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Waste Heat to Power

Selecting a Technology

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Presentation Outline

Overview of Waste/Reject Heat in Industrial Processes

- Refining
- Petrochemical
- Inorganic chemicals
- Process Steam
- Engine exhaust

Technologies for Waste Heat to Power Conversion

- Commercial Technologies
- Emerging Technologies

Technology Merits

- Conversion efficiency and effective utilization of waste heat
- Heat transfer equipment
- System integration and interfacing with industrial processes
- System reliability
- Economic values

Selecting a Technology

Perspectives on Waste Heat Recovery and Utilization

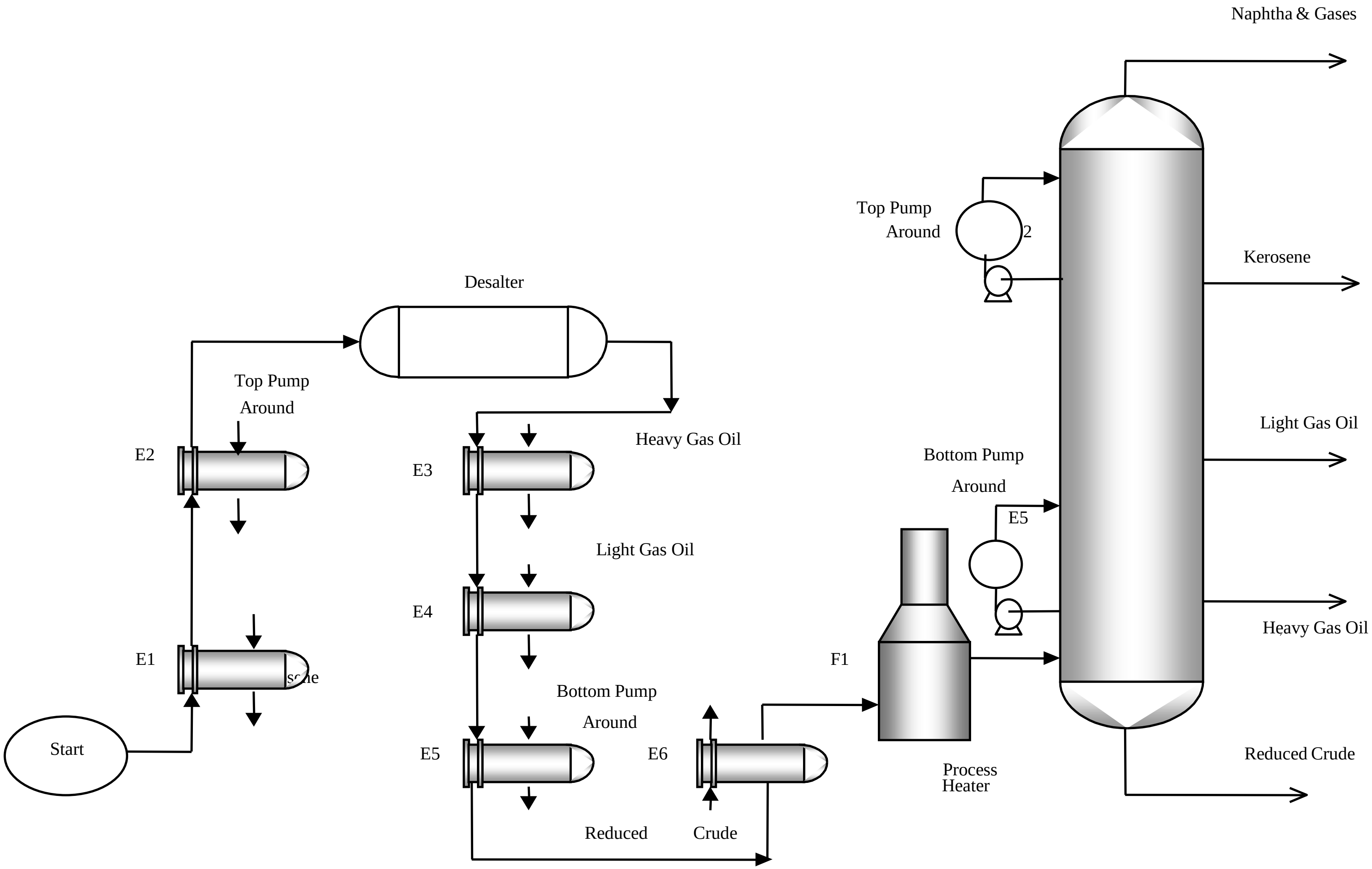
Energy Consumption in a Typical Refinery

Energy consumption in a typical refinery is 441,000 Btu/bbl crude, most of which must be rejected to the atmosphere or cooling water

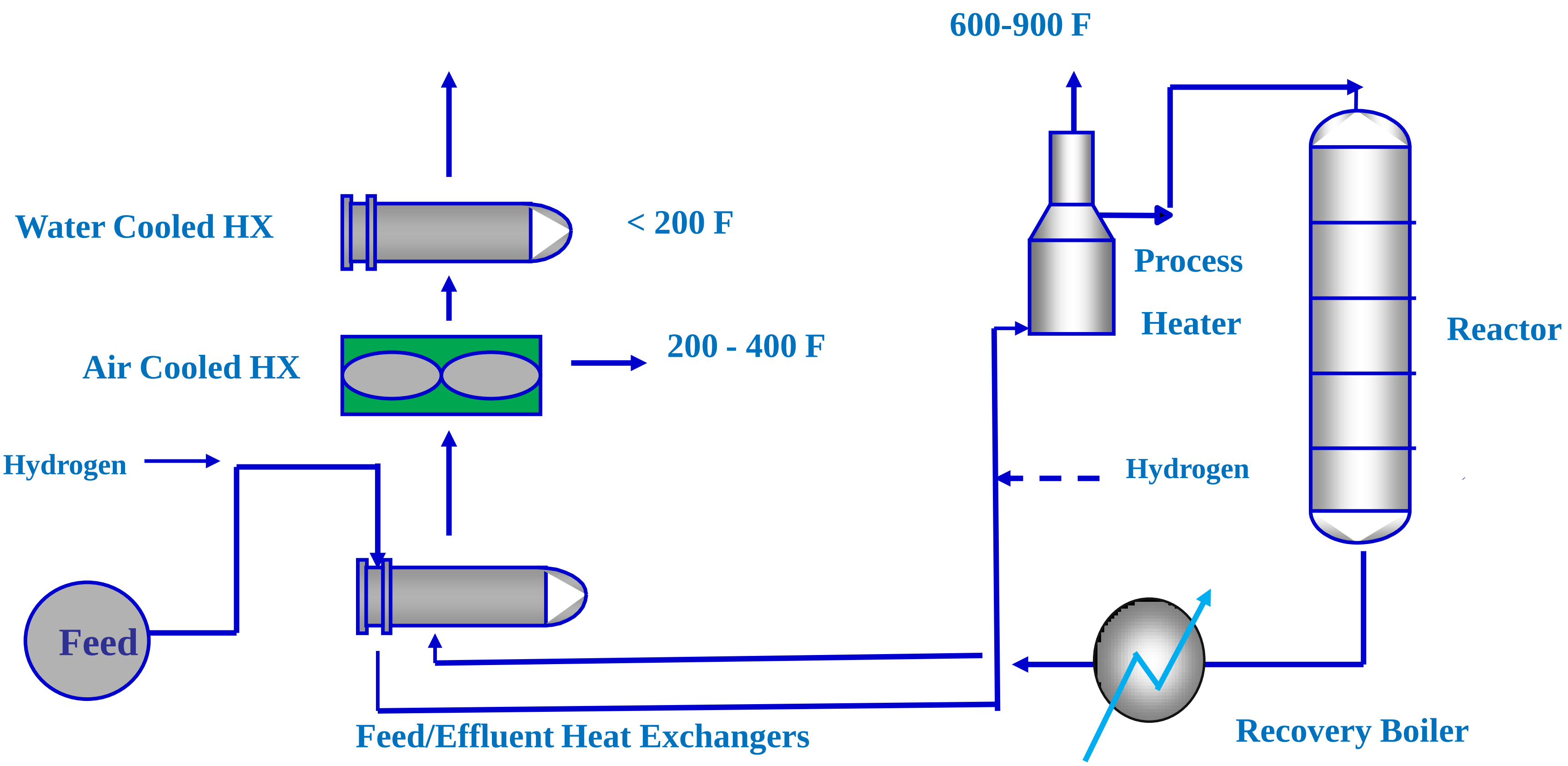
Process heaters and steam boilers (600F – 800F+)	87,000 Btu/bbl
Process heat (200F – 400F)	40,000 Btu/bbl
Process heat (< 200F) to cooling water	Remaining

	Average KBtu/bbl	US Energy Use TrillionBtu/Year
Crude distillation	205.3	880
Delayed coking	166.0	101
FCC	100.0	190
Hydrotreating/Hydrocracking	360.0	581
Reforming	284.0	373

Crude Distillation Major Energy Consuming Process



Hydrotreating and Reforming Processes



600-900 F

Water Cooled HX

< 200 F

Process

Heater

Reactor

Air Cooled HX

200 - 400 F

Hydrogen

Hydrogen

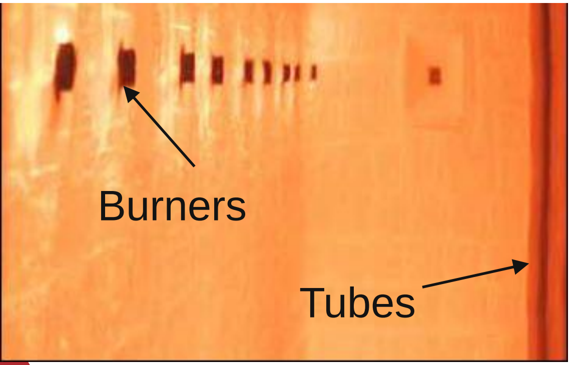
Feed

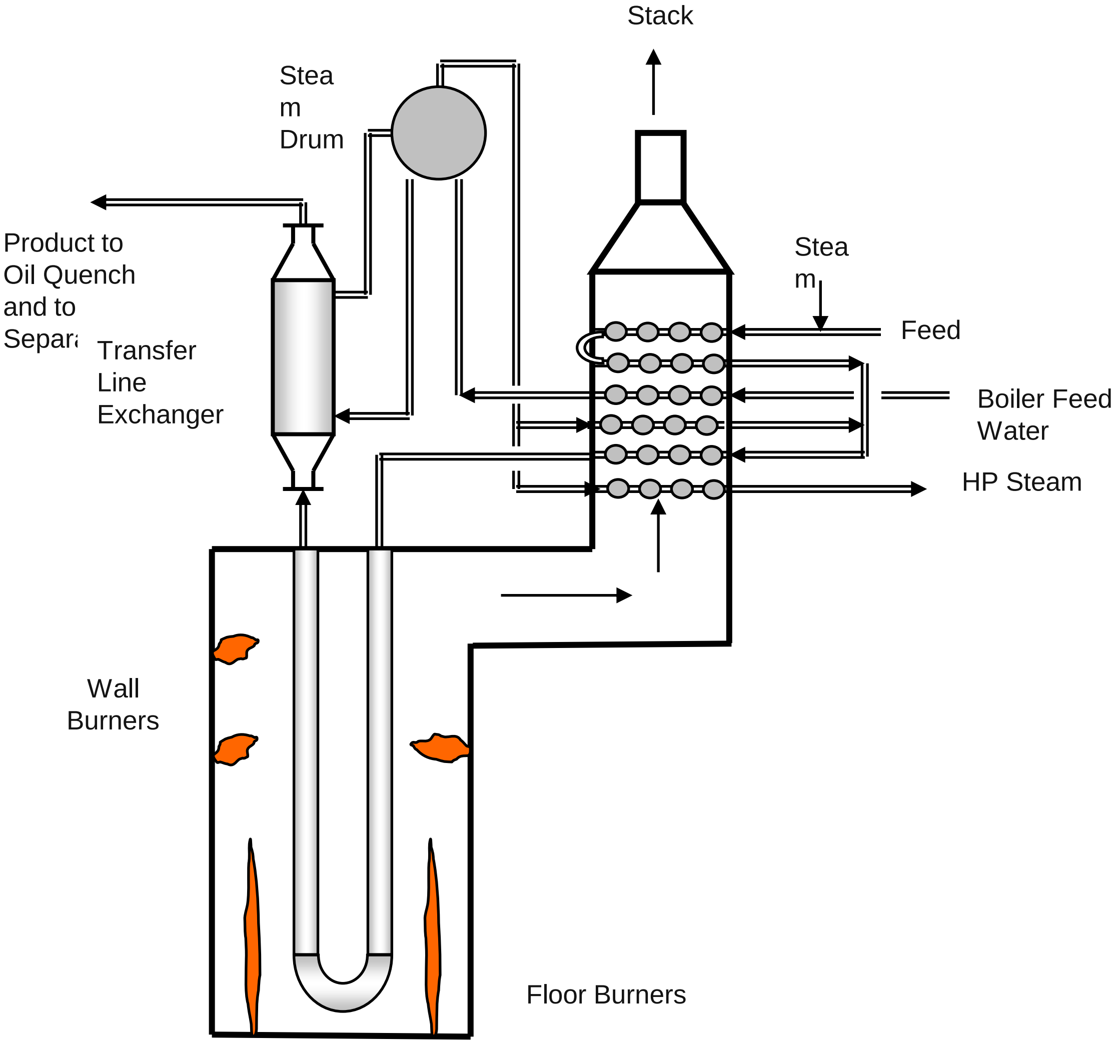
Feed/Effluent Heat Exchangers

Recovery Boiler

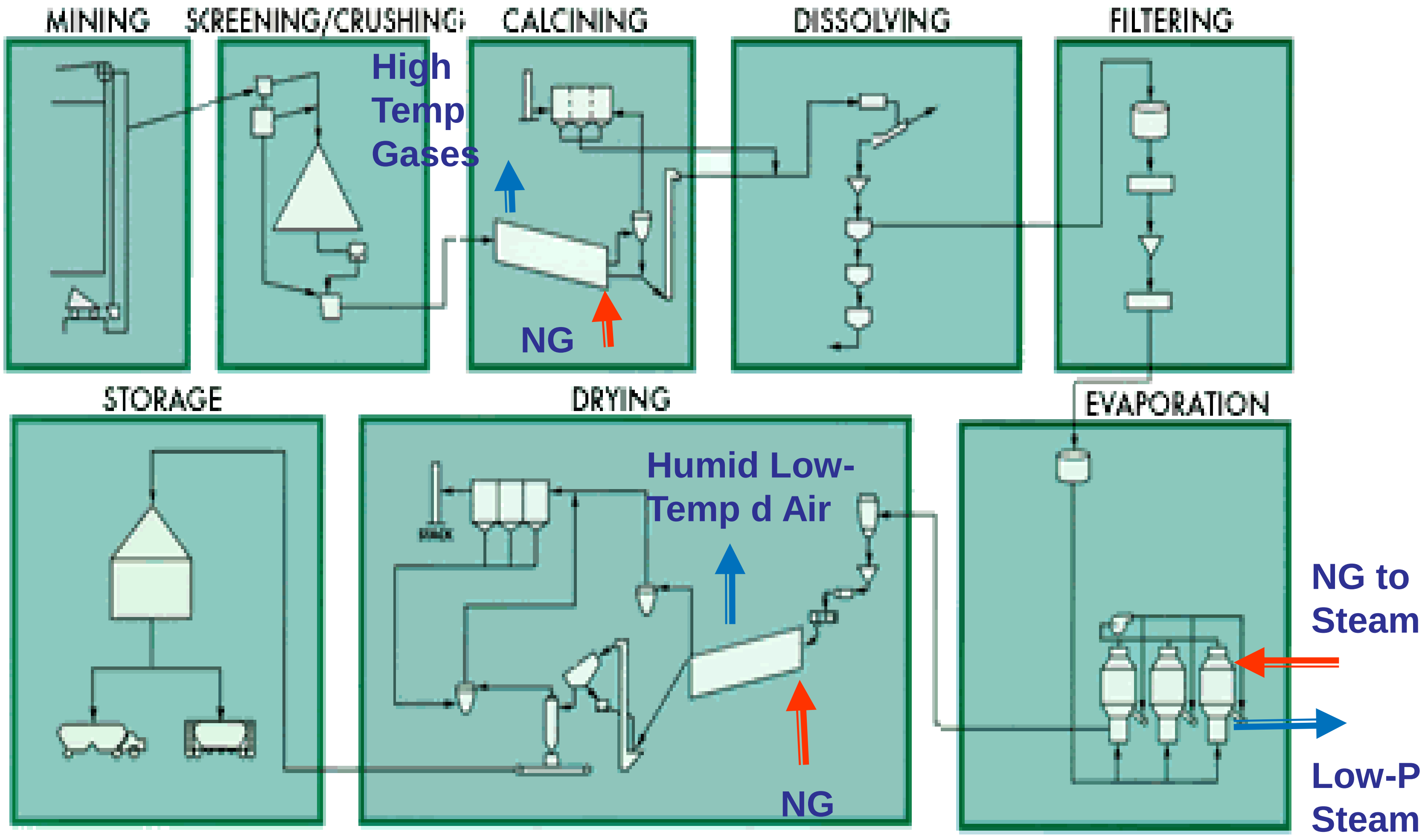
Olefin Reactor – Complex Furnace Design

Inside of Ethylene Furnace





Soda Ash Process – Complex Furnace Design



High Temp Gases

NG

Humid Low-Temp d Air

NG

NG to Steam

Low-P Steam

Steam Utilization in Process Industries

- Steam is major heat carrier in refining, petrochemical, and pulp&paper, and food processing industries
- Steam optimization is an on-going effort with commercial softwares in the market
- Cost effective topping cycle provides opportunity to improve steam economy
- Effective utilization of low-pressure steam can significantly improve the overall steam economy and plant energy efficiency

Current Practices of Heat Recovery

Heat recovery is generally considered in the process design optimization

- **Feed/effluent heat exchangers to recover high-level heat**
- **Waste heat recovery boilers for high-pressure steam generation**
- **Fired-heater stack gas heat recovery for preheating combustion air**

Current Practices of Heat Rejection in the Process Industry

Heat rejection is generally not considered in the process design optimization

- Air-cooled heat exchangers to reject medium-level (200F to 400F) heat
- Cooling water to reject low-level heat (< 200 F)
  - Cooling tower (1000+ lb of water consumed per million Btu heat rejected)
  - Once through - river, seawater, and lakes (environmental restrictions)

Regional scarcity of cooling water needs to be taken into consideration for waste heat to power.

Technologies for Waste Heat to Power

Commercial Technologies

- Single Fluid Rankine Cycle
  - *Steam cycle*
  - *Hydrocarbons*
  - *Ammonia*

- Binary/Mixed Fluid Cycle
  - *Ammonia/water absorption cycle*
  - *Mixed-hydrocarbon cycle*

Emerging Technologies

- Supercritical CO2 Brayton Cycle
- Thermoelectric conversion

Combined Cycles

Rankine Cycle

- Steam Cycle
  - High temperatures
  - Waste heat-recovery boilers commonly used
  - High-pressure steam used for large compressors and air blowers
- Hydrocarbons Cycle (Organic Rankine Cycle)
  - Medium to high temperatures
  - Developed for geothermal applications
  - Diesel engine exhaust – DOE project on ORC
- Ammonia
  - Low temperatures
  - Developed for ocean thermal energy
  - Bottoming cycle with potential dry cooling

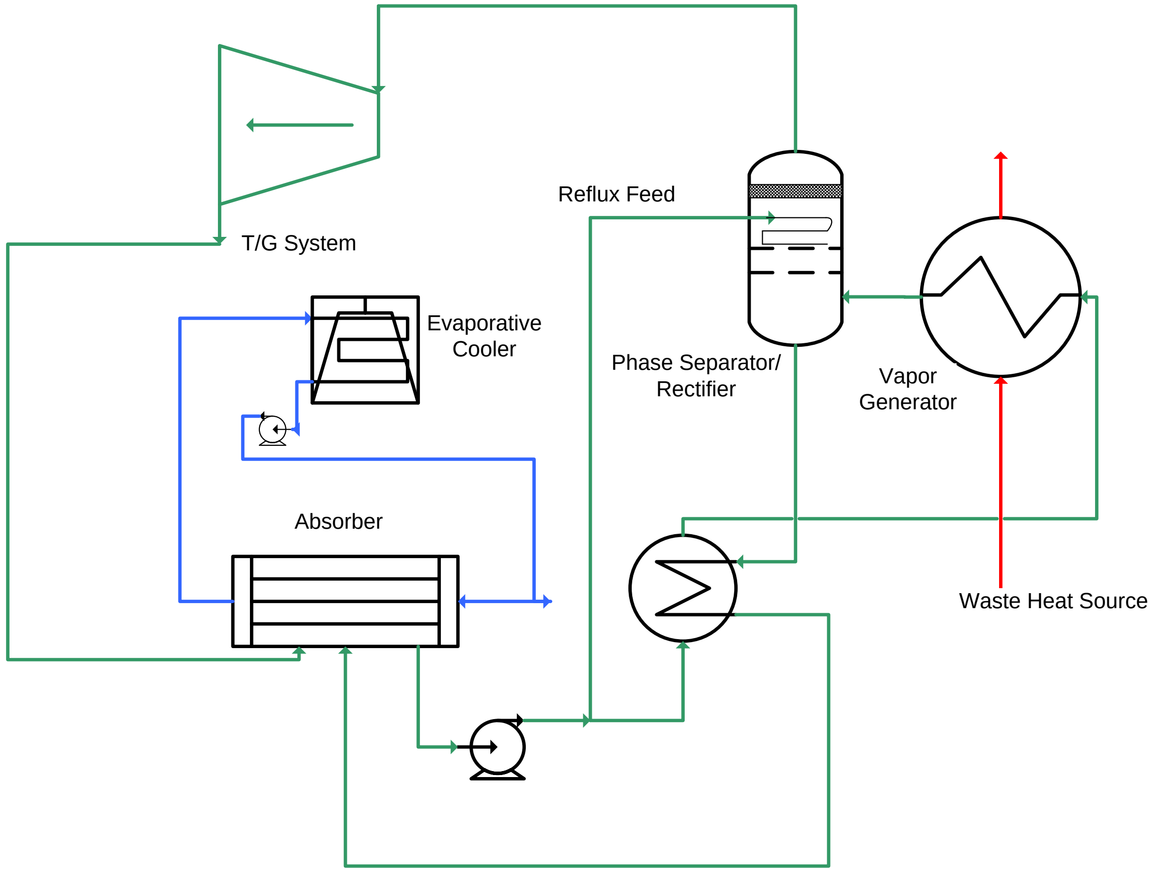
Ammonia/Water Absorption Power Cycle

Historical Perspectives

- Ammonia/water absorption cycle is commercially used for heat-activated refrigeration
- Ammonia absorption power system proposed in 1981 by H. Sheets for ocean thermal energy
- First patented as Kalina cycle in 1982, followed by publication in 1984
- In 1999-2000 first commercial scale 2.0 MW Kalina cycle plant installed at a geothermal site in Iceland
- Further developments continue:
  - Cycle configuration and integration for improved thermal efficiency
  - Development of heat/mass transfer equipment

Ammonia/Water Absorption Power Cycle

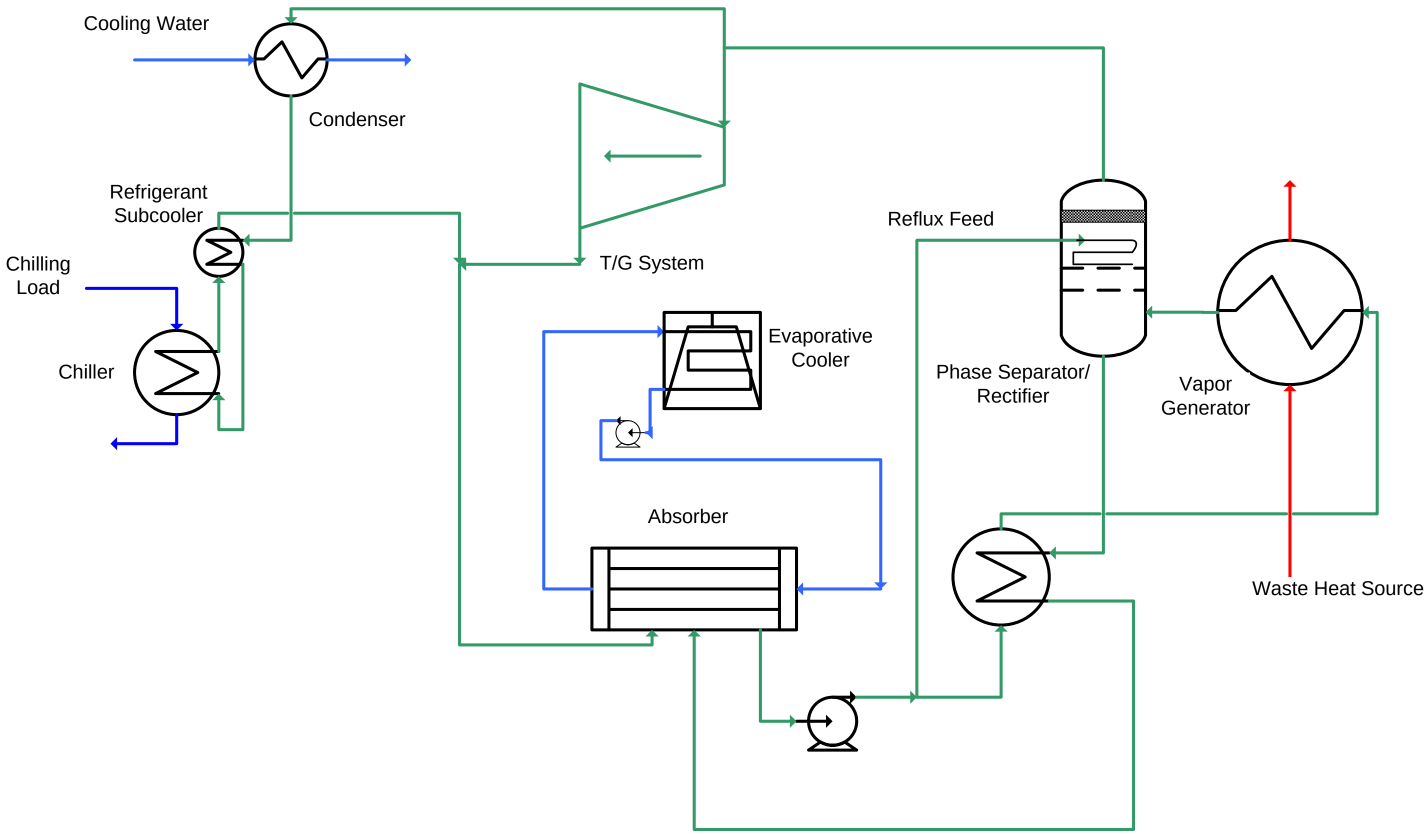
Basic Cycle



Heat recuperation within the cycle is key to high thermodynamic efficiency

Ammonia/Water Absorption Power Cycle

Dual-Function Cycle for Power and/or Refrigeration



- **Dual-function cycle concept developed at Energy Concepts Company, LLC**
- **Power and refrigeration can be used interchangeably or simultaneously**

Mixed-Hydrocarbon Cycle

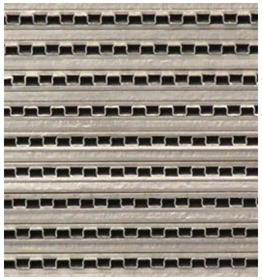
Underlying Technologies Developed

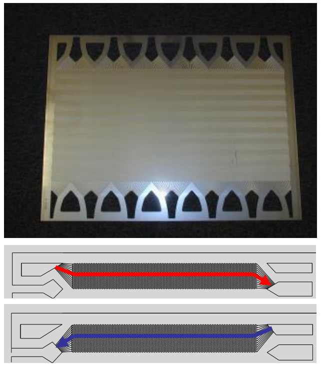
- Advancement of Organic Rankine Cycle with improved thermal efficiency
- Significant literature on cycle analysis
- Industry is familiar with the technology
- Commercially available heat transfer equipment and turbine/generator
- System integration – No major technical risks

Supercritical CO2 (SCO2) Brayton Cycle

Being Developed for Nuclear Plants

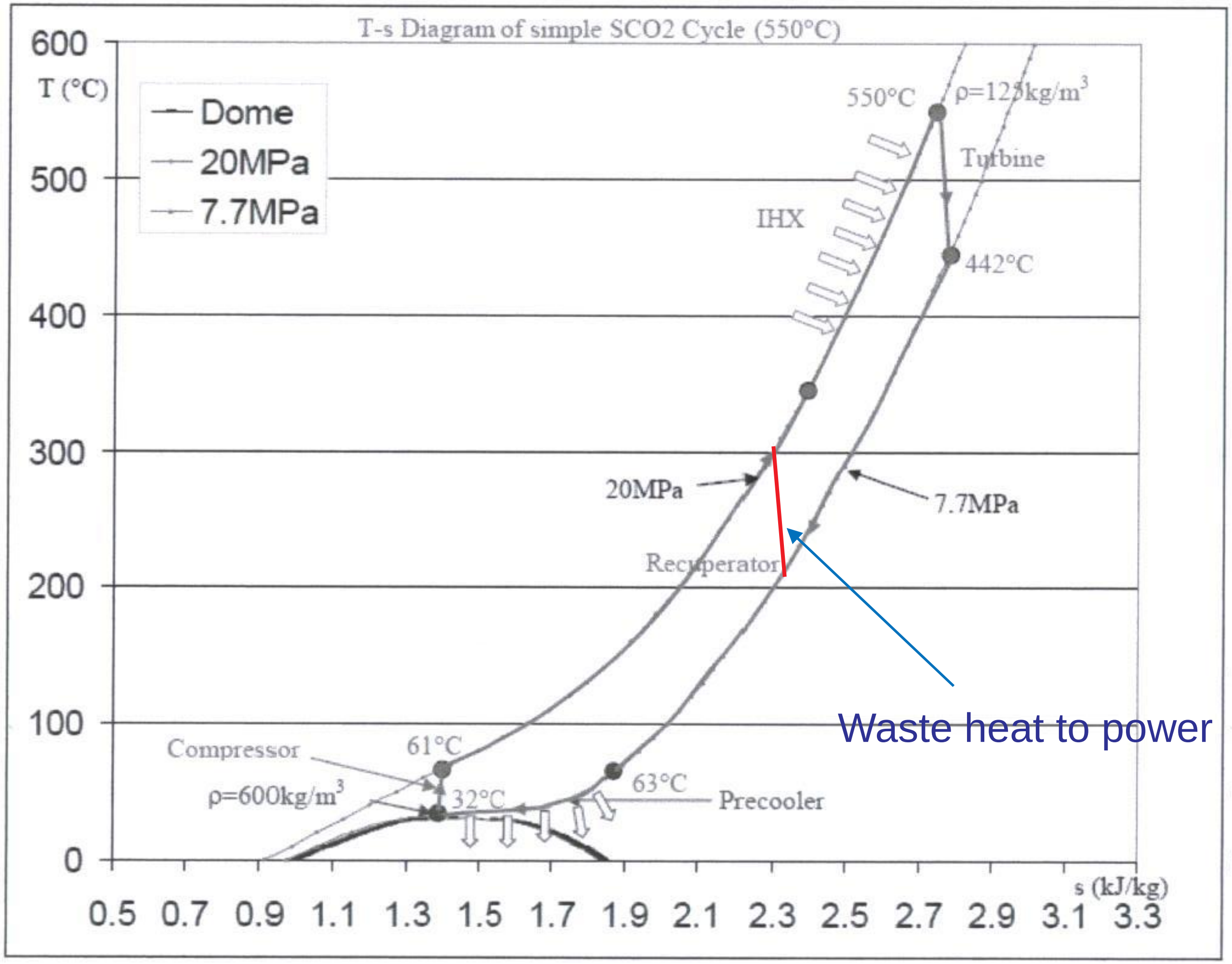
- SCO2 Brayton cycle achieves high thermal efficiency
- Development of heat transfer equipment
  - Internal heat recuperation crucial for achieving high thermal efficiency
  - Compact narrow flow passage heat exchangers
- Turbine/Compressor
  - Single-stage and two-stage centrifugal compressors
  - Six-stage axial flow turbine
- For waste heat to power applications, combined cycle may have advantages





Supercritical CO2 (SCO2) Brayton Cycle for Nuclear Reactor

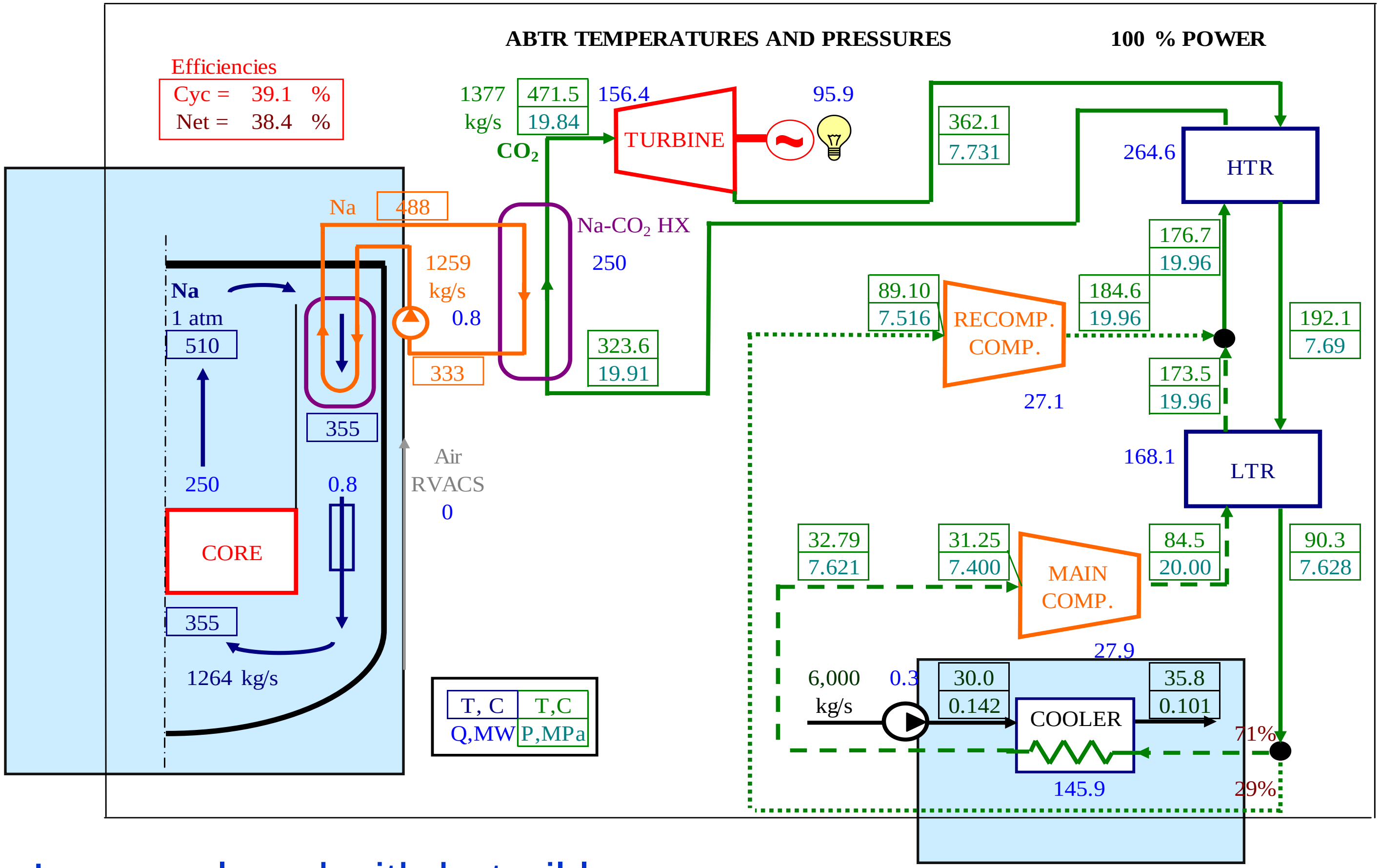
T-S Diagram



Waste heat to power

Supercritical CO2 (SCO2) Brayton Cycle for Nuclear Reactor

Flow Schematic

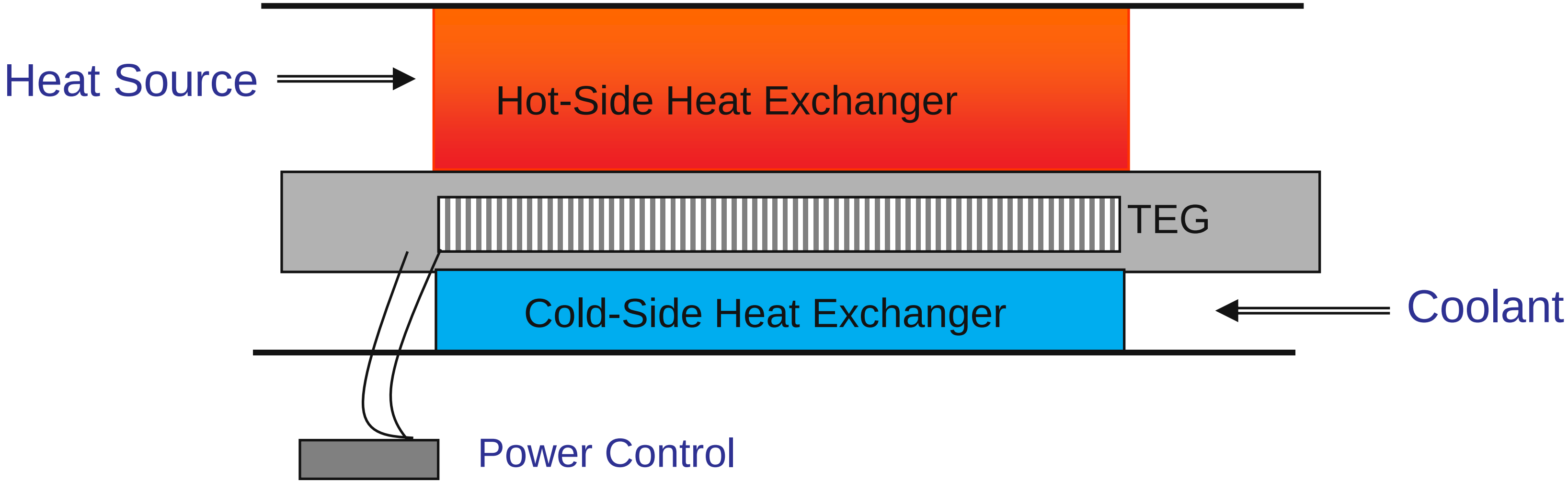


Na-Loop replaced with hot-oil loop for waste heat to power cycle

Low-temp bottoming cycle or Absorption refrigeration cycle

Thermo-Electric Generation System

- Thermo-Electric Generator (TEG) device known for some time for TEG cooling (example – thermocouples)
- Development focused on material-pair with high figure-of-merit
- DOE funded project to evaluate technical/economic viability of TEG system



Thermo-Electric Generation System

Figure of Merit

$ZT = (\alpha^2 \sigma / \lambda)\, T$

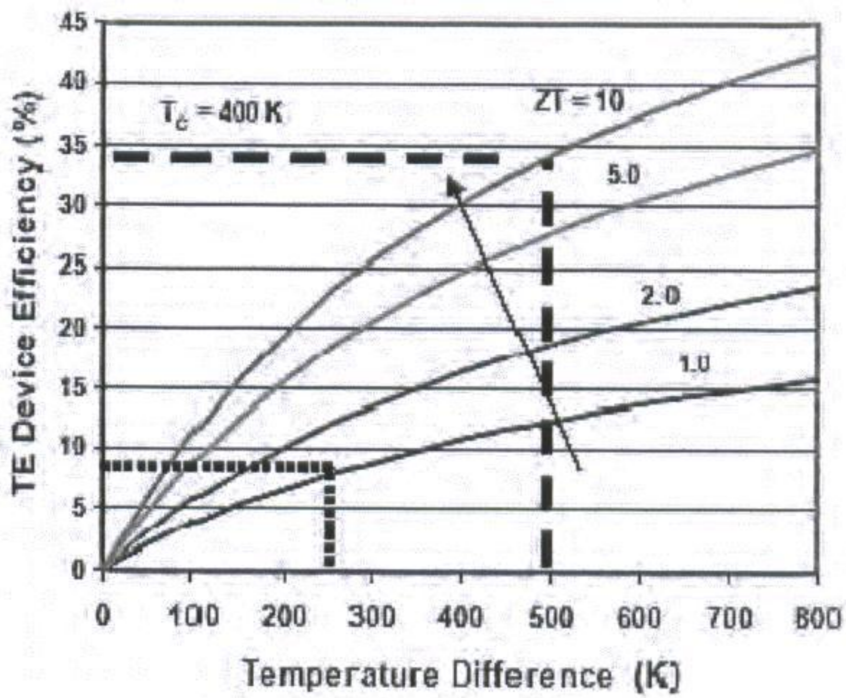
α = the Seeback coefficient (volt/K)

σ = electric conductivity (amp/volt m)

λ = thermal conductivity (w/m K)

Thermal Efficiency

$$\eta_c = \left[\frac{T_h - T_c}{T_h}\right]\left[\frac{\left(1+Z^*\overline{T}\right)^{1/2} - 1}{\left(1+Z^*\overline{T}\right)^{1/2} + 1}\right]$$



Combined Cycle

- An integrated combined cycle with advantageous features of two different cycles can be more economical than individual cycles
- Combined power and refrigeration can significantly improve the overall economics

For an example: SCO2 and ammonia/water or organic cycle

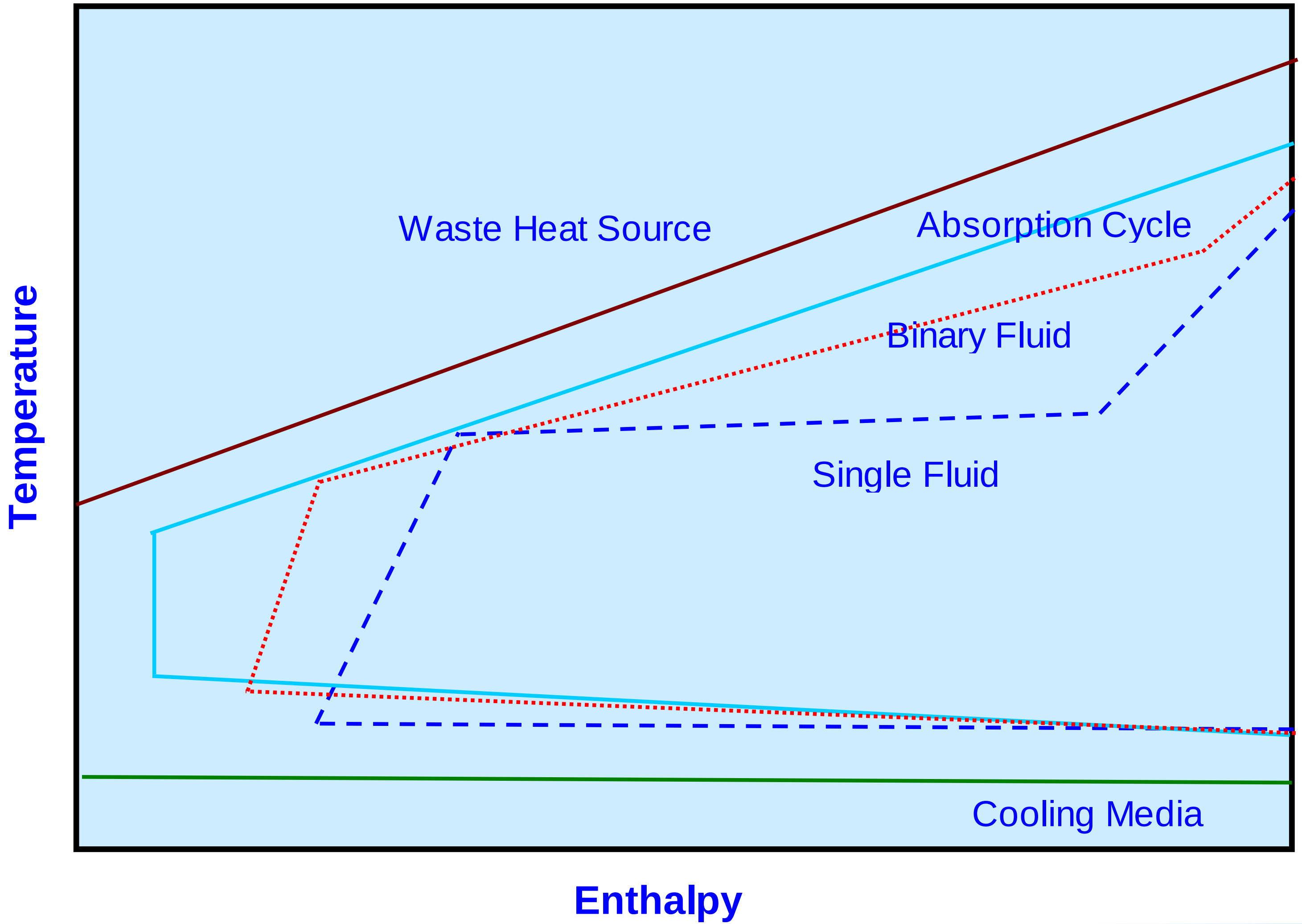
Advantages:

- *Cycle configuration*
- *Cost-effective interfacing with heat source*
- *Dry cooling*
- *Mitigating material issue*
- *Refrigeration*

Technology Merits

Criteria-1

Conversion Efficiency and Effective Utilization of Waste Heat



Conversion Efficiency and Effective Utilization of Waste Heat

Understanding Cycle Efficiency – 1st Law of Thermodynamics

Commercial Power Plants

$$\eta_c = \frac{\text{Work}_{\text{Net}}}{\text{Heat Source}} \qquad \eta_c = \frac{\text{Work}_{\text{Net}}}{\text{Heat Content of Primary Soure}}$$

Commonly thermal efficiency is based on recovered waste heat

$$\eta_{WH} = \frac{\text{Work}_{\text{Net}}}{\text{Heat Recovered}}$$

Thermal efficiency should be based on total recoverable waste heat

$$\eta_{WH} = \frac{\text{Work}_{\text{Net}}}{\text{Total Recoverable Heat}}$$

Conversion Efficiency and Effective Utilization of Waste Heat

Understanding Cycle Efficiency – 2nd Law of Thermodynamics

Carnot Efficiency

$$\eta_c = \frac{\text{Work}_{\text{Net}}}{\text{Heat Source}} \qquad \eta_c = \frac{T_1 - T_2}{T_1}$$

Cornot Efficiency for Waste heat to Power

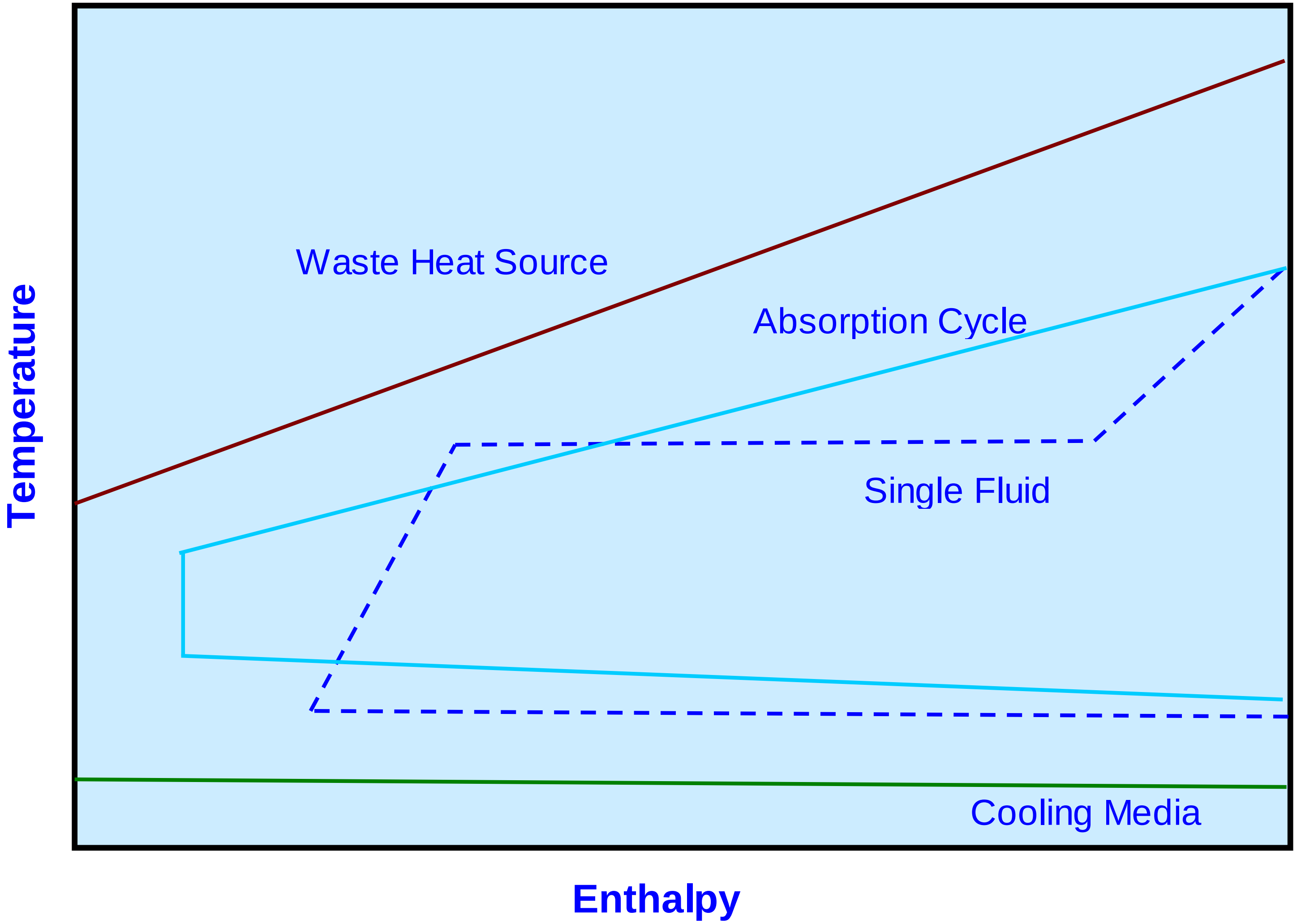
$$\eta_{WH} = \frac{T_{HeatSource} - T_{\mathrm{Re}\,jection}}{T_{HeatSource}}$$

Thermal efficiency should be based on total recoverable waste heat

$$\eta_{WH} = \frac{\text{Cycle Efficiency Based on Heat Recovred}}{\text{Carnot Efficiency}}$$

Conversion Efficiency and Effective Utilization of Waste Heat

Impact of Heat Transfer Performance on Cycle Efficiency



Criteria-2

Heat Transfer Equipment

- Waste heat source to the cycle
  - Corrosion and material considerations
  - Fouling: severity, mitigation, monitoring, cleaning
- Internal heat transfer equipment
  - Numbers and complexity
  - Design constraints and impact on cycle performance
- Heat rejection exchanger
  - Availability of cooling water or make-up water for evaporative coolers/condenser
  - Dry cooling

Criteria-3

System integration and interfacing with industrial processes

- **Interfacing of waste heat source to the cycle: space, accessibility, interfacing piping, impact on the process unit, need for a closed loop to transfer waste heat to power cycle**
- **Heat rejection: Integrated with the plant cooling system or independent system, availability of make-up water or dry cooling**
- **Power system integration and controls**
- **Maintenance requirements that would impact system integration**
- **<u>Availability of Space for the Power System</u>**

Criteria-4

System reliability

- Validated performance of individual components
- Validated performance of the prototype power system
- Dynamic performance of the power system that may impact industrial processes
- Impact of fouling of waste heat recovery heat transfer equipment on the system performance
- Inherent safety measures for ammonia and hydrocarbon systems

Criteria-5

Economic values

- Cost of electricity (COE): present and projected COE over the life of the waste heat to power system
- Combined power and refrigeration: value of refrigeration on energy efficiency as well as improved productivity
- Productivity improvements
- Environmental benefits

Selecting a Technology

Step 1: Determine incentives: Just COE or end-use benefits (refrigeration, operating rotating equipment, expanding capacity)

Step 2: Characterize the waste heat source and evaluate technical issues of interfacing with the power system

Step 3: Use technology merit criteria to screen different power cycles, including combined cycles, and down select to two (may be three) options

Step 4: Perform a conceptual design to identify major technical issues, and possibly down select to one option

Step 5: Preliminary design with planning-stage cost estimates based on budgetary quotes of components and subsystems

Step 6: Decision to go forward with the installation of the waste heat to power system

Perspectives
Waste heat – a hidden source of energy

- Significant loss of thermal energy from furnace/fired heater/boiler stack gases and calciners & driers
- Significant low-level (150F to 250F) energy is lost to cooling towers in the form of latent heat from overhead condensers in distillation
- Low pressure steam a major source of waste heat
- Lack of incentives, such as GHG emission credits
- Lack of design/economic tools to evaluate effective utilization of recovered process waste heat in ***High-Value*** applications – power, refrigeration, heat pumping
- Process heat recovery must be applied to existing plants, with uncertain costs of retrofitting
- Major technical barriers of fouling and corrosion of waste heat sources
- Scarcity of fresh water in some regions for heat rejection