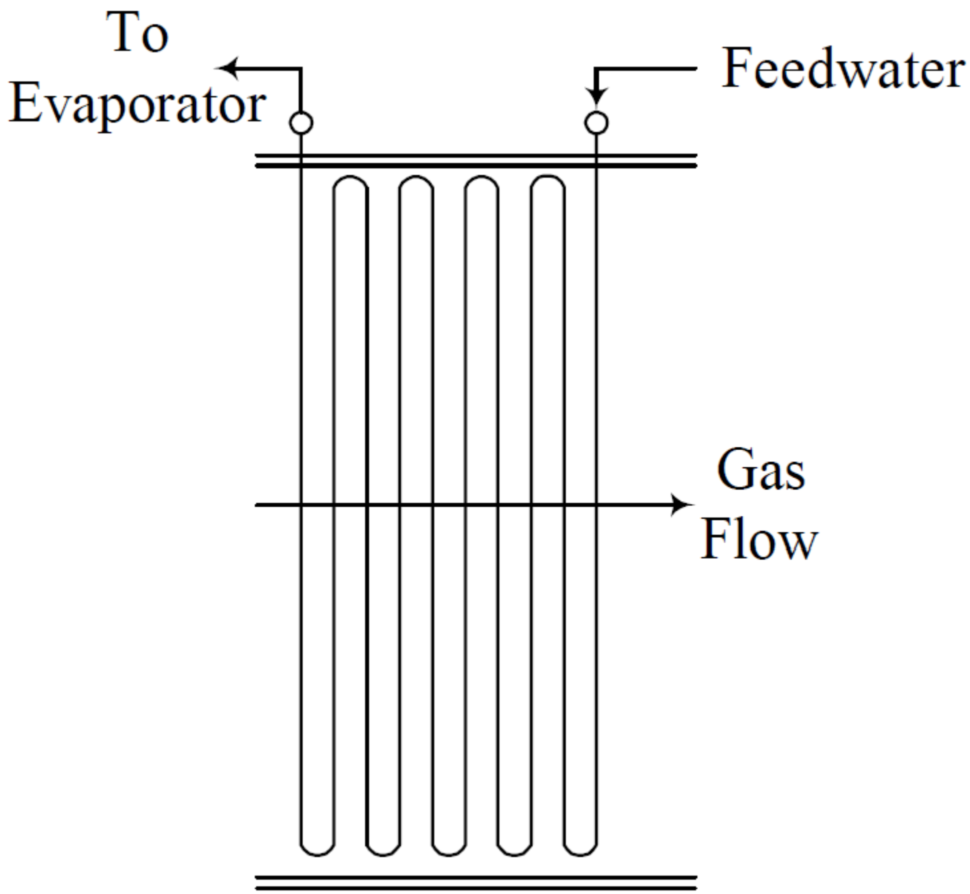
- Vaporize water to produce steam
- Water/steam circulates from lower drum to steam drum
- Steam exits from the steam drum after passing through steam separating equipment
- Water level must be carefully maintained



Economizers

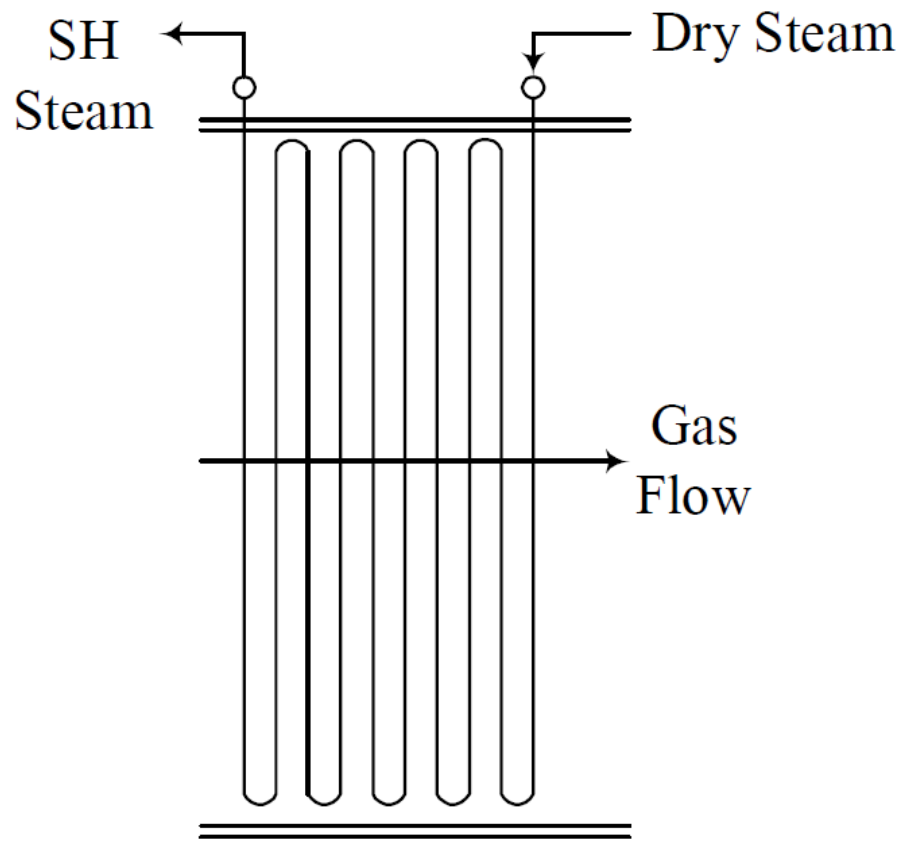
- Preheats water prior to entry into the steam drum

- It is desirable to prevent steam from forming in the economizer



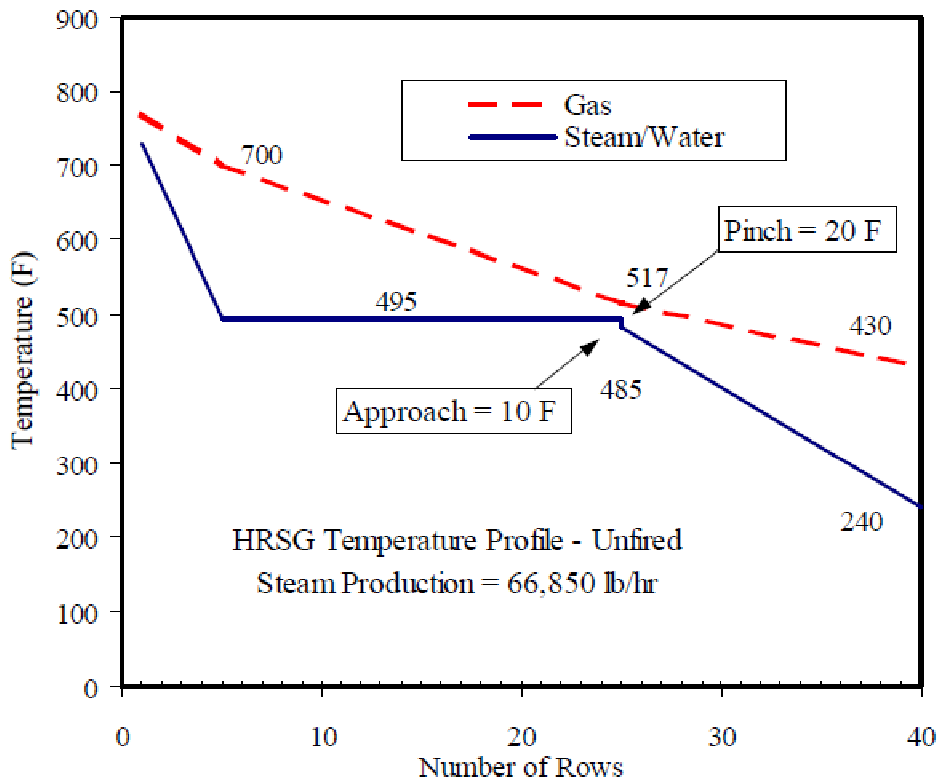
Superheaters / Reheaters

- Saturated steam from evaporator to superheater to produce dry steam
- Dry steam is required for turbines



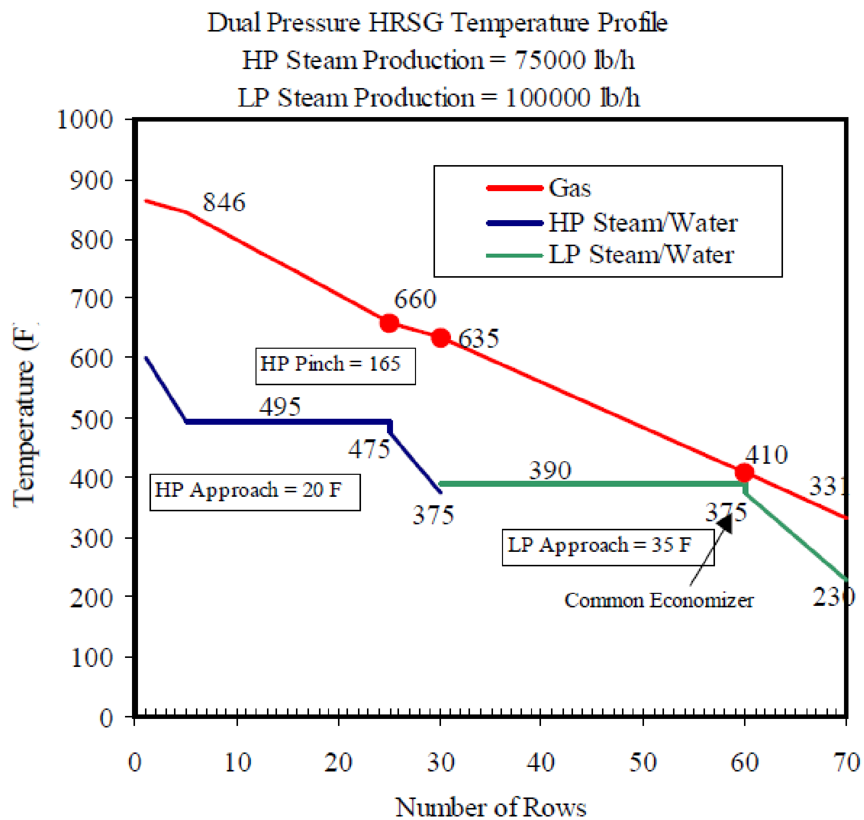
HRSG Design Philosophy

- Exchange heat from the exhaust gas to the fluid at the highest temperature difference available
- Accomplished by making the exhaust gas and the fluid (steam/water) temperature gradients as nearly parallel to each other as possible



Single vs. Multiple Pressure HRSGs

- Adding additional pressure levels in the HRSG can increase the amount of heat that can be recovered from the exhaust gas
- As the saturation temperature are lower at successive pressures, the stack temperature can be lowered.

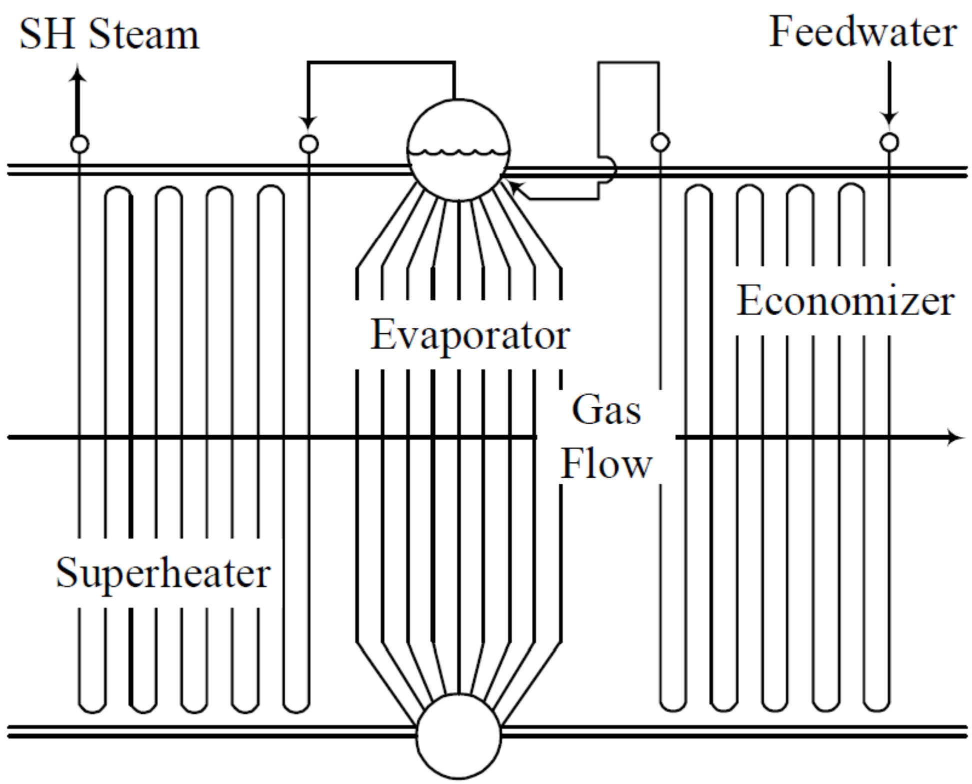


HRSG Types

- There are three (3) main types of HRSG:
  - Natural Circulation HRSGs
  - Forced Circulation HRSGs
  - Once Through HRSGs

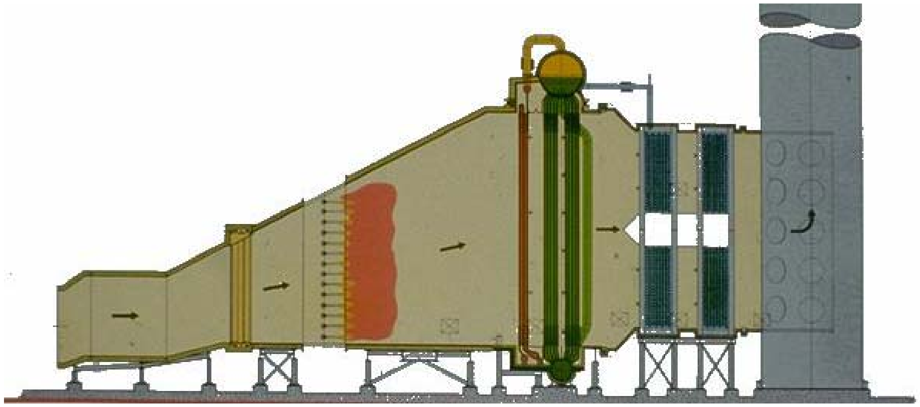
Natural Circulation HRSGs

- Typically horizontal gas flow and vertical tubes
- Tube bundles typically grow thermally down
- For gas turbines less than 50 MW, evaporator is shipped to site in single pieces
- For larger gas turbines the evaporator is shipped in multiple sections

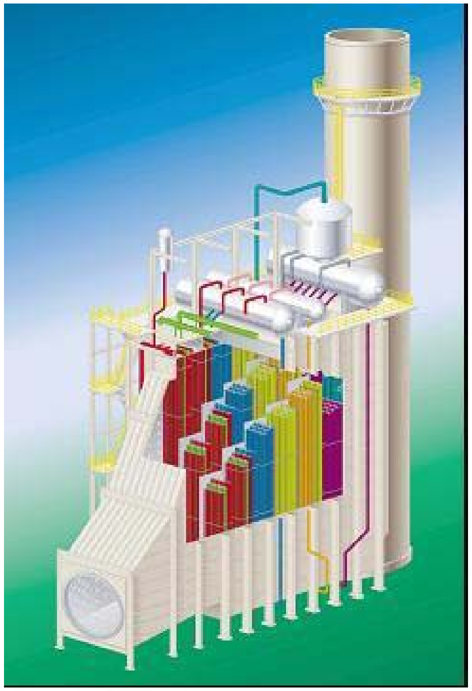


Natural Circulation HRSGs

- Smaller HRSGs can have the evaporator section shop assembled as a single component (up to approx 400,000 lbs).

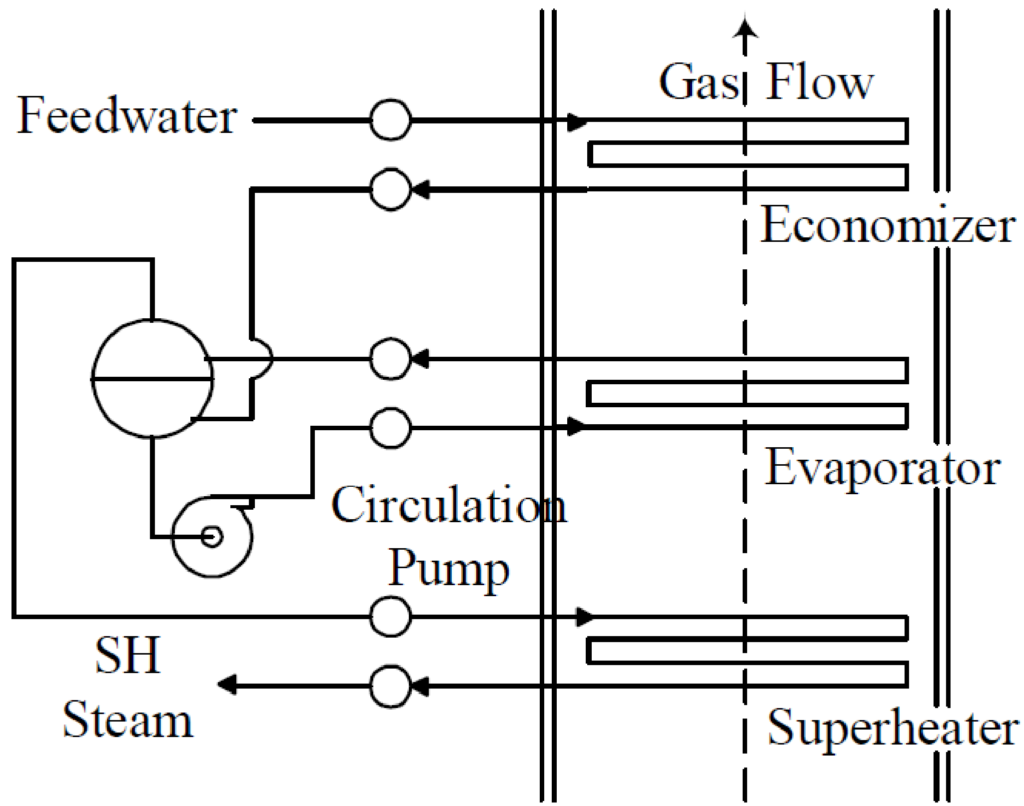


- In larger HRSGs, the evaporator is shipped to site in multiple sections. This incurs larger field erection costs.

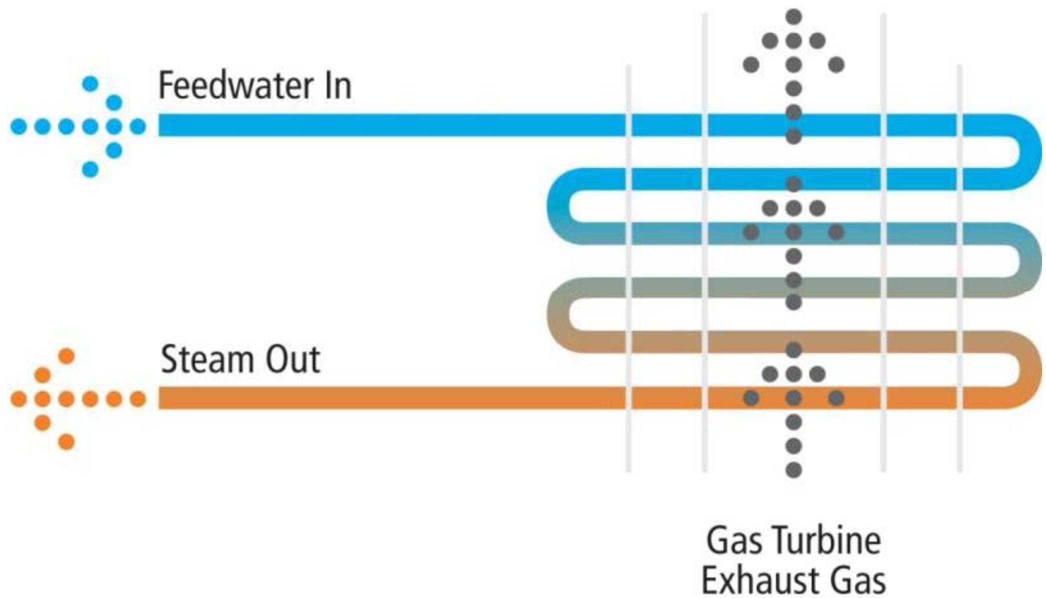


Forced Circulation HRSGs

- Typically vertical gas flow and horizontal tubes
- Steam/water mixture circulation through evaporator tubes and to/from drum with a pump
- Historically common in Europe due to a small footprint



Once Through HRSG

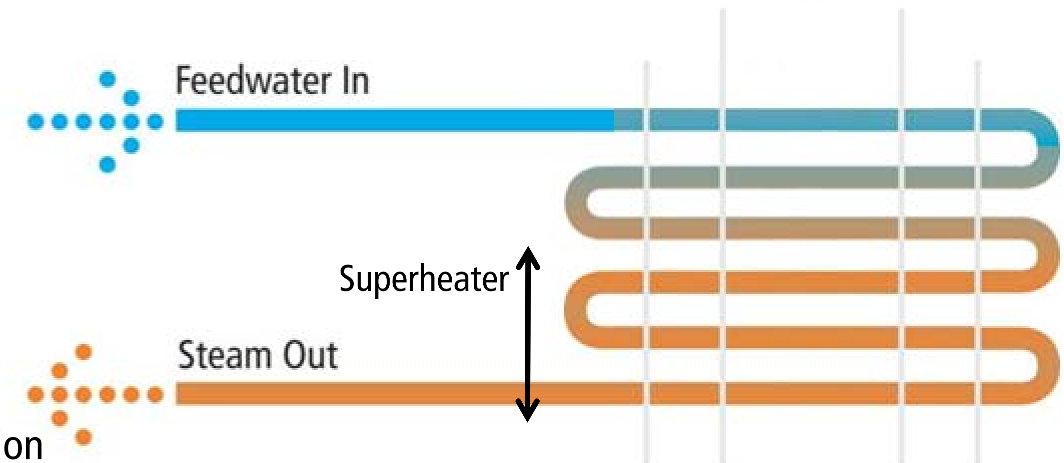


- All tubes thin-walled → low thermal mass → fast cycling
- Compact lightweight pressure bundle
- Once through steam path

Turndown of the OTSG

Normal Operation

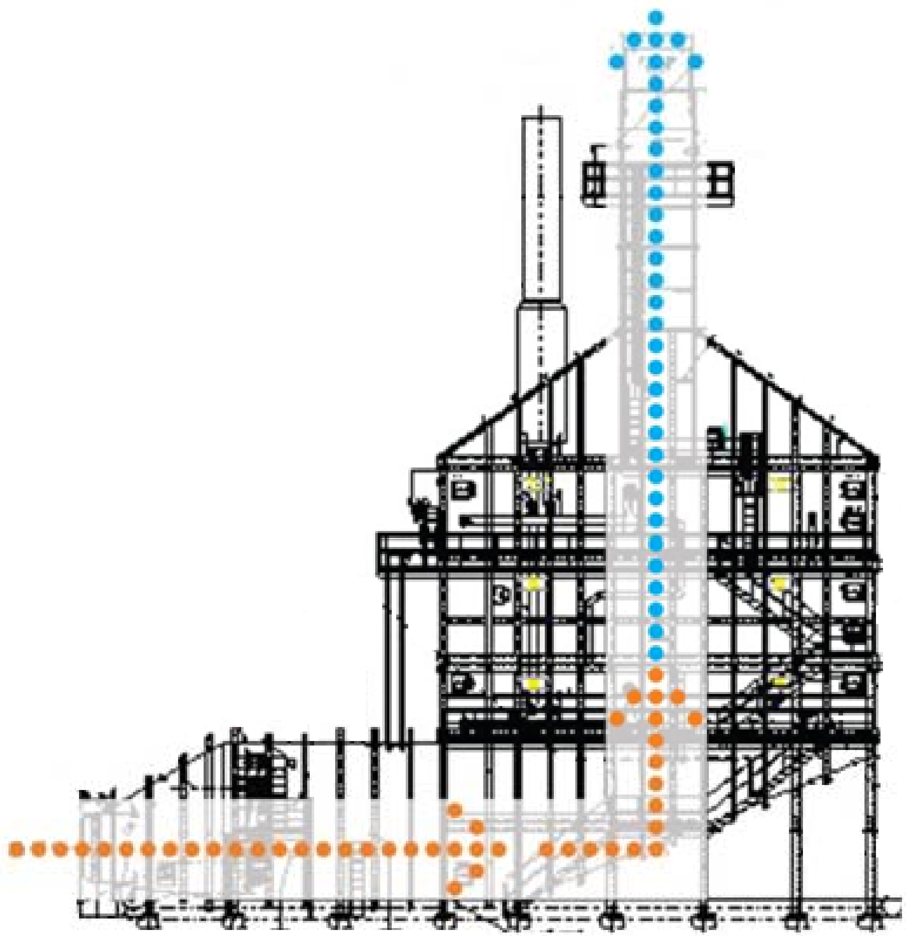
- 2+ rows of economizer section
- 1 row of superheated steam

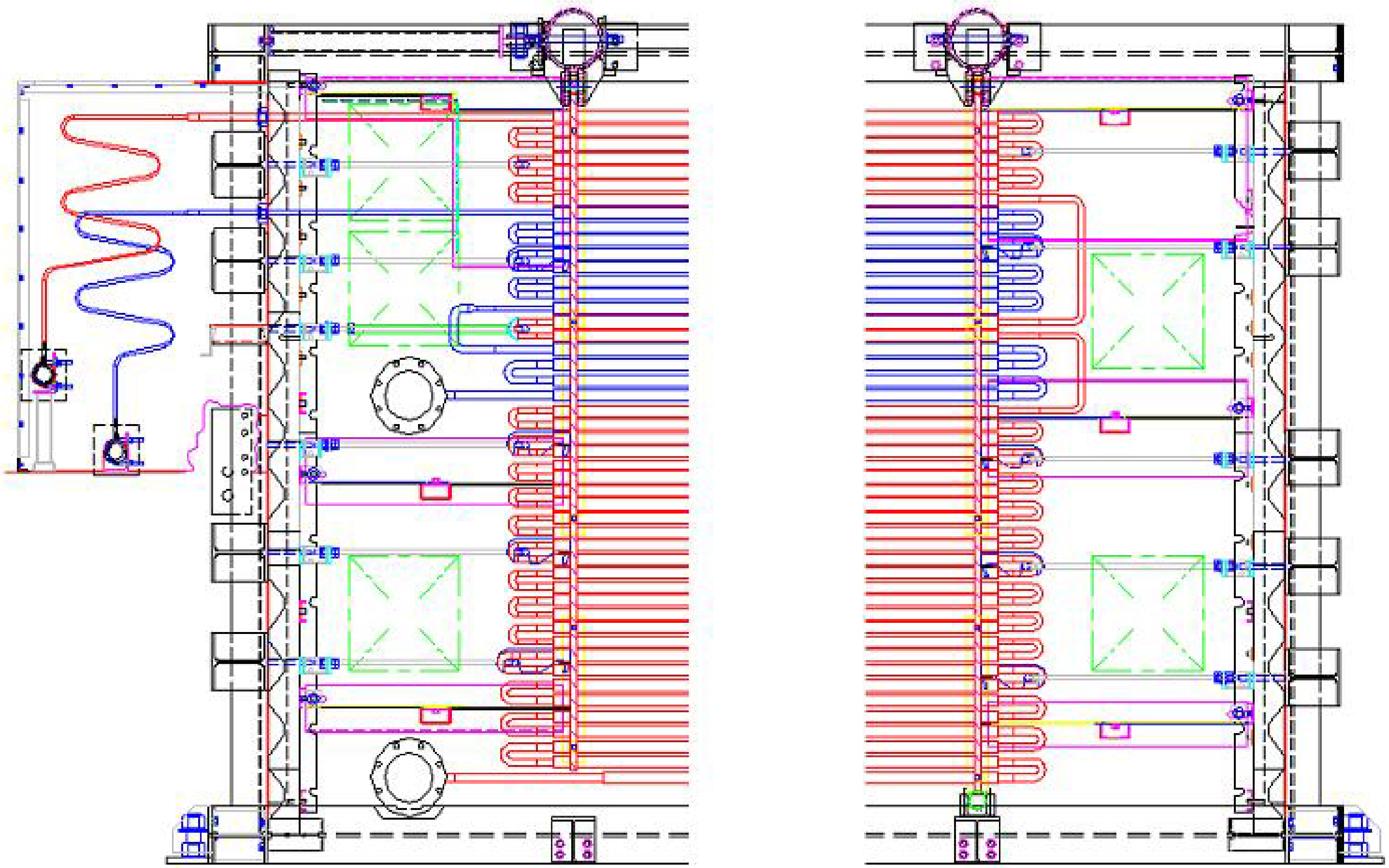


Turndown Operation

- 1-2 rows of economizer section
- 3+ rows of superheated steam

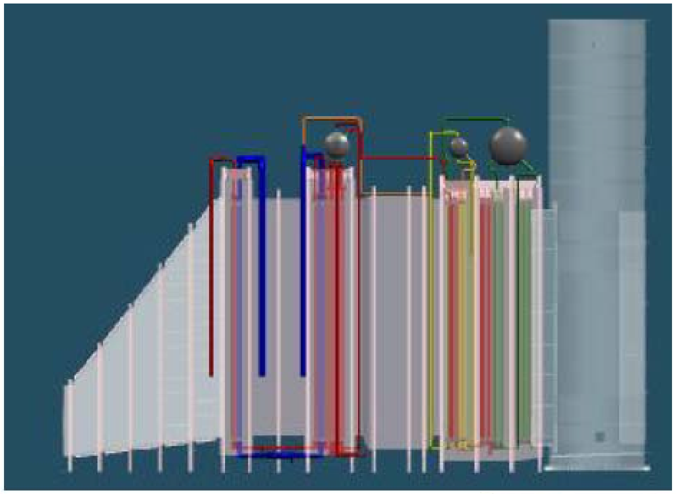
Once Through Vertical Gas Path

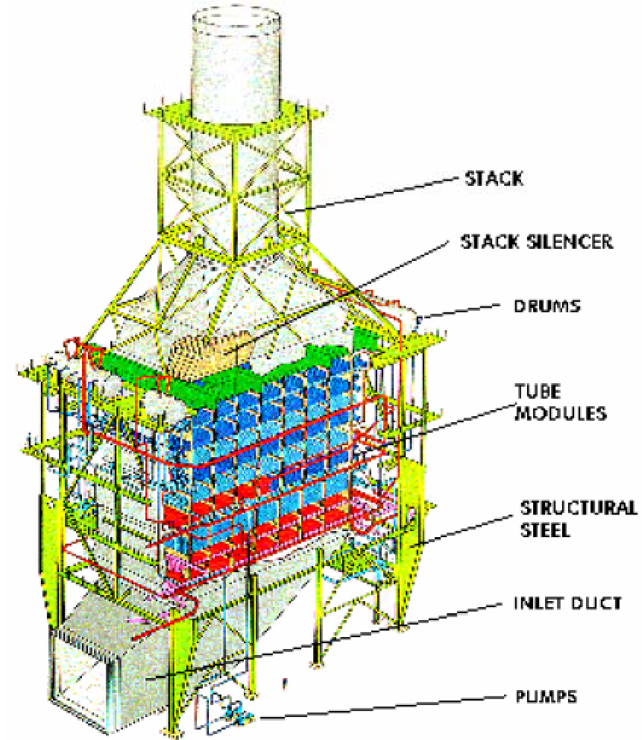




- Typical dual pressure unit
- Note the feedwater flex tube and steam header locations

Summary of HRSG types

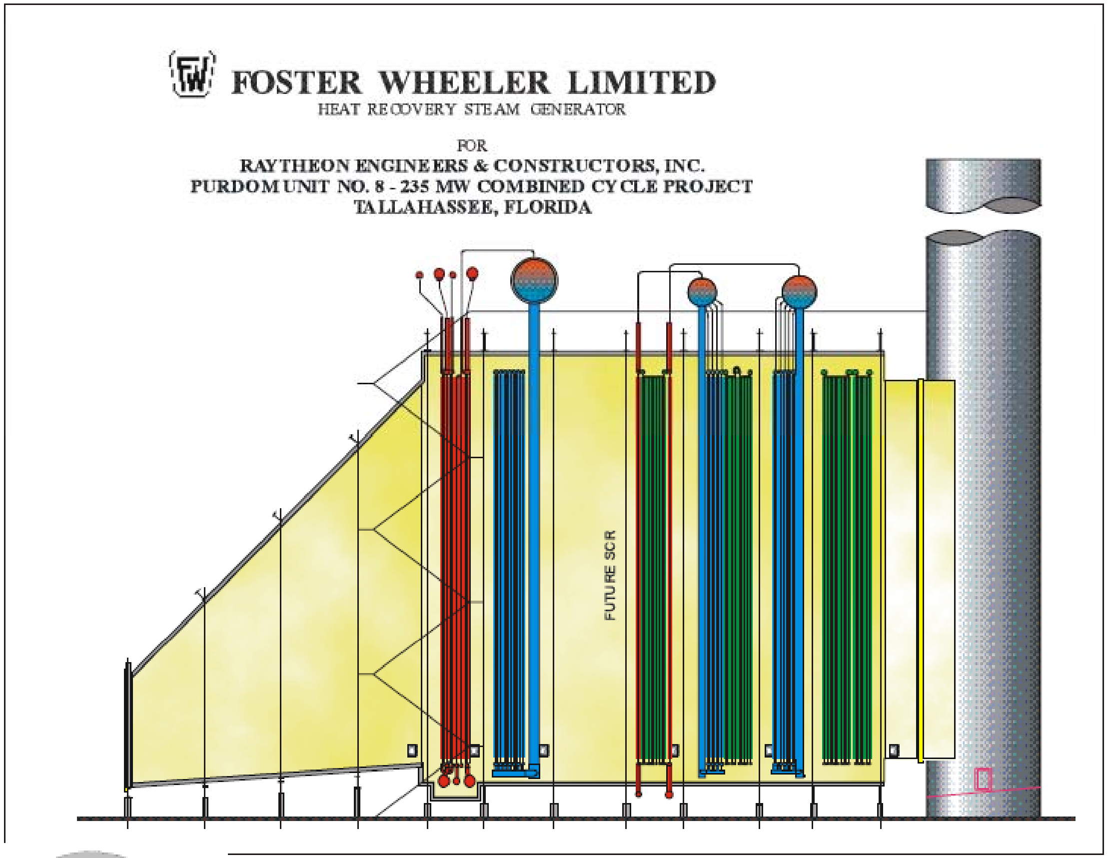


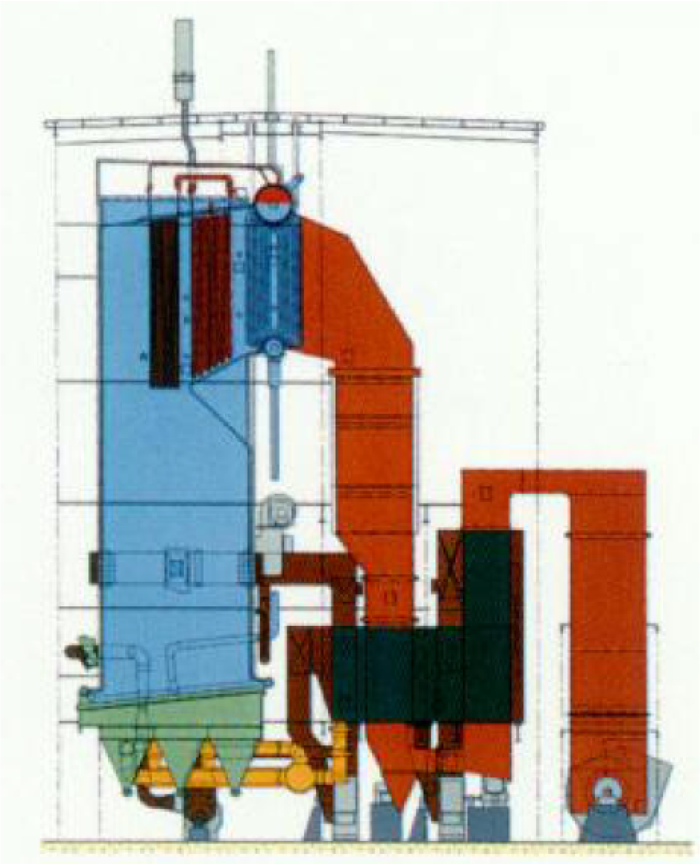


HRSGs vs. Conventional Boilers

- HRSGs use exhaust from a gas turbine as a heat source and do not need a dedicated firing system (burner, fan, motor, etc.)
- HRSGs typically do not use fans (draft is from gas turbine exhaust)
- HRSGs generate steam at multiple pressure levels to improve heat recovery efficiency
- Heat transfer is by convection rather than radiation
- HRSGs do not use membrane water walls
- HRSGs use finned tubes to maximize heat transfer

HRSGs vs. Conventional Boilers





Finned Tubing

- Finned tubing is used to increase heat transfer
- Two types – solid fins and serrated fins
- Heat transfer can be adjusted by changing fin height, fin thickness, fin density and fin materials
- Fins are spiral wound onto tubes using various processes:
  - Brazing
  - Welding

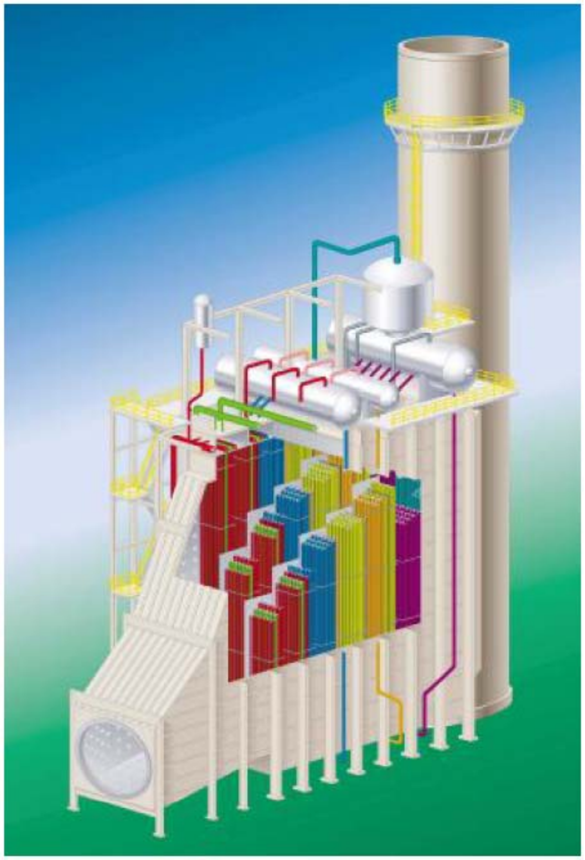
Finned Tubing

Serrated Finned Tube

Solid Finned Tube

Fabrication of HRSGs

- Large HRSGs typically made from pressure part modules referred to as "harps"
- Significant field assembly



Fabrication of HRSGs

- Smaller HRSGs such as the OTSG maximize shop fabrication, minimizing field assembly

Erection of HRSGs

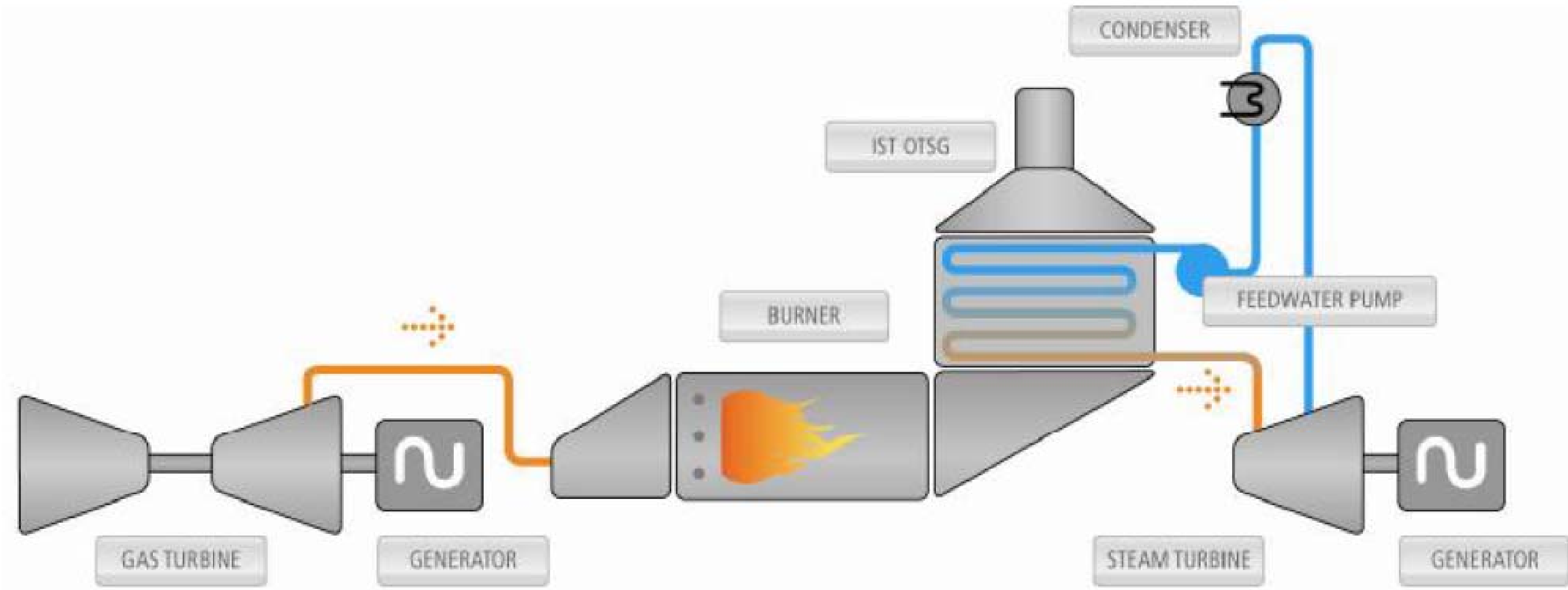
- Shipment of harps, cased or uncased sent to site
- Modules stacked up to three (3) wide

Erection of HRSGs

- Steam drum sent to site separately
- Exhaust stack sent to site in multiple sections

Duct Burners

- Add heat to the gas turbine exhaust stream
- Exhaust gas typically has enough oxygen to sustain stable combustion



Duct Burners

- Steam demand increases without any change in the gas turbine exhaust
- Desired steam flow of final steam temperature cannot be achieved with the available heat from the gas turbine
- Gas turbine is completely down but steam is still needed

Duct Burners

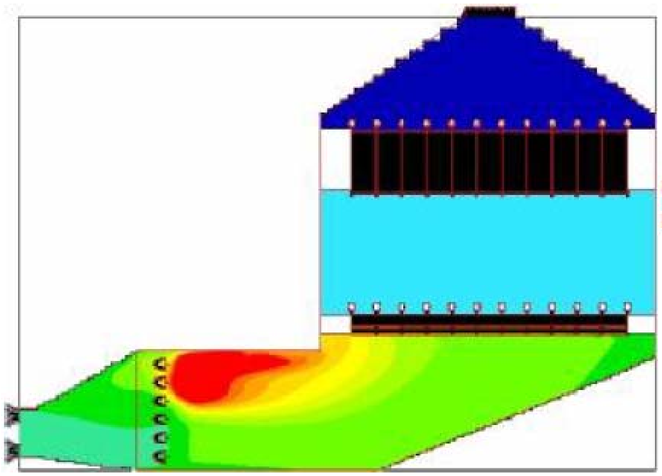
- Burners can be configures to burn a variety of different fuels from natural gas to oil

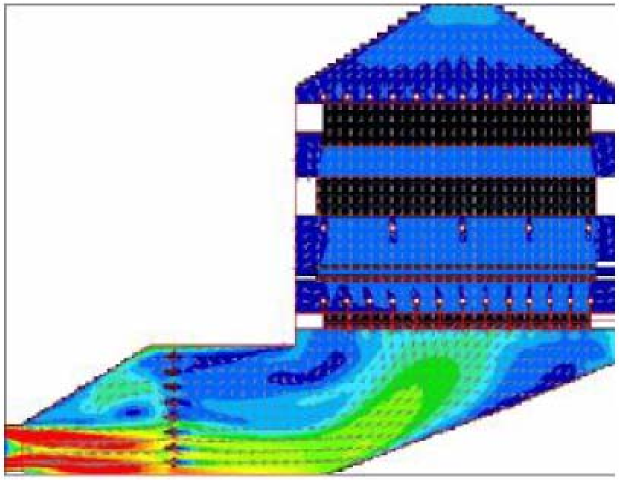
Distribution Grids

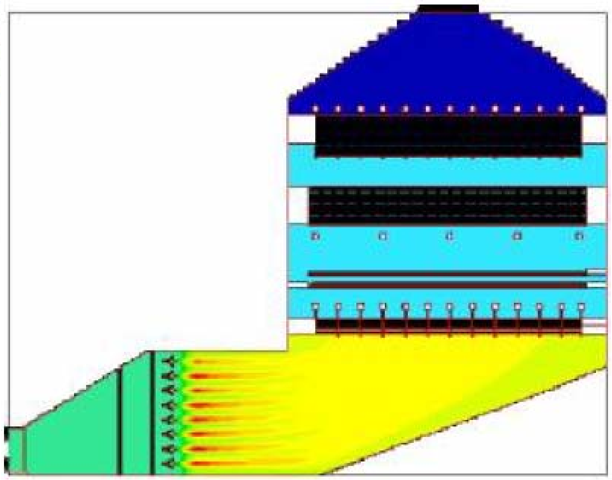
- Used to correct flow maldistribution
- Variable porosity plates and turning vanes are commonly used
- Typical gas side pressure drop for a variable porosity plate ranges from 0.5” H2O to 3 inches H2O

Flow Modeling

- Gas flow distribution leaving the gas turbine is non-uniform
- Proper performance of the HRSG, duct burner and emission equipment requires uniform flow and temperature profile







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SCR/CO Technology

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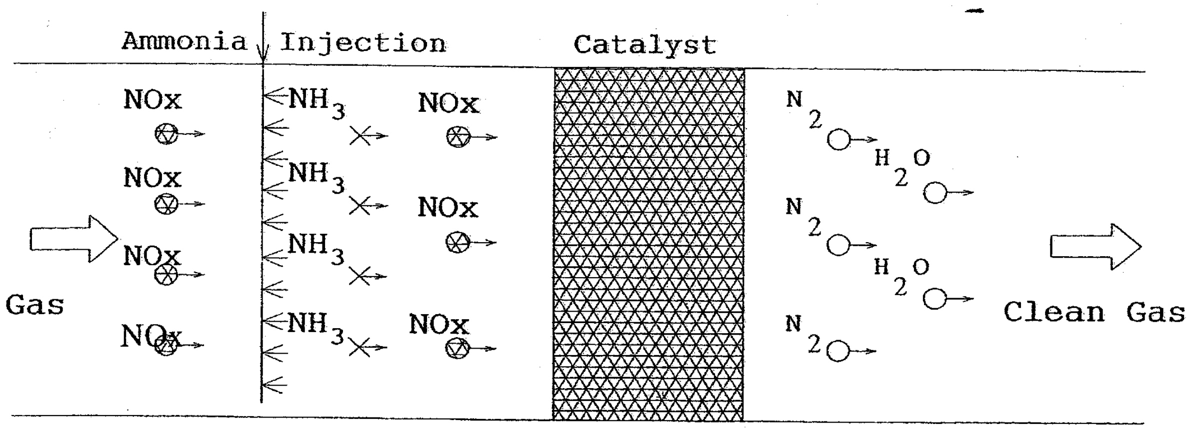
SCR Technology

A process in which ammonia (NH_3) is injected into the gas stream upstream of the SCR catalyst. The gas stream then passes through the catalyst layer decomposing NOx (nitrous oxides, principally NO and NO_2) into N_2 and H_2O.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

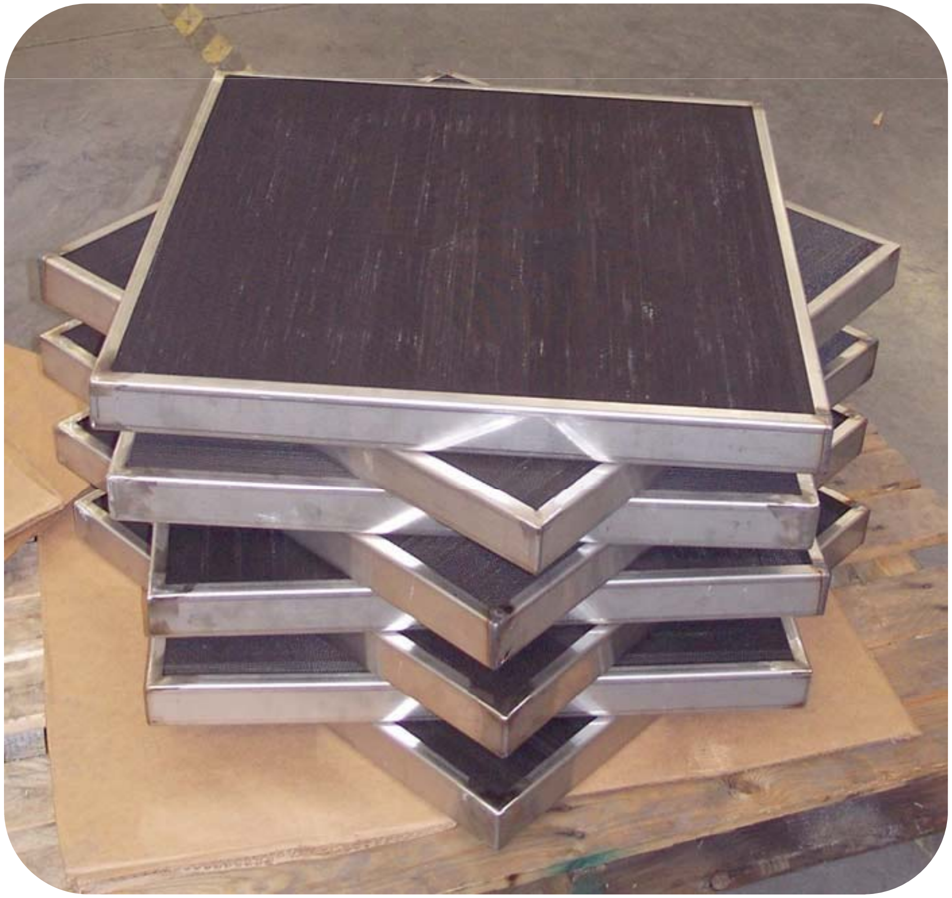
$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$$



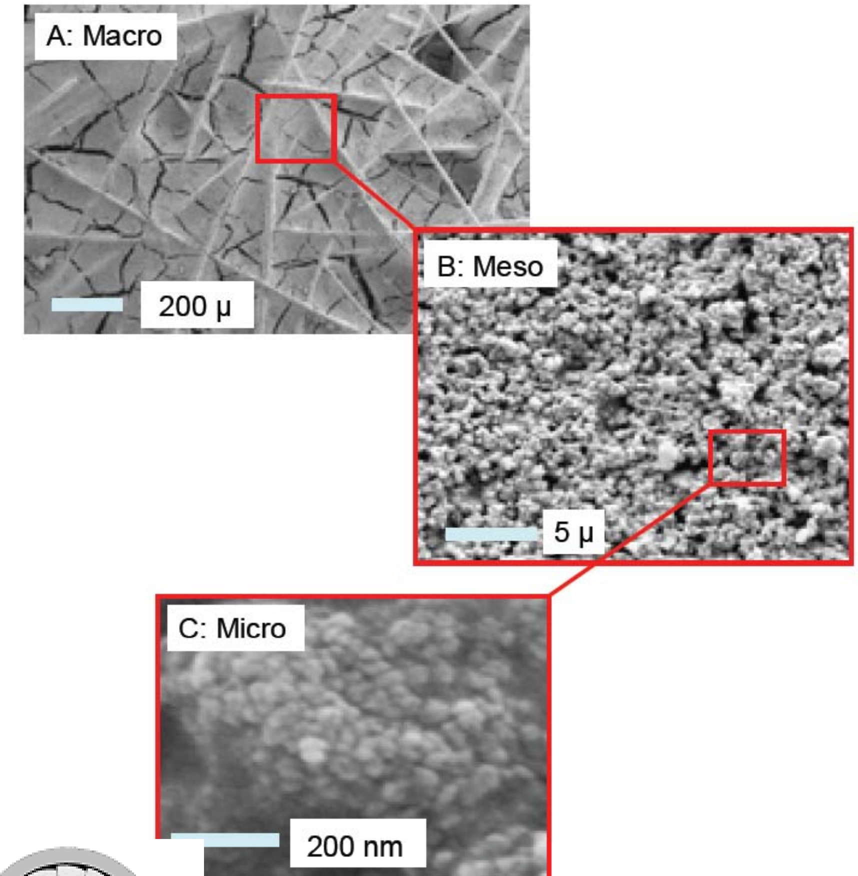
CO Catalyst Systems

- Converts CO and VOC emissions
- Effective at medium and high temperatures
- Located upstream of SCR catalyst
- Catalyst blocks are hand-loaded into a pre-installed frame in the OTSG



Performance of Catalysts

- What happens to catalysts that overheat?
  - The catalyst depends on its surface area in order to maintain a certain level of reactivity



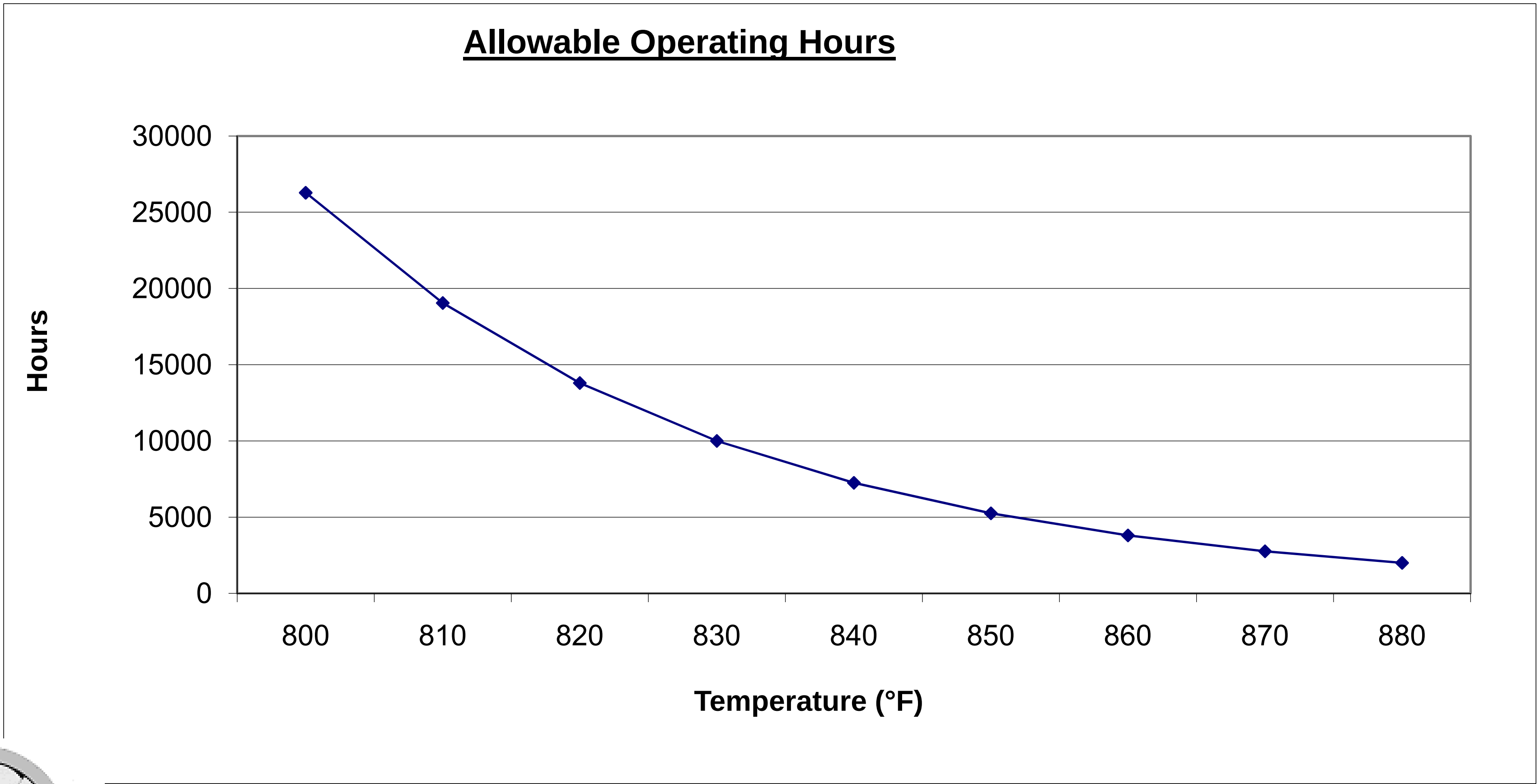
http://www.topsoe.com

The catalyst is manufactured in such a way that the surface area is maximized.

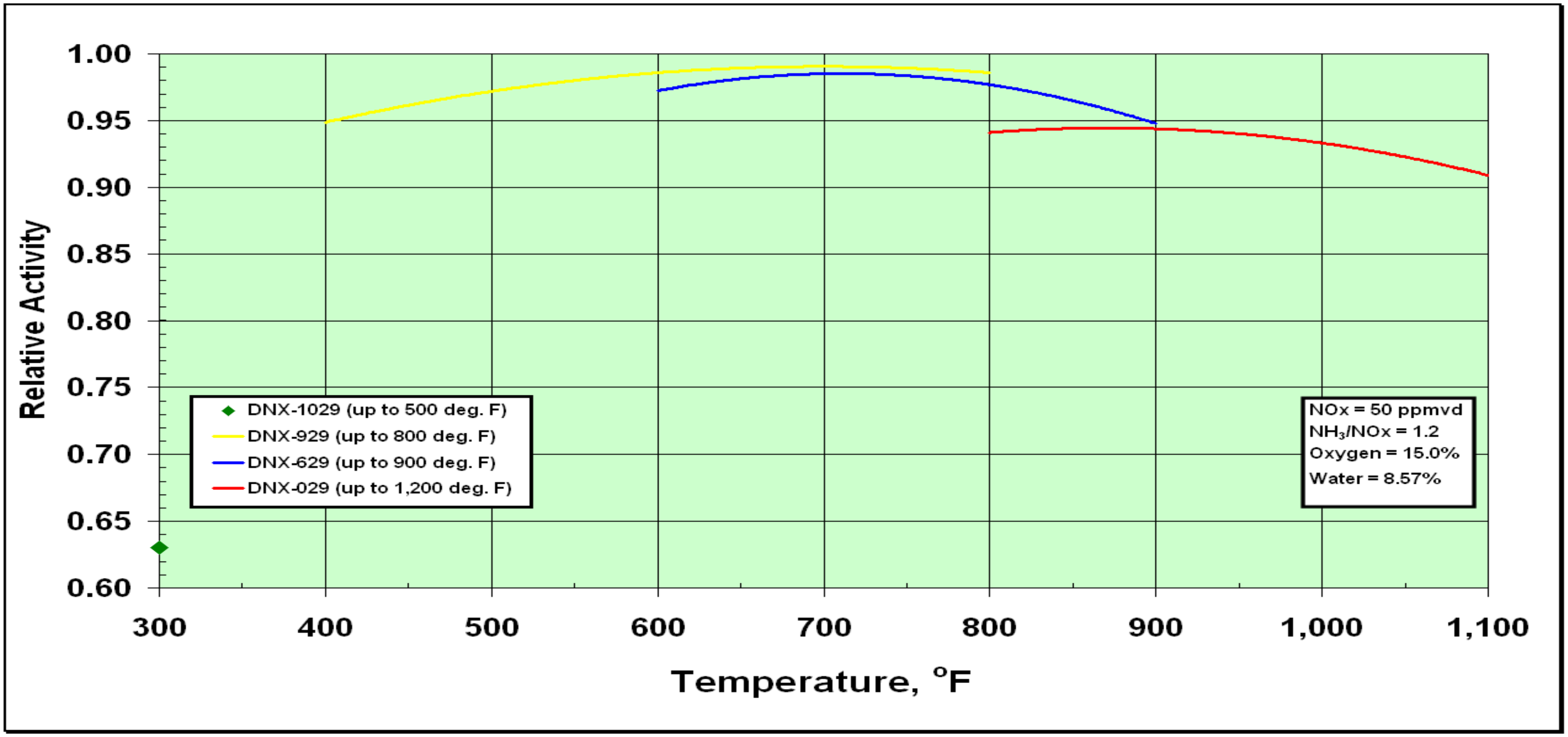
Beyond a certain temperature, these pores begin to sinter together, decreasing reactivity.

Performance of Catalysts

- What happens to catalysts that overheat?
  - Manufacturers will limit the duration of temperature excursions that can occur without voiding the guarantee



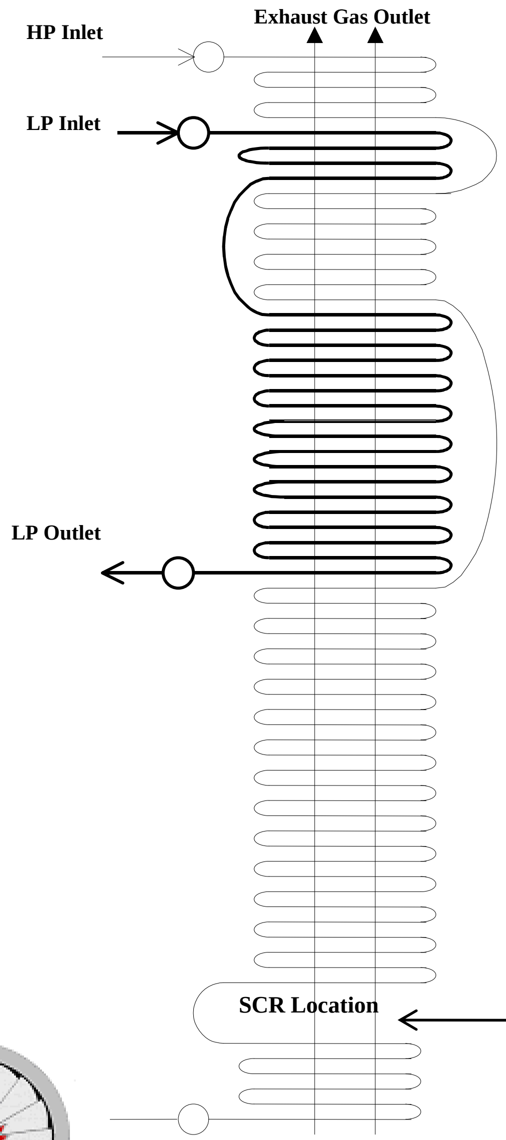
SCR Catalyst Offerings



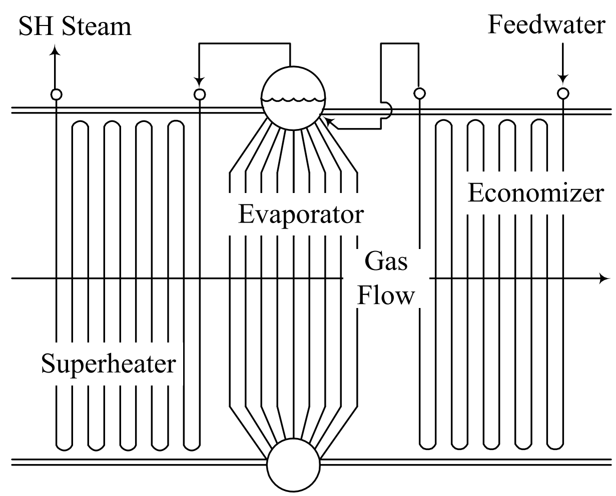
Location of SCR Catalyst

- SCR catalyst is located in the appropriate gas temperature zone for maximum efficiency
- Dual range catalysts have peak efficiency at ~750 to 775F. Maximum continuous temperature is 950F (with reduced efficiency)
- OTSG bundle is designed to balance temperature exposure of catalyst in all operating scenarios (ie. unfired, fired, turndown, etc.)

Installed Configuration



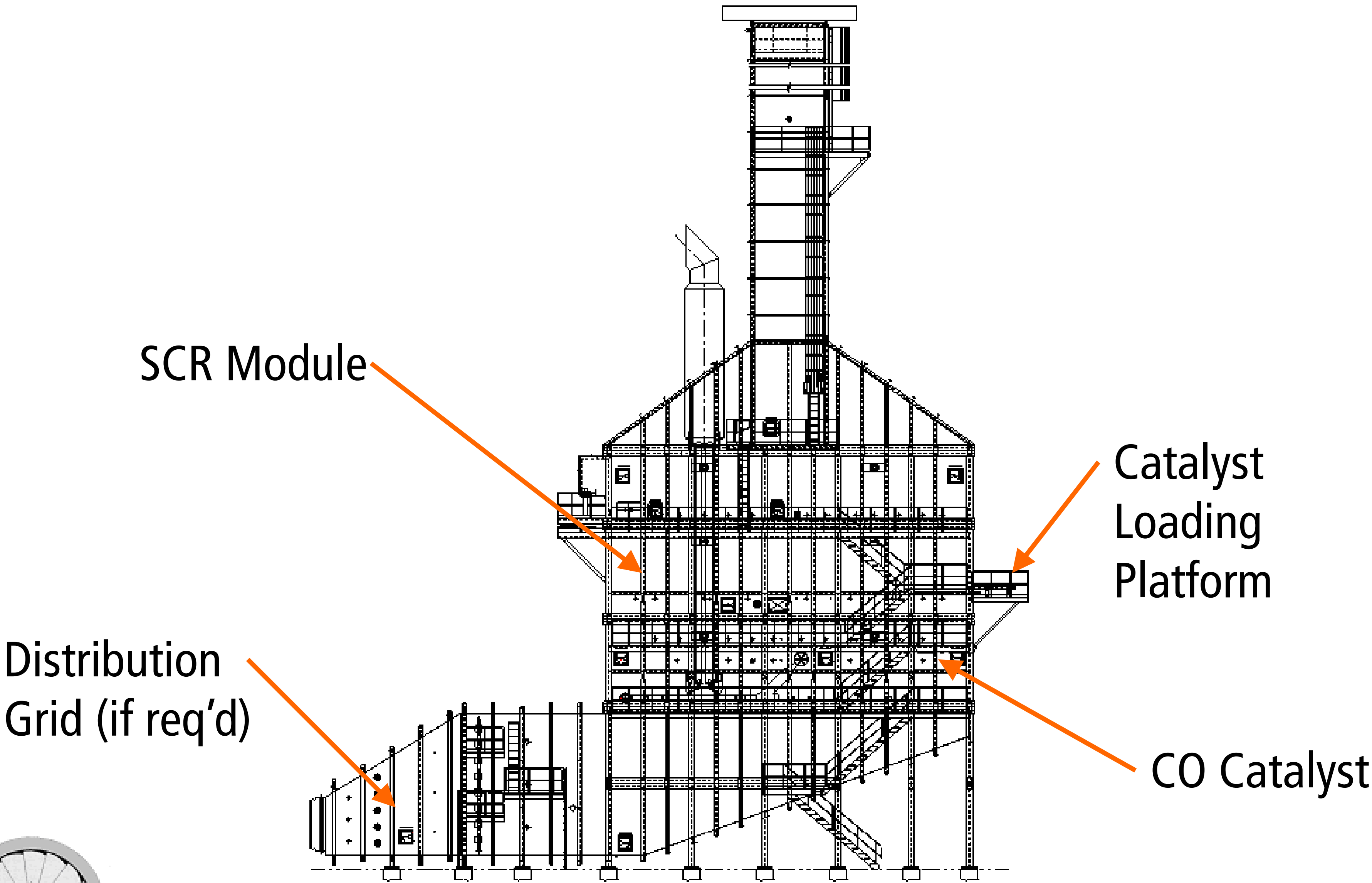
Flexibility of the OTSG allows for optimum placement of the SCR in either the evaporator or superheater section



The drum connections limit the sites for where an SCR can be located within a drum type HRSG

Tubes are "jumpered" around the SCR surface

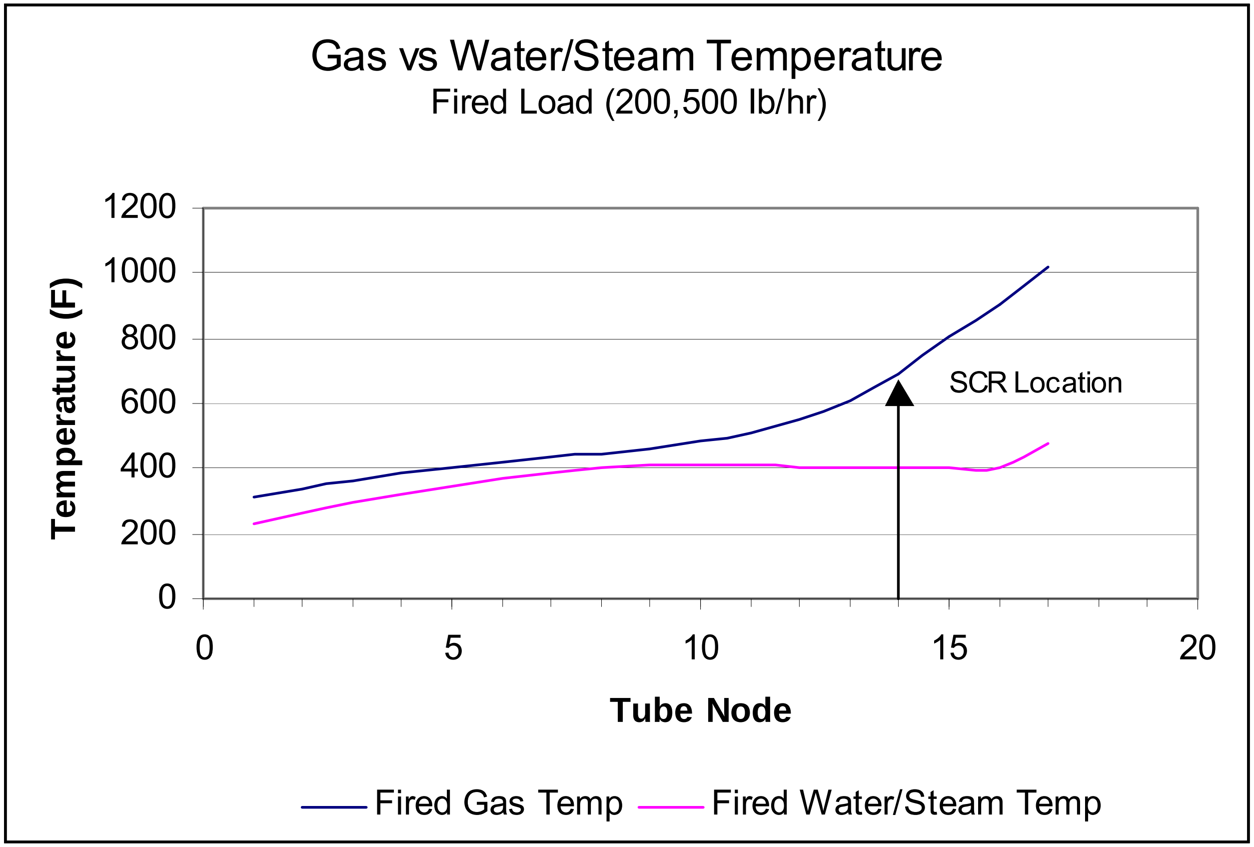
Typical Layout of OTSG w/ SCR & CO Catalysts



OTSG System Start-Up (With SCR)

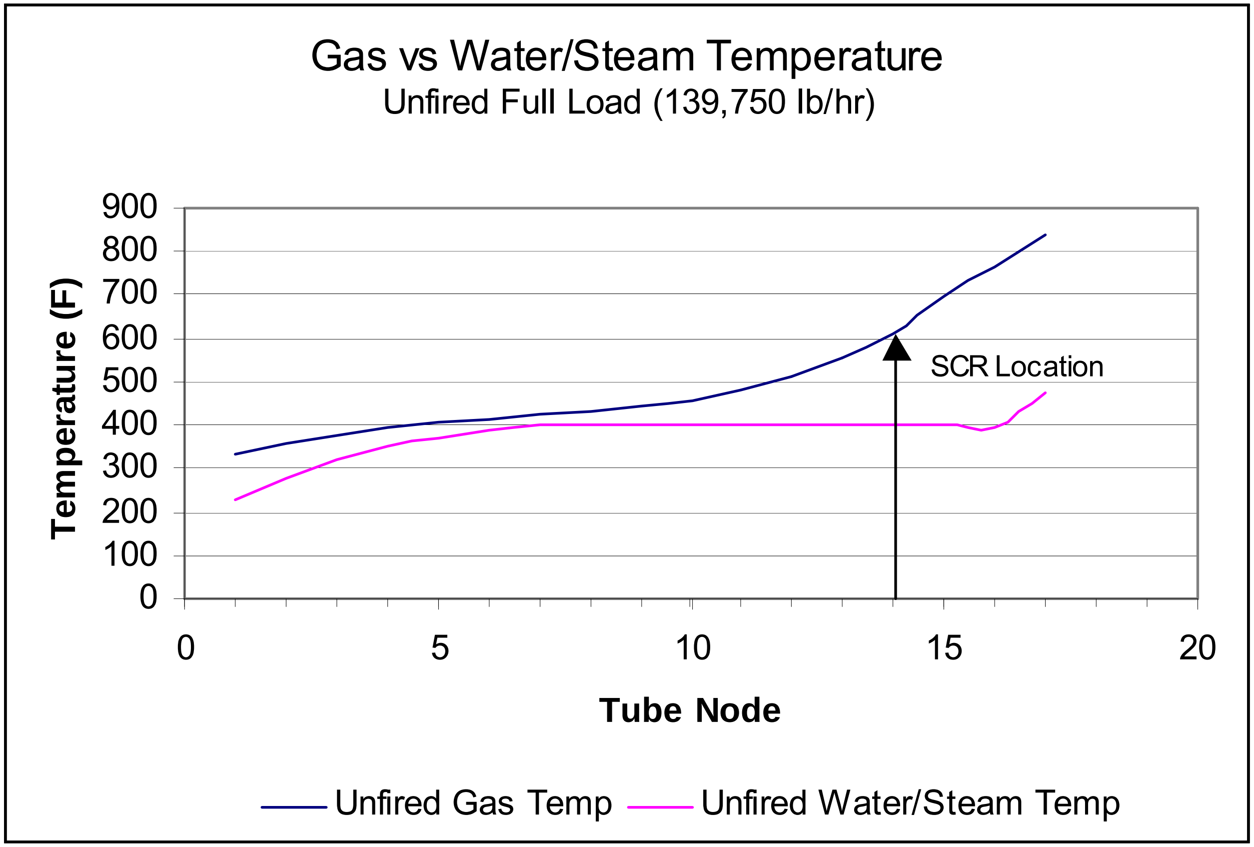
- Gas turbine is started
- When catalyst reaches minimum temperature NH_3 is injected to gas path (500°F). Emissions control is achieved in approximately 8 minutes.
- With dual range catalyst system, GT is allowed to run to full load independently
- OTSG is started by allowing feed water into the unit. No cool down required.

SCR Operation



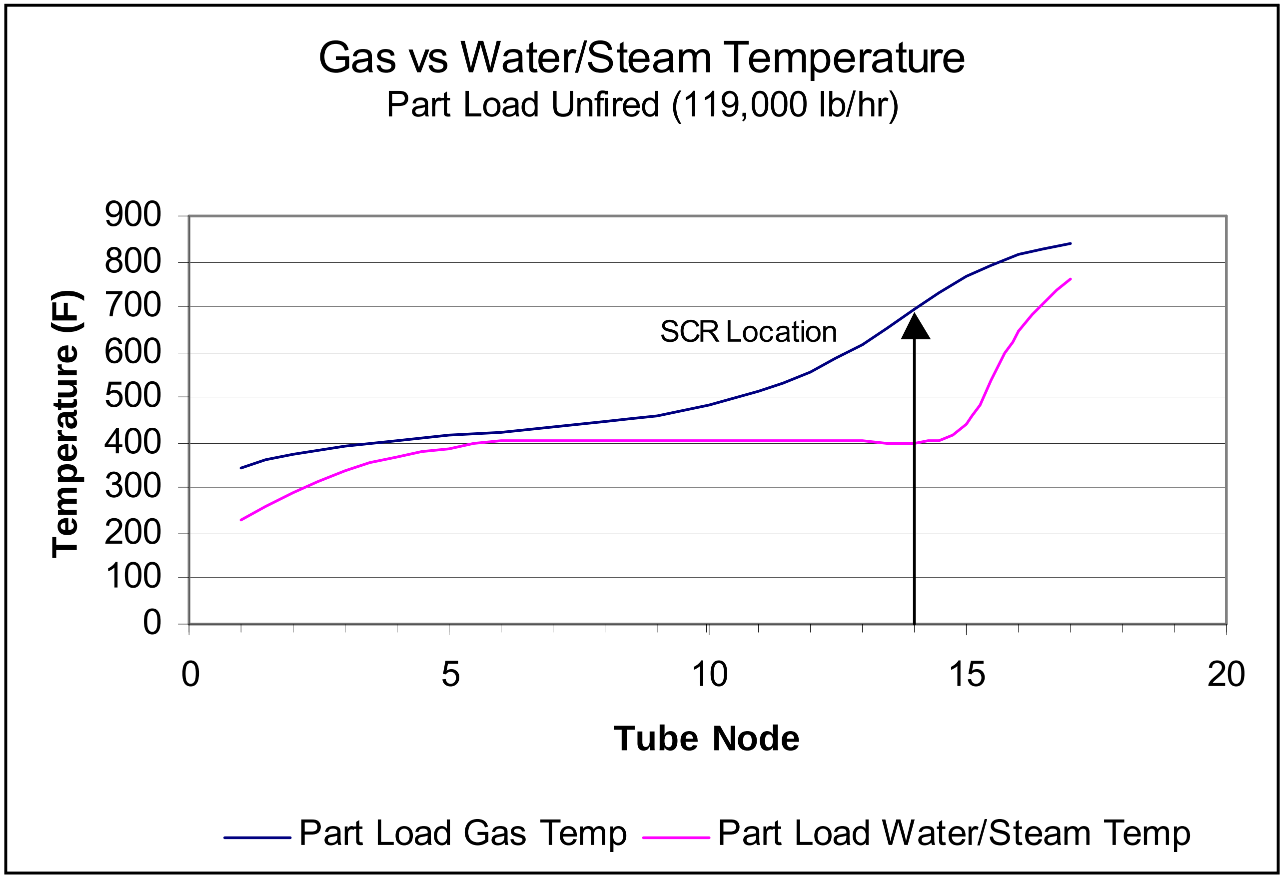
- Design point for SCR location
- Gas temp at SCR catalyst is 690 Degrees F
- SCR operating at maximum efficiency

SCR Operation



- At full unfired load, the temperature entering the SCR is 613 Degrees C
- Not at maximum efficiency of SCR operation
- Can reduce water from to the OTSG to control the gas temperature upstream of the SCR

SCR Operation



- Reducing the water flow to the OTSG changes the gas temperature upstream of the SCR catalyst to 694 Degrees F
- SCR now operating at maximum efficiency

Ammonia Slip

- The distribution of turbine exhaust will not be uniform or constant at the SCR surface for all turbine/burner conditions
- Some tuning can be done to match turbine exhaust mass flow to corresponding ammonia mass flow
  - Part load / off design conditions may have the greatest efficiency at another tuning point
- When ammonia does not react within the catalyst and continues to follow the exhaust path, this is known as ammonia slip

Corrosion/Fouling

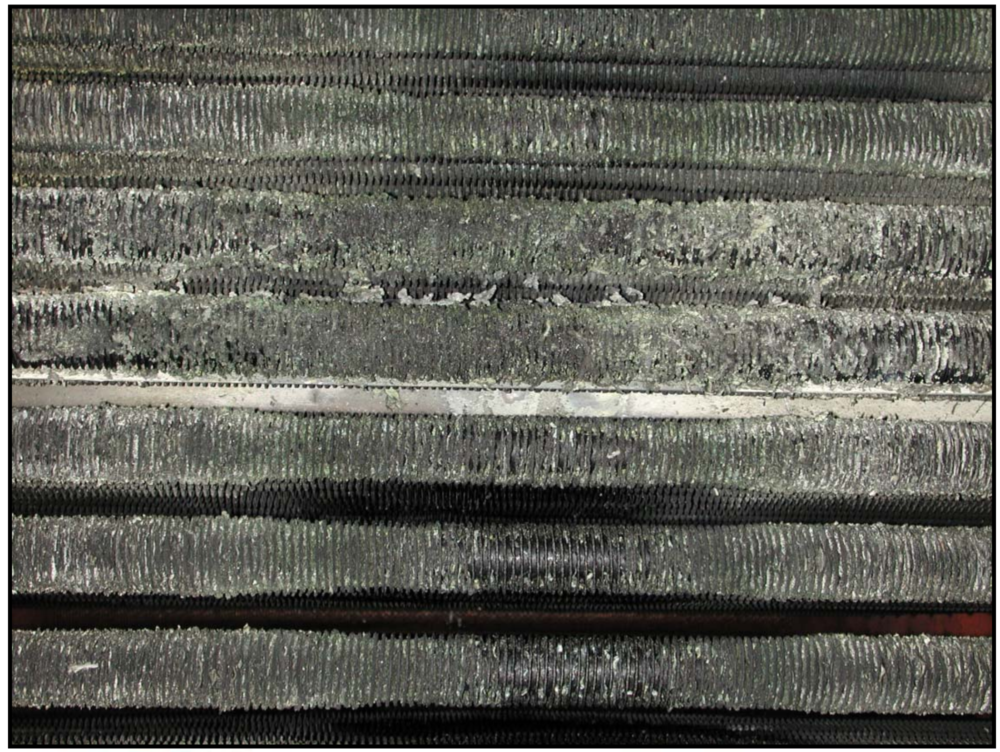
- Ammonia slip is detrimental for the following reasons:
  - The release of ammonia into the atmosphere
  - Formation of ammonium sulphate and/or ammonium bisulphate
    - The type of contaminant depends on ammonia/sulphur levels and gas temperatures
- In natural gas fired applications with low slip, ammonium sulphate formation is the most common
- Operation of pressure parts below the water dew point can lead to formation of sulphuric acid and hydrochloric acid
- Selection of pressure part material is critical

Corrosion/Fouling

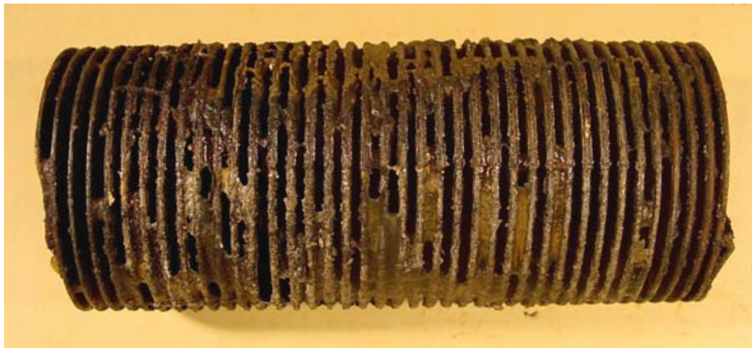
Corrosion/Fouling

View during start up.
Ammonium deposits are returning to the flue gas and resulting in an opacity event

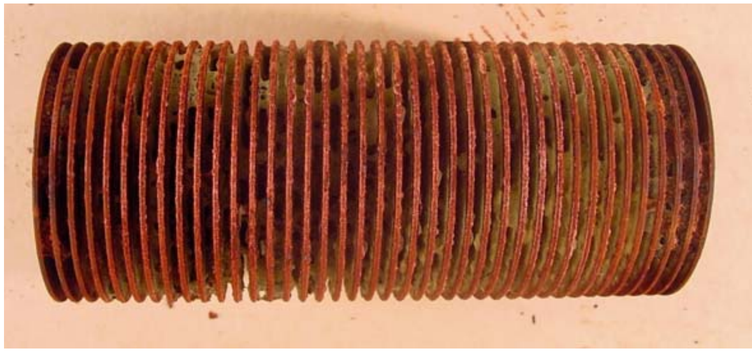
Soot deposits on inlet tubing of liquid fired LM2500 with SCR



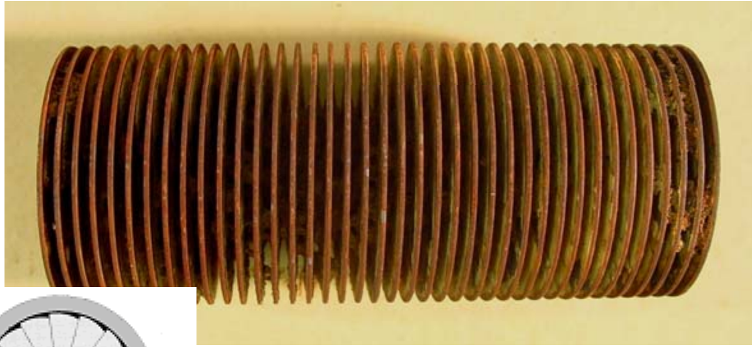
Corrosion/Fouling



Tube coated with ammonium sulphate

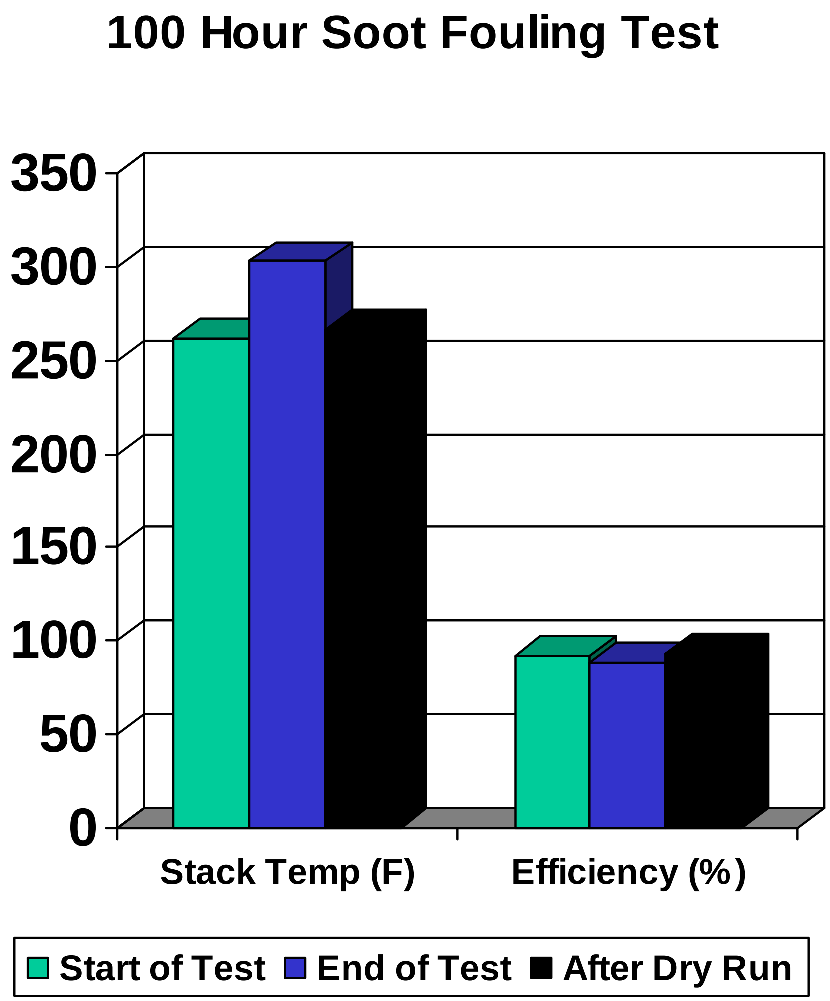


After heating at 900 F for four hours



After blowing with compressed air

Corrosion/Fouling



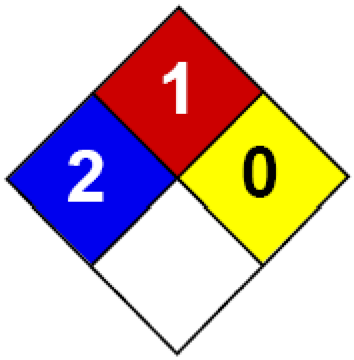
- Dry running can restore thermal performance on oil fired units
- Test completed by IST on diesel fired OTSG
- Heat transfer performance diminished by 5% in 100 hours of operation
- Recovery by performing a dry run at 900 F for 100 minutes
- However, don't overheat the catalyst!

Chemical Storage/Handling

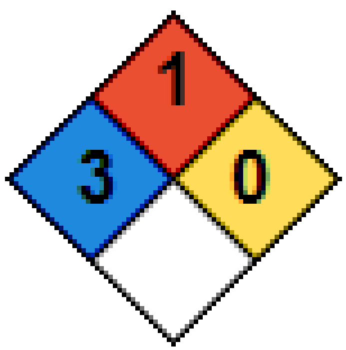
- Anhydrous ammonia is the easiest to use with an SCR
  - SCR manufacturers typically recommend reagent grade ammonia.
  - A technical grade of ammonia can be used if within the SCR manufacturers spec
  - Do NOT use agricultural grade ammonia
    - This contains Na, K, Ca, Mg impurities which can poison a catalyst

Chemical Storage/Handling

- Anhydrous ammonia is the easiest to use with an SCR, but on site urea to ammonia systems are available



- Urea
- Dry Powder
- Can be stored in waterproof sacks
- Shipping is easy



- Anhydrous Ammonia
- Special shipping requirements
- Requires storage facilities – high pressure, low temperature

Chemical Storage/Handling

- Urea to ammonia systems are advantageous in terms of receiving, handling and storing urea vs. ammonia, but suffer from several drawbacks:
  - Corrosion of the reaction vessel and instrumentation
  - Heavy liquid accumulation
    - Partial urea decomposition products can make heavy compounds
  - Deposits in down stream piping
    - The compounds described above can be entrained in the gas phase to downstream piping, AIG and catalyst

Organic Rankine Cycle

- Introduction
- Project Participants
- Plant Description
- Plant Construction
- Opportunities Beyond the Case Study
- Conclusions

Introduction

- Many small gas turbines are run simple cycle
  - An opportunity for improved system efficiency
  - However, at existing sites there is rarely a local use for the heat
- Until recently, the emphasis has been on recovering heat from large gas turbines
  - Waste heat to power plants have been developed at natural gas compressor stations using the heat from gas turbines with a capacity ≥ 11 MW (15,000 HP)

TransGas Rosetown Project

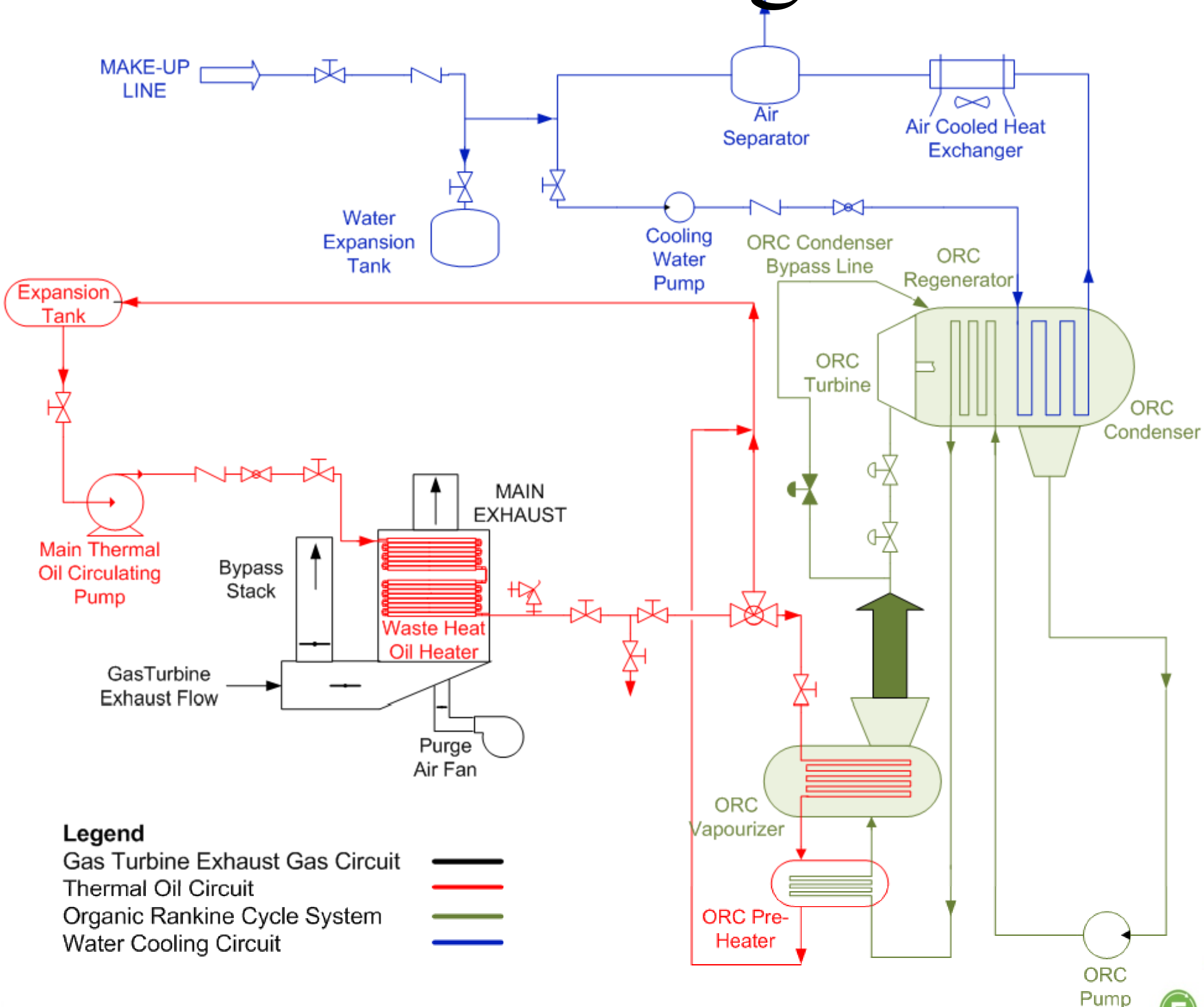
- Natural gas compressor station in southwestern Saskatchewan
- Compressor driven by Solar Centaur Gas Turbine (4500 HP)

- Found Energy supplying an EPC turnkey 1MW power plant utilizing waste heat from the Solar Centaur GT

Plant Systems

- The waste heat to power plant is composed of the following four systems:
  1. The gas turbine exhaust system
  2. The thermal oil circuit
  3. The Organic Rankine Cycle (ORC)
  4. The water cooling circuit

Process Flow Diagram



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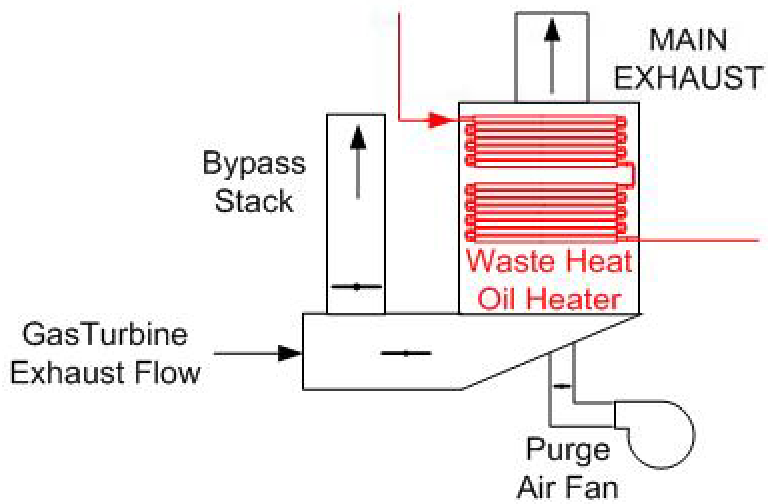
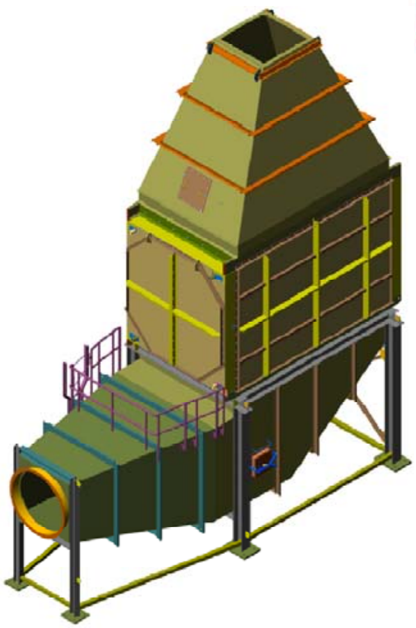
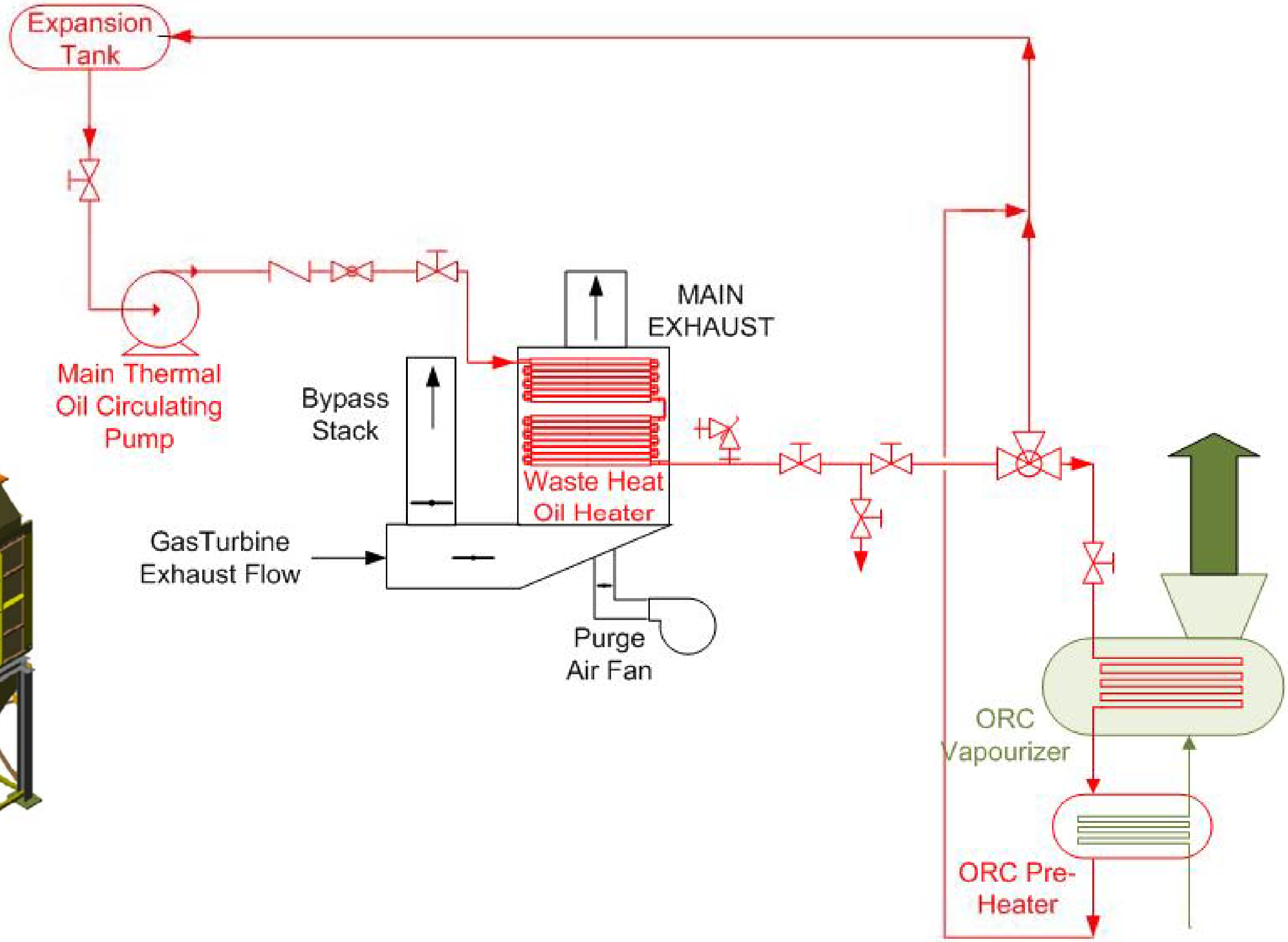
Turbine Exhaust



Thermal Oil System





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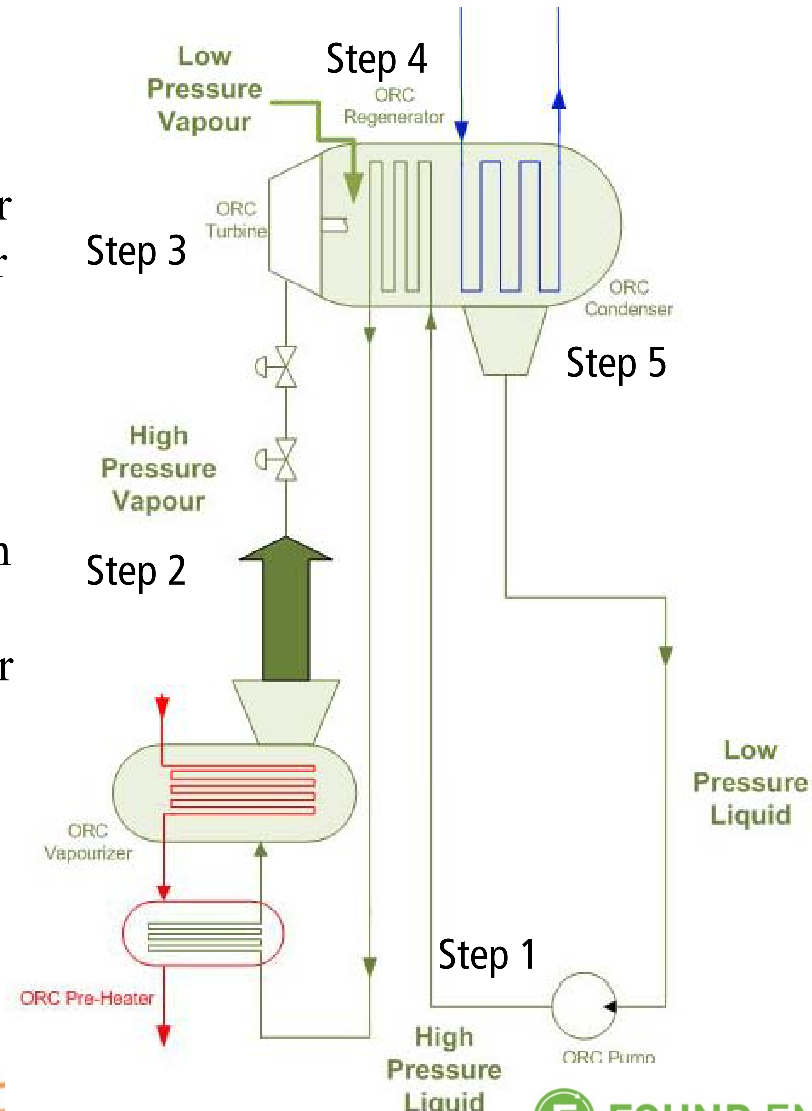
Organic Rankine Cycle

Process Description:

1. Liquid working fluid is pumped to higher pressure and sent through the regenerator to the evaporator
2. Hot thermal oil preheats and evaporates the pressurized working fluid
3. High-temperature, higher-pressure vapor expands through a turbine which spins an electrical generator
4. Lower-temperature, lower-pressure vapor exiting the turbine preheats the liquid working fluid in a regenerator
5. Vapor is condensed to a low-pressure liquid by transferring heat to the water cooling loop



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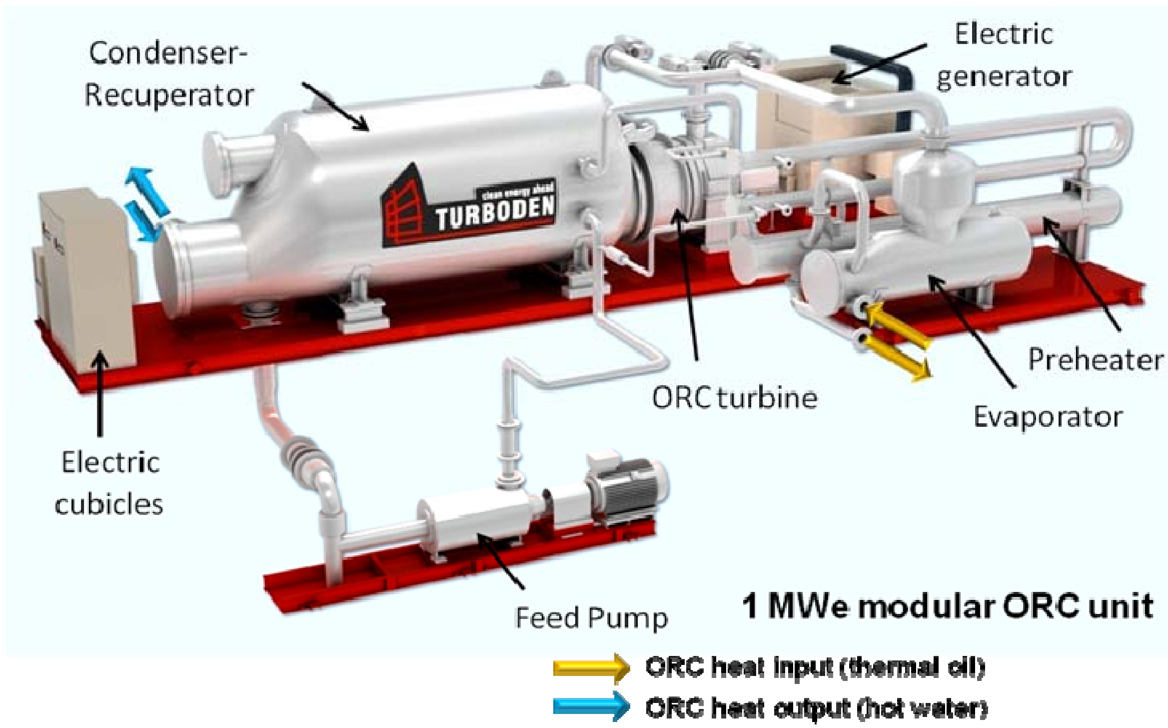
Advantages of ORC

- Lower boiling point
- Fully automated plants
- Operate at lower system pressures than comparable steam systems.
- Higher molecular weights.
  - Low speed turbines that increase the system reliability and efficiency.
- 'Dry fluids': Vapour always leaves the turbine in a supersaturated condition.
  - Recover heat from vapour exiting turbine
  - No risk of damaging turbine with liquid.

ORC Plant Layout



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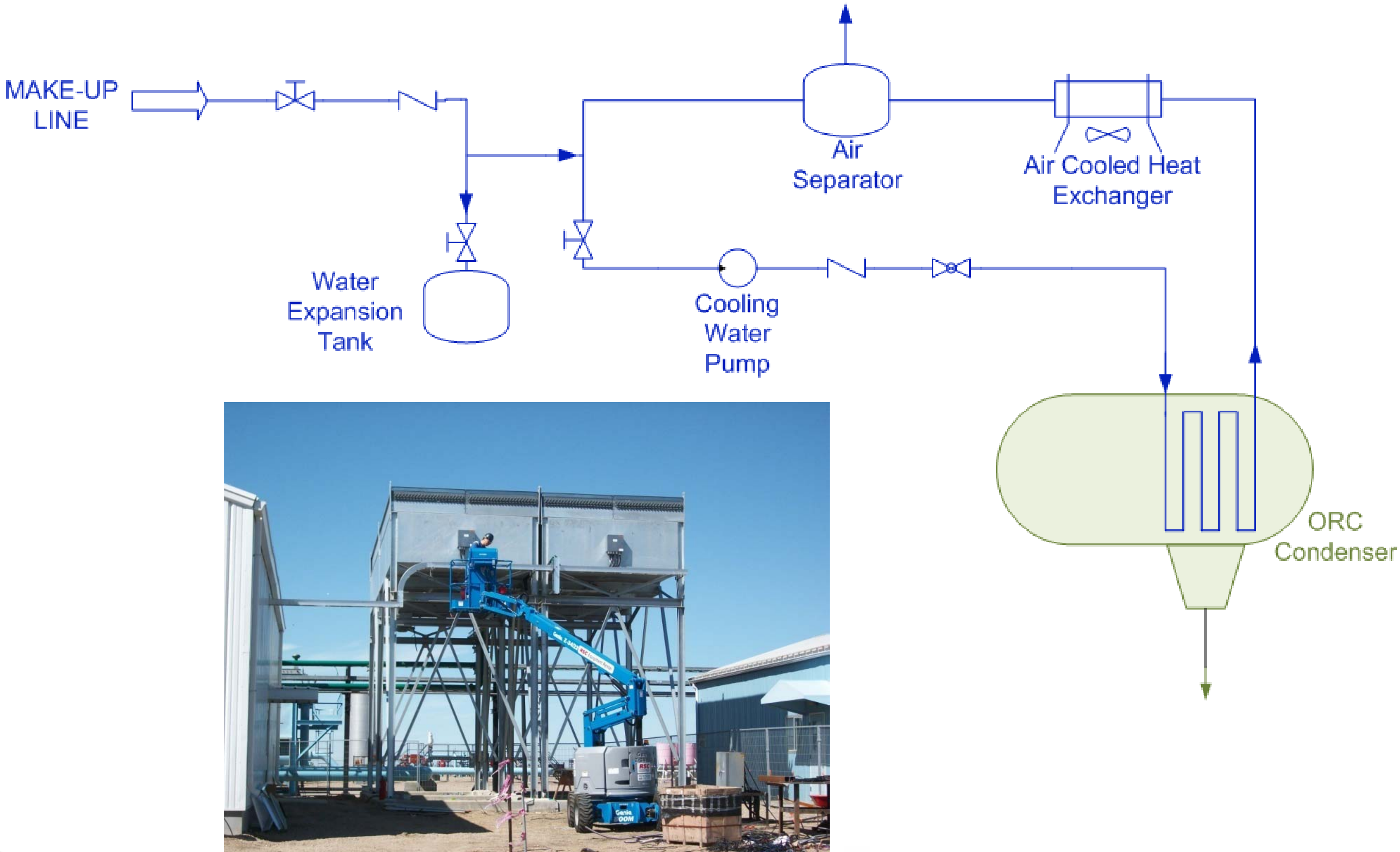
Water Cooling Circuit



Plant Performance

- Nominal 1 MW plant

		Cold Ambient	Moderate Ambient	Hot Ambient
Ambient Temperature	°C	-18	4	37
Exhaust Gas Temperature	°C	405	438	470
Exhaust Gas Flow	kg/h	62.6	58.5	52.0
Thermal Power Recovered	kW	4422	4730	4655
ORC Gross Electrical Power	kW	896	943	641

Construction

- Modular prefabricated design for all major components
  - Reduced site costs
- Typical construction time of 6-8 months

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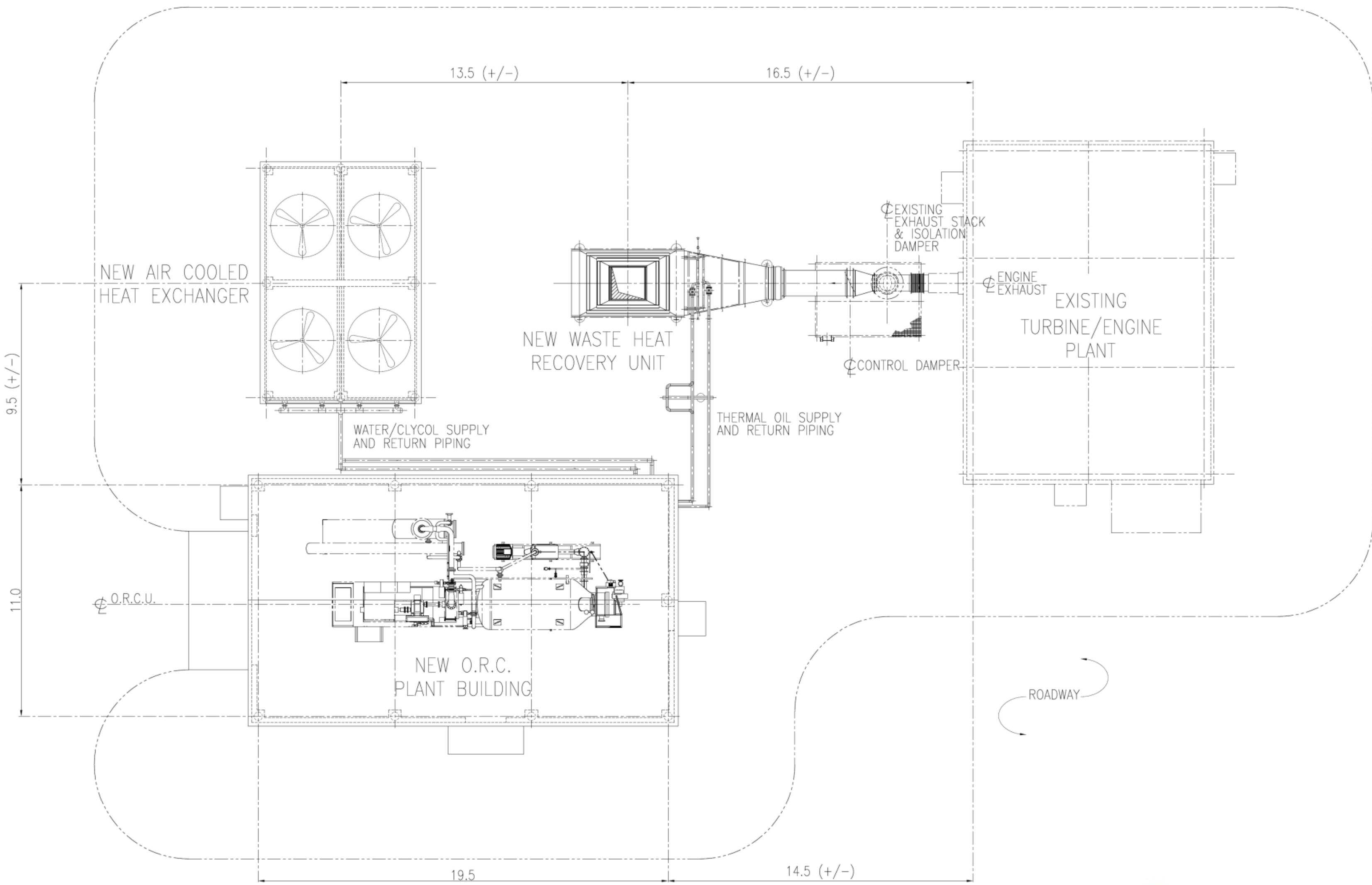
Plant Site Layout



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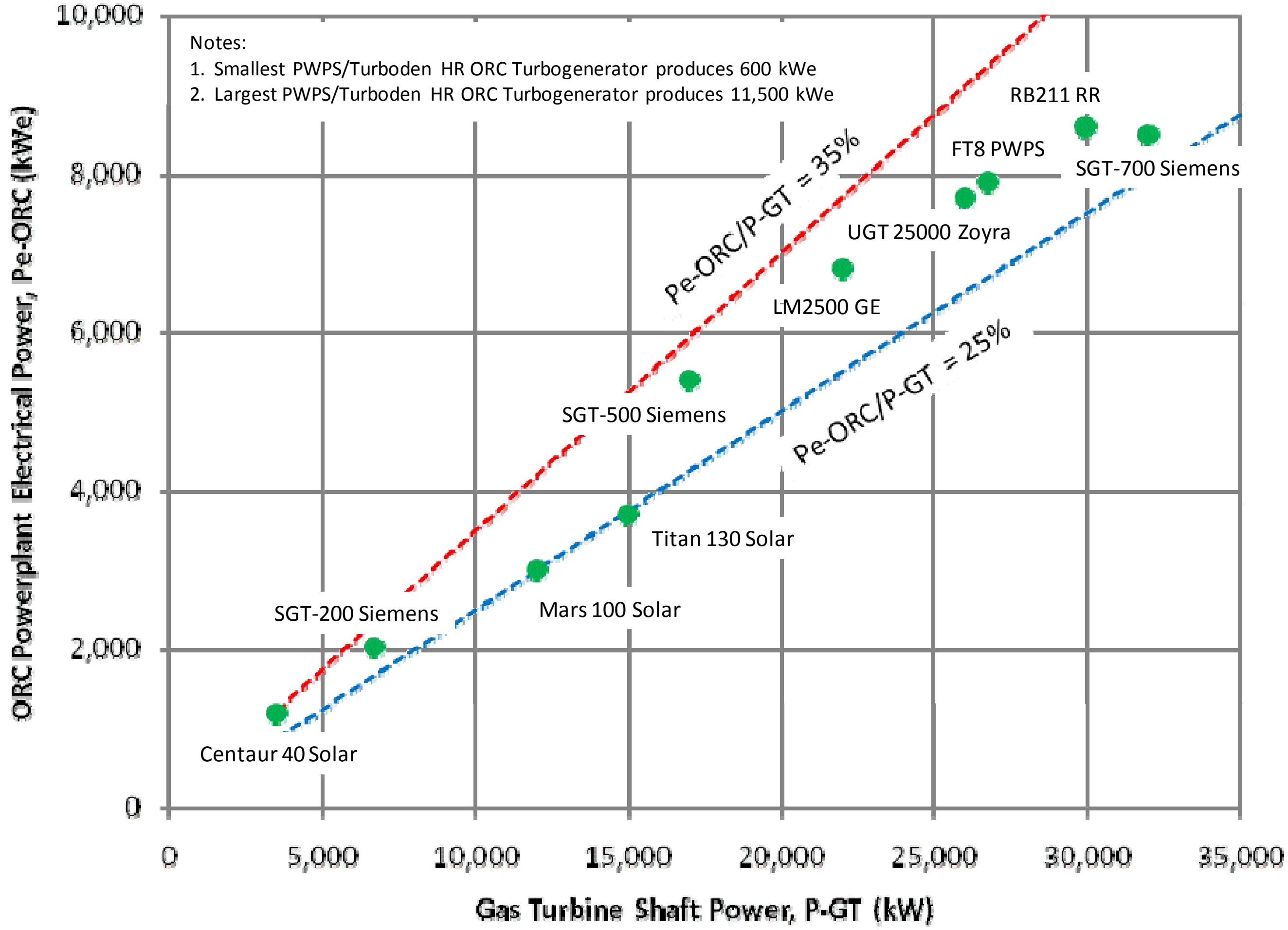
ORC Power vs Gas Turbine Power



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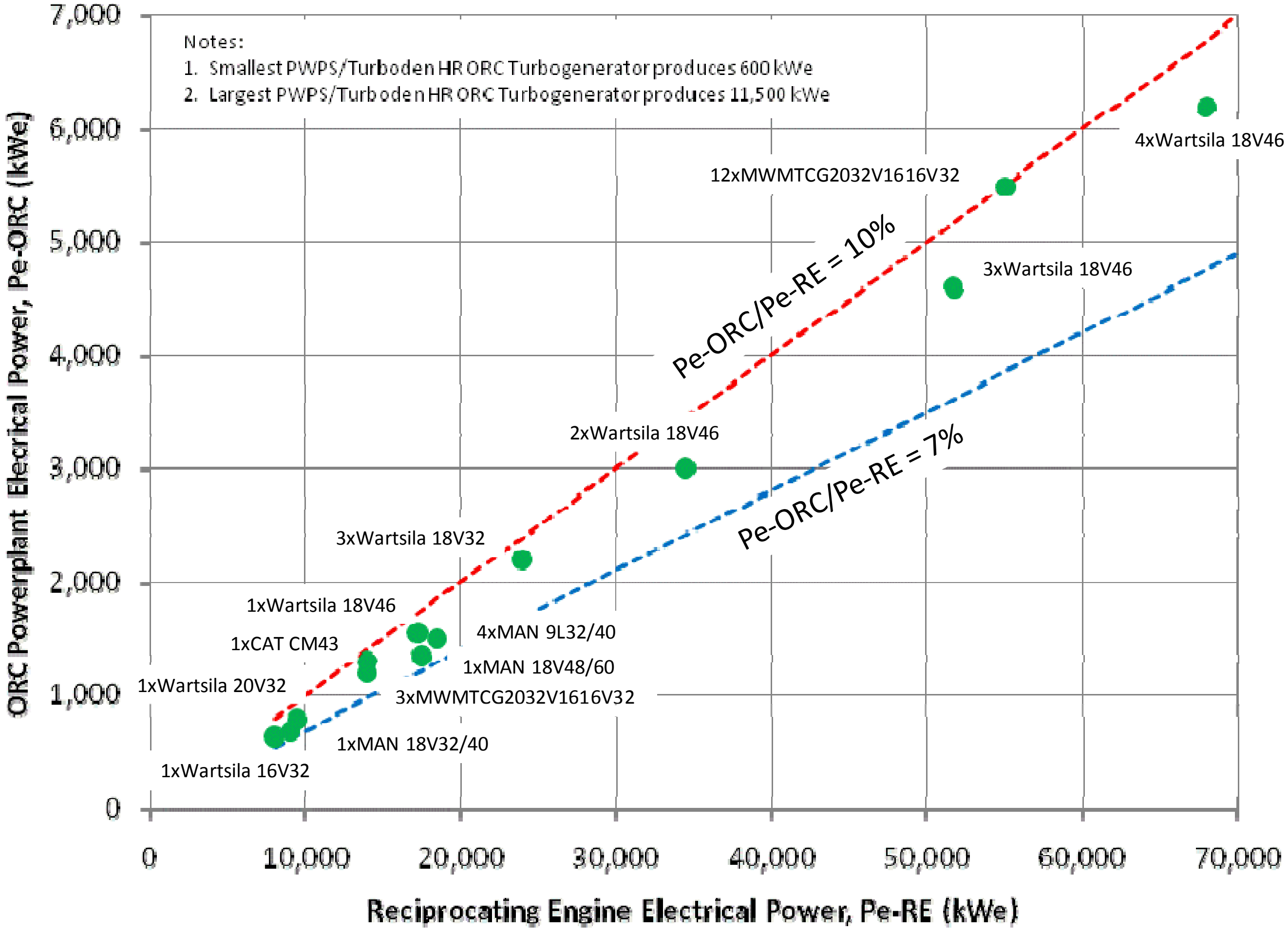
ORC Power vs Recip Engine Power



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Conclusion

- ORC plants are a viable means to use waste heat
- Even small gas turbines are potential candidates for a waste heat to power plant
- In North America, the natural gas industry is actively developing waste heat to power plants