Low temperature / small capacity ORC system development

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Carrier — A United Technologies Company | Danfoss TURBOCOR

1980 - 2008 | 2008 - present

Syracuse, NY 13221

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The ORC situation in 2005

- "The number of papers written about ORC systems exceeds the number of commercial ORC system installations"
  - *Lucien Bronicki (founder of Ormat) introducing his paper "Bottoming Organic Cycle for Gas Turbines" at the 2005 ASME gas turbine conference in Reno, Nevada*

The ORC situation in 2011

- "The number of papers written about ORC systems exceeds the number of commercial ORC system installations"
  - *Lucien Bronicki (founder of Ormat) introducing his paper "Bottoming Organic Cycle for Gas Turbines" at the 2005 ASME gas turbine conference in Reno, Nevada*
- The success of this conference with its large number of presentations is one of the reasons that the above statement still holds.

Low temperature / small capacity ORC system development based on HVAC equipment

Contents

- **Thermo 1.01: the vapor compression refrigeration cycle versus the Rankine power cycle**
- The economical challenge of low temperature ORC systems
- The transition from a power consuming centrifugal chiller to a power producing ORC plant
- The lowest temperature ORC: Power from 73 ^{0}C water: the Chena Hot Springs units in AK
- Working fluid selection for power density similarity with HVAC equipment
- The product launch customer for the water-cooled low temperature ORC: Raser technologies
- The carbon footprint of ORC system using HFC refrigerants: GWP considerations
- The first air-cooled prototypes and its potential applications
- The challenge: mass producing ORC's

Thermodynamics 1.01

Thermodynamic Energy Conversion:

Given two of the following quantities the third one can be obtained through a thermal energy conversion process.

=> 3 SYSTEMS POSSIBLE

Refrigeration Cycle

Heat Source

T_{low}

Heat Sink

$T_{ambient}$

Mechanical Energy

$$COP_{CARNOT,cooling} = \frac{T_L}{T_H - T_L}$$

If $T_L =$ 5 ^{0}C and T_H is 40 ^{0}C :

$$COP_{CARNOT,cooling} = \frac{5+273}{(35+273)-(5+273)} = \mathbf{9.37}$$

Actual systems are reaching around 50% of that value

Heat Pump

Heat Source

$T_{ambient}$

Heat Sink

T_{high}

Mechanical Energy

$$COP_{CARNOT,heating} = \frac{T_H}{T_H - T_L}$$

If T_L = **15 ^{0}C** and T_H is **75 ^{0}C** :

$$COP_{CARNOT,heating} = \frac{15+273}{(75+273)-(15+273)} = \mathbf{5.8}$$

Actual systems are reaching around 50% of that value

Power Cycle

Heat Source
$T_{ambient}$

Heat Sink
T_{high}

Mechanical Energy

$$\eta_{CARNOT,power} = \frac{T_H - T_L}{T_H} \longrightarrow \eta_{CARNOT,power} = \frac{1}{COP_{CARNOT,heating}}$$

If $T_L =$ **15 ^{0}C** and T_H is **120 ^{0}C**

$$\eta_{CARNOT,power} = \mathbf{0.26}$$

Actual systems are reaching around 50% of that value

Refrigeration Cycle

Heat Source

T_{low}

Heat Sink

$T_{ambient}$

Mechanical Energy

$COP_{id}=T_{low}/(T_{amb}-T_{low})$

Heat Pump Cycle

Heat Source

$T_{ambient}$

Heat Sink

T_{high}

Mechanical Energy

$COP_{id}=T_{high}/(T_{high}-T_{amb})$

Power Cycle

Heat Source

T_{high}

Heat Sink

$T_{ambient}$

Mechanical Energy

$\eta_{id}=(T_{high}-T_{amb})/T_{high}$

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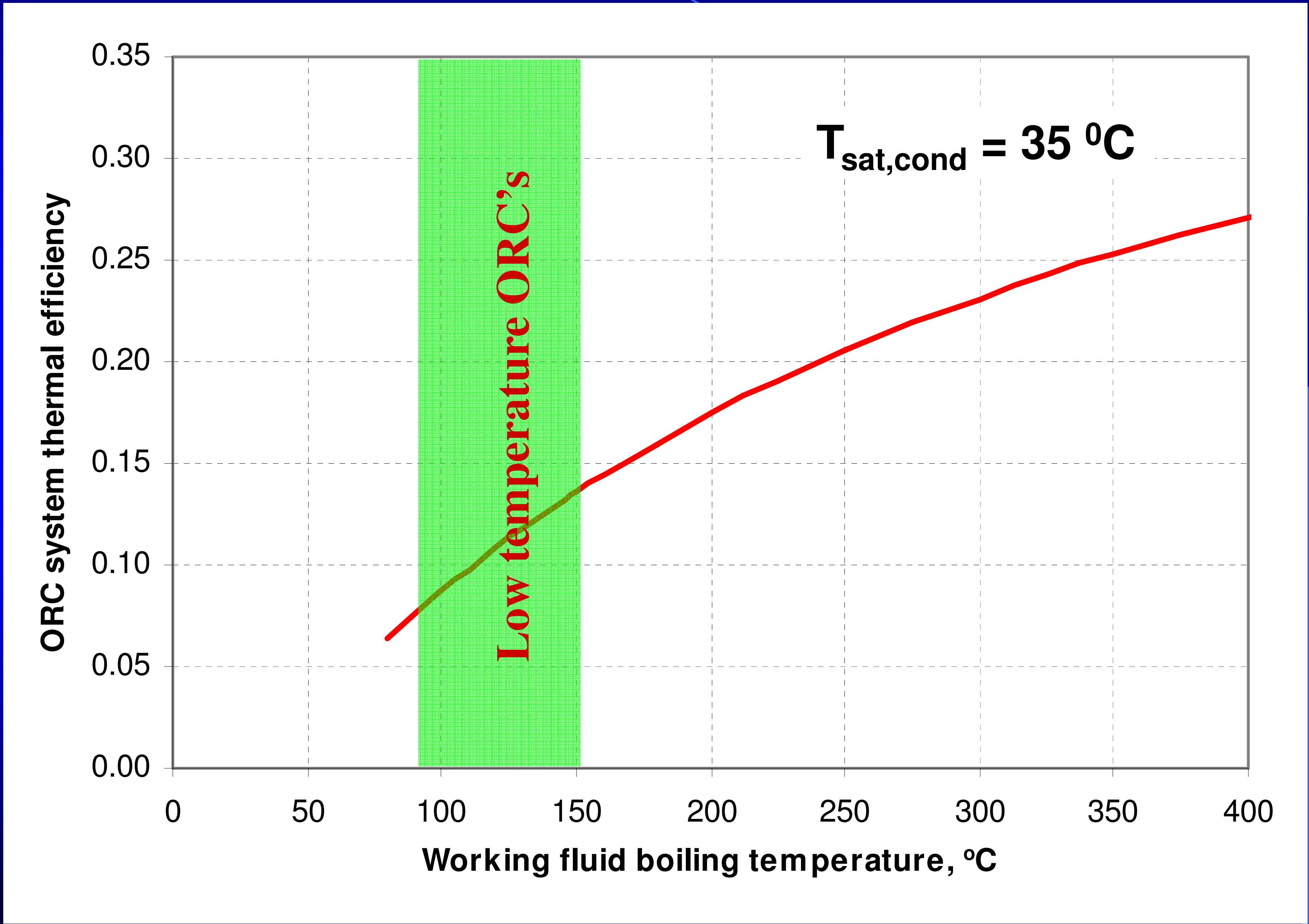
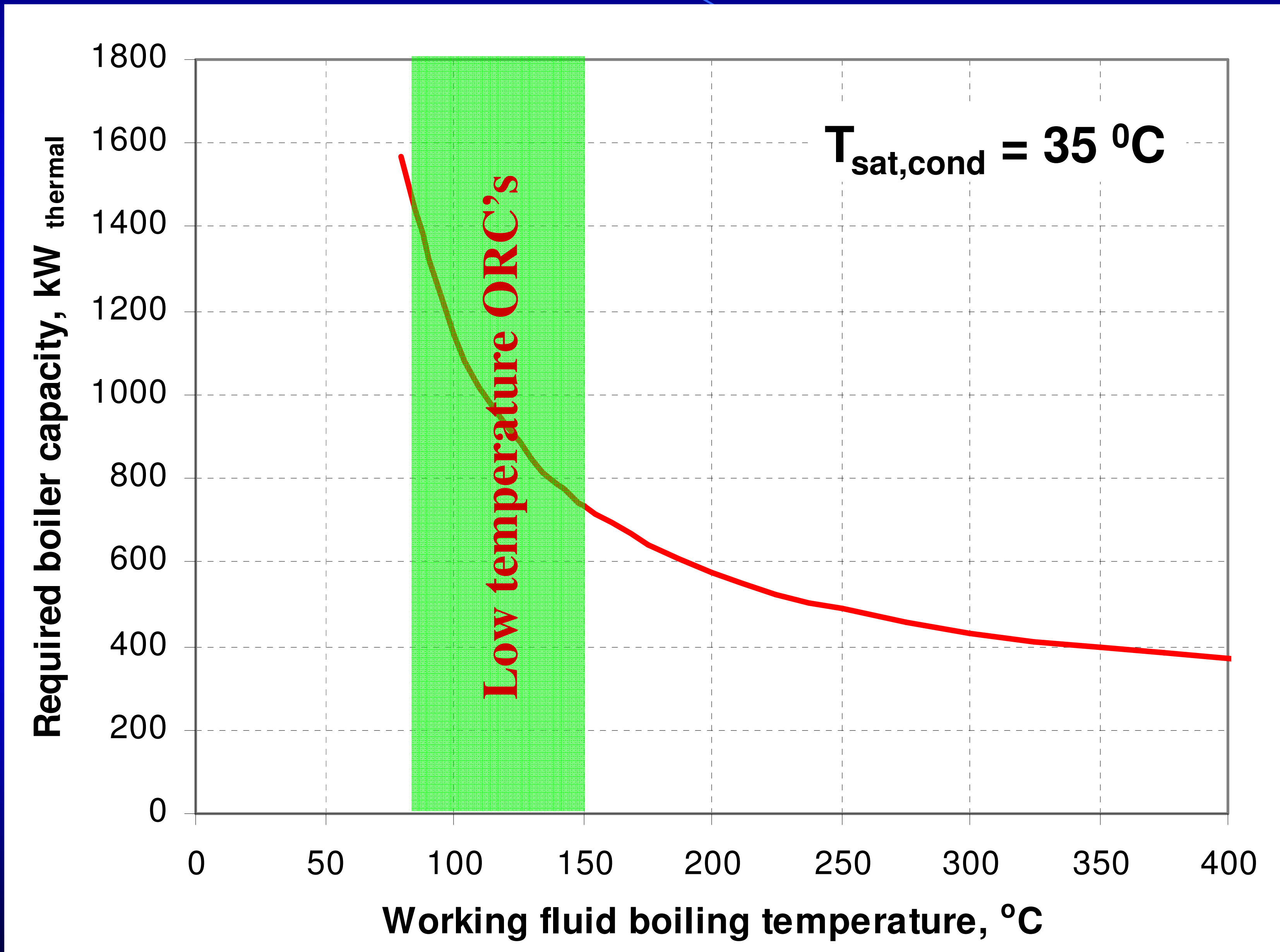
ORC thermal efficiency as a function of working fluid boiling temperature



Required ORC boiler capacity as a function of working fluid boiling temperature for a 100 kW_{el} ORC turbine



Price comparison: HVAC versus Power Generation

- HVAC: ~ $ 500 / kW (installed)
- ORC Power generation: ~ $ 2,500/kW

- Adapt HVAC equipment for ORC duty

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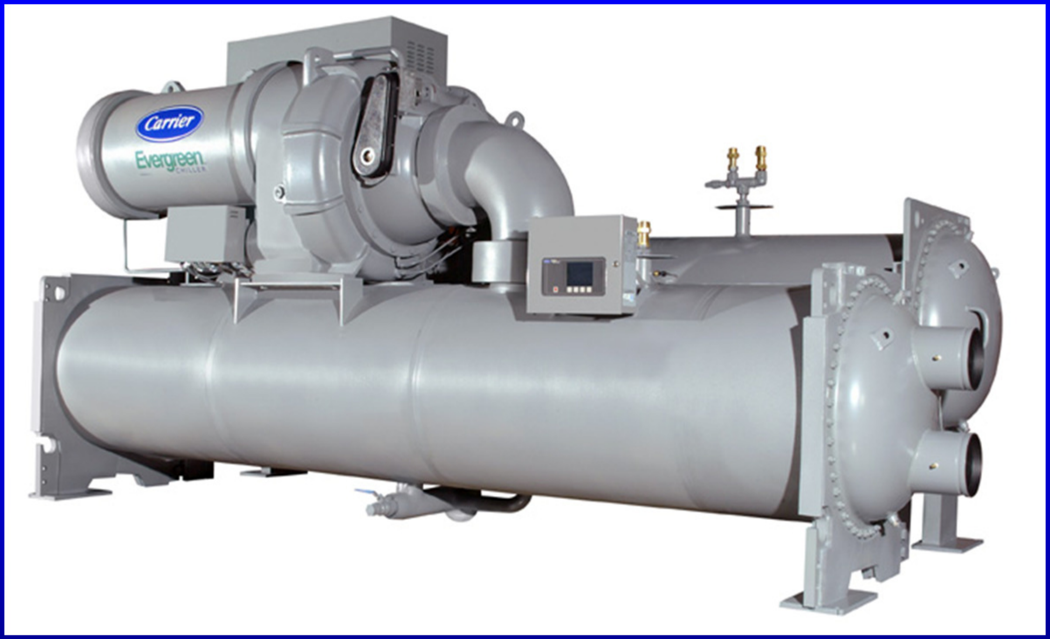
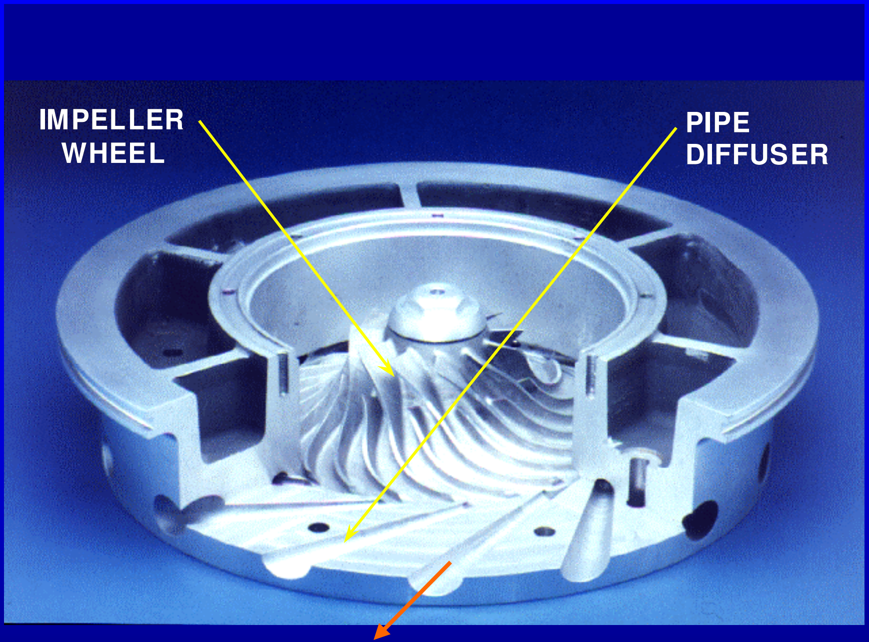
From centrifugal chiller to ORC power plant

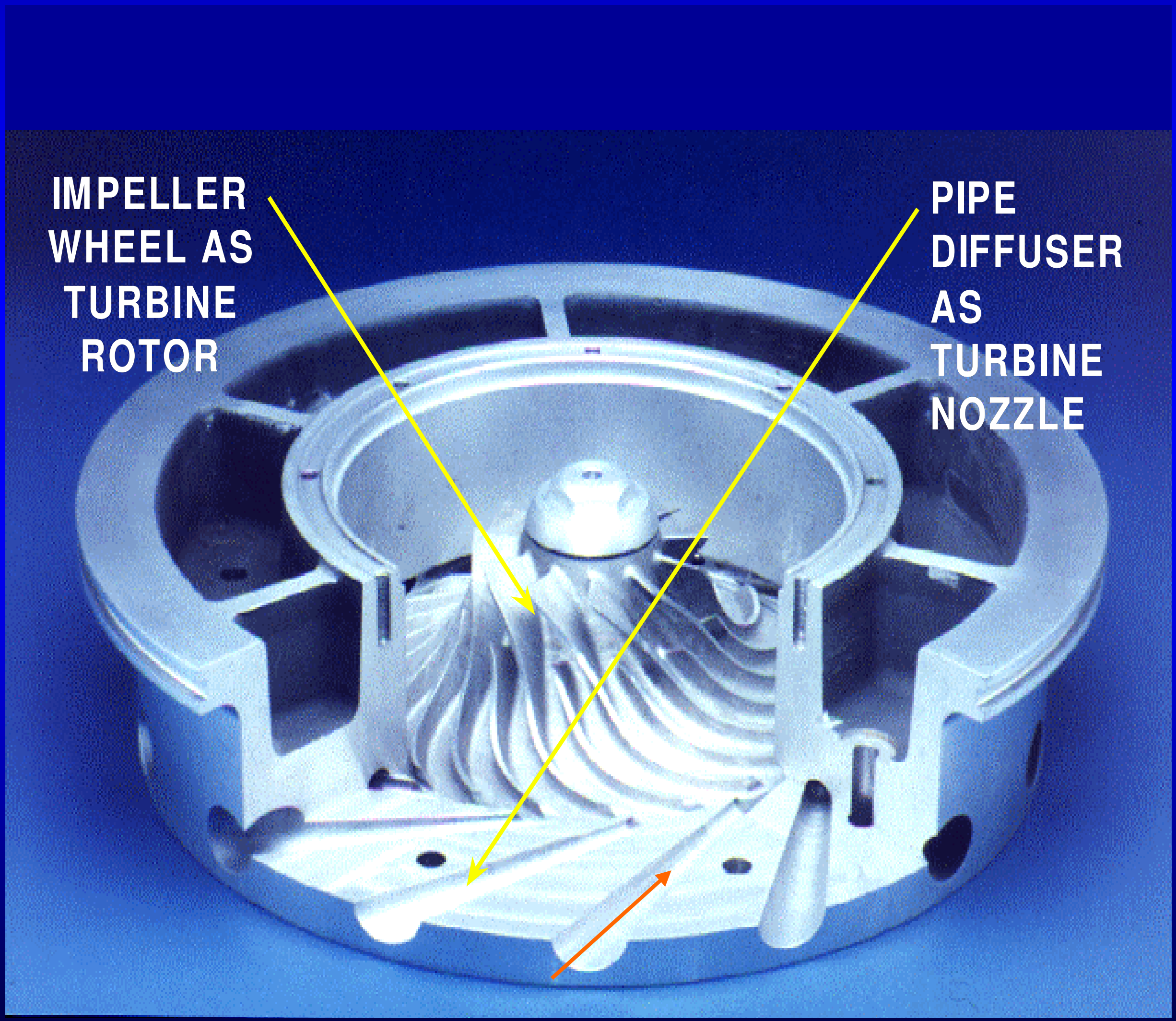
- **In 1992 Carrier introduced a centrifugal chiller platform that utilizes compressors with so-called "pipe diffusers" to increase efficiency**



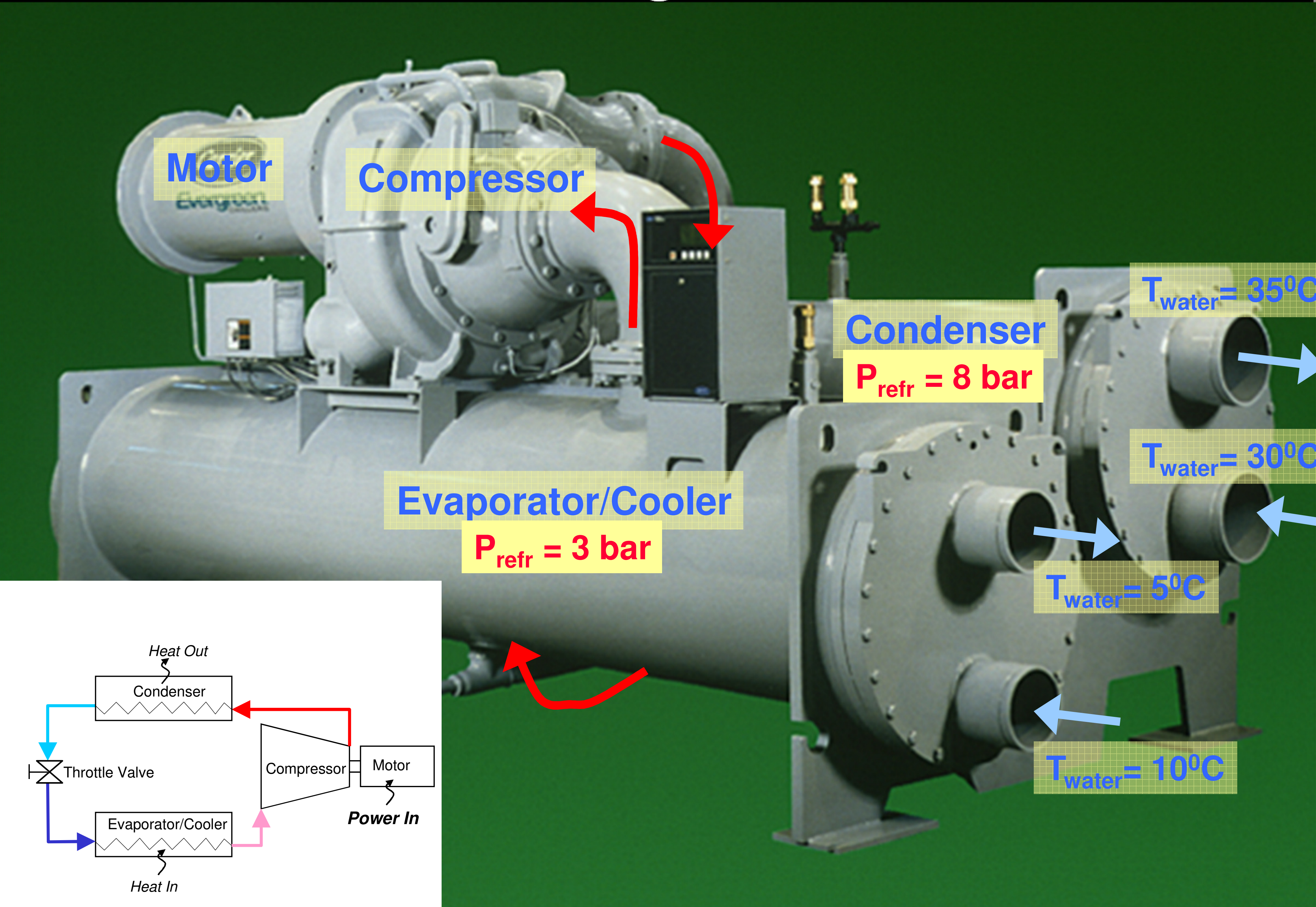


From centrifugal refrigeration machine to ORC

These "pipe diffusers" also act as perfect "nozzles". It was discovered more or less accidentally that this compressor was also an efficient turbine

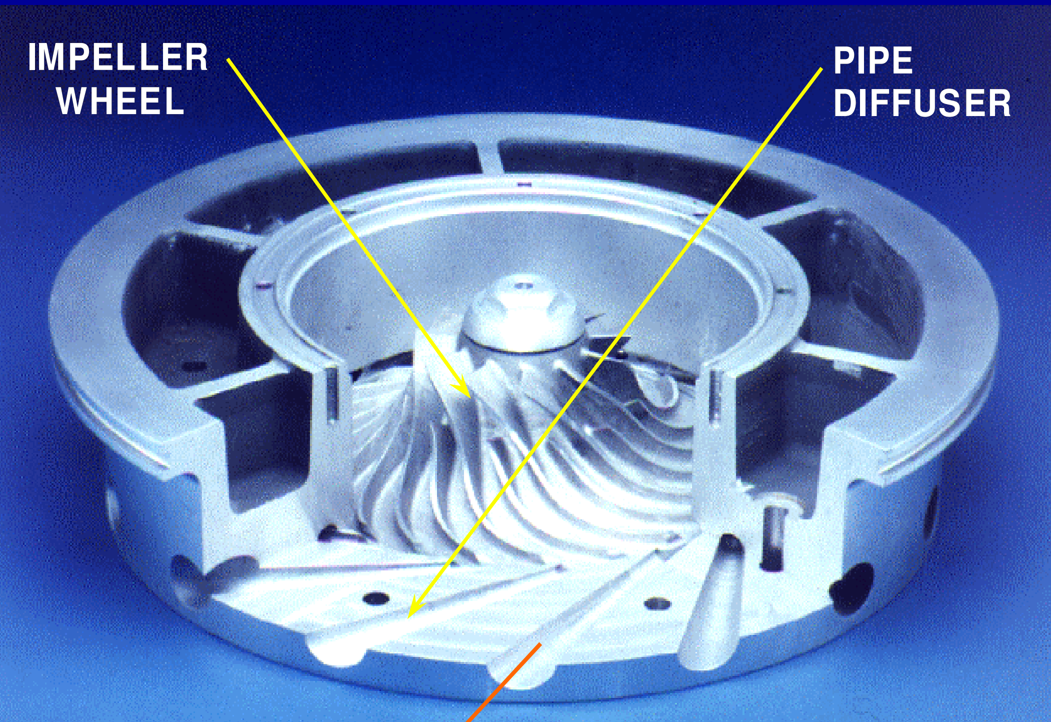


Centrifugal Chiller

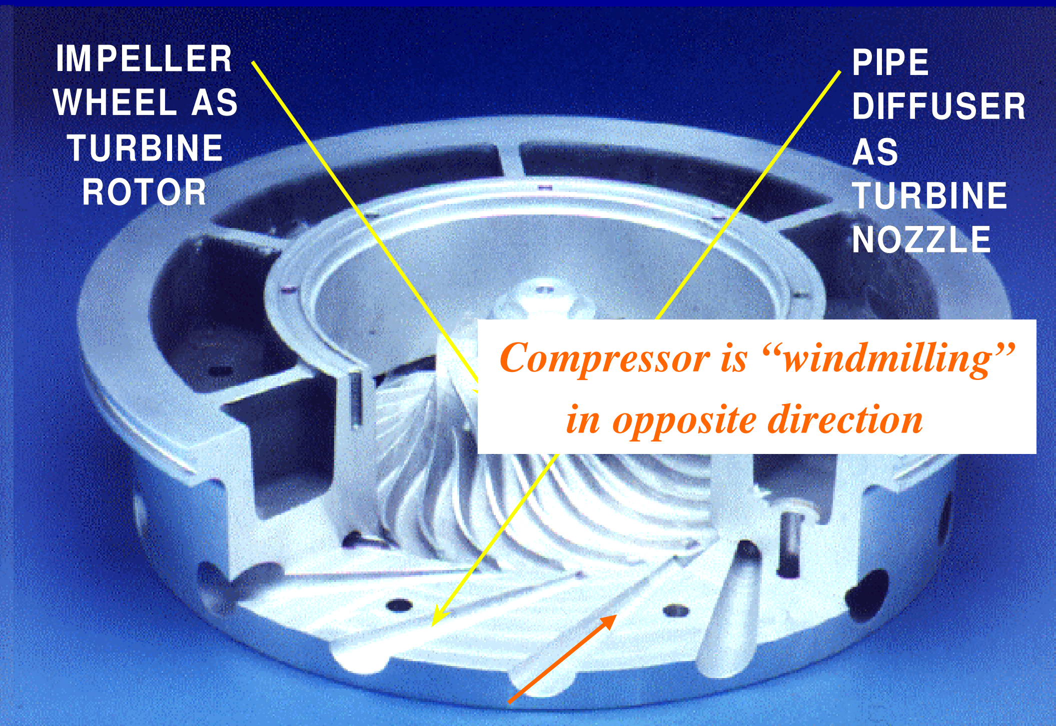


What happens during a sudden power failure?

Centrifugal compressors don't have a check valve.
Therefore , the flow through the compressor reverses because condenser pressure is higher than evaporator pressure



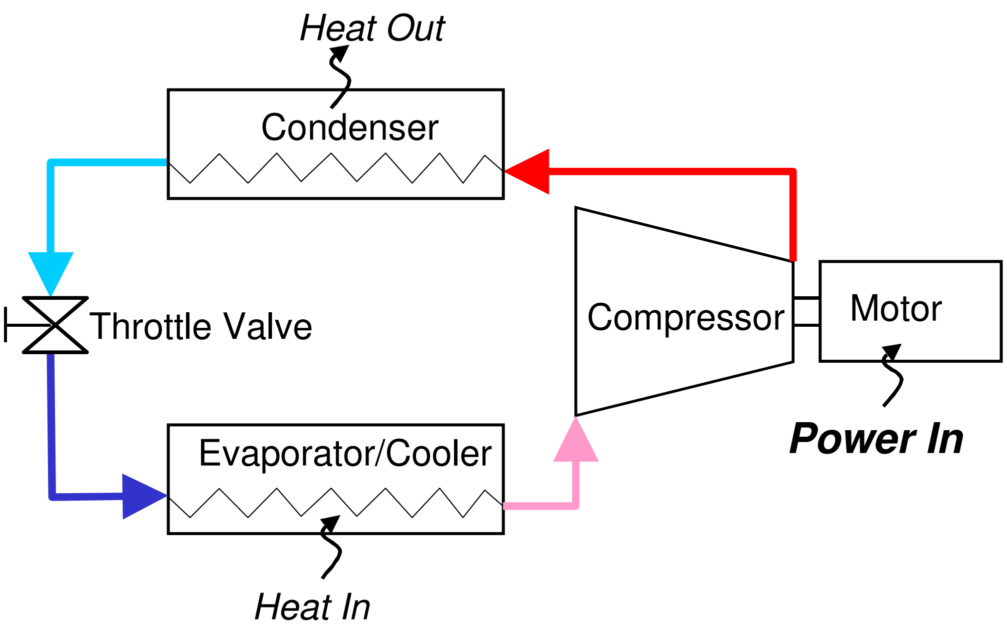
Compressor Operation:
Cut-away Of Impeller
(Spinning Clockwise)
and Pipe Diffuser
(Radial Outward Flow)

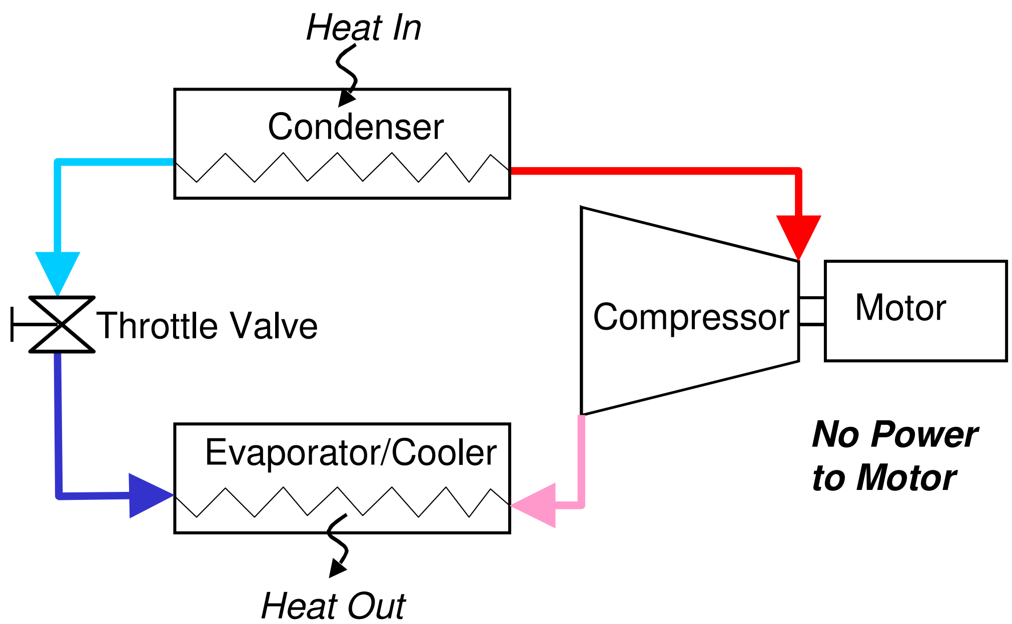


Turbine Operation:
Cut-away Of Impeller
(Spinning Counter-clockwise)
and Pipe Nozzle
(Radial Inward Flow)

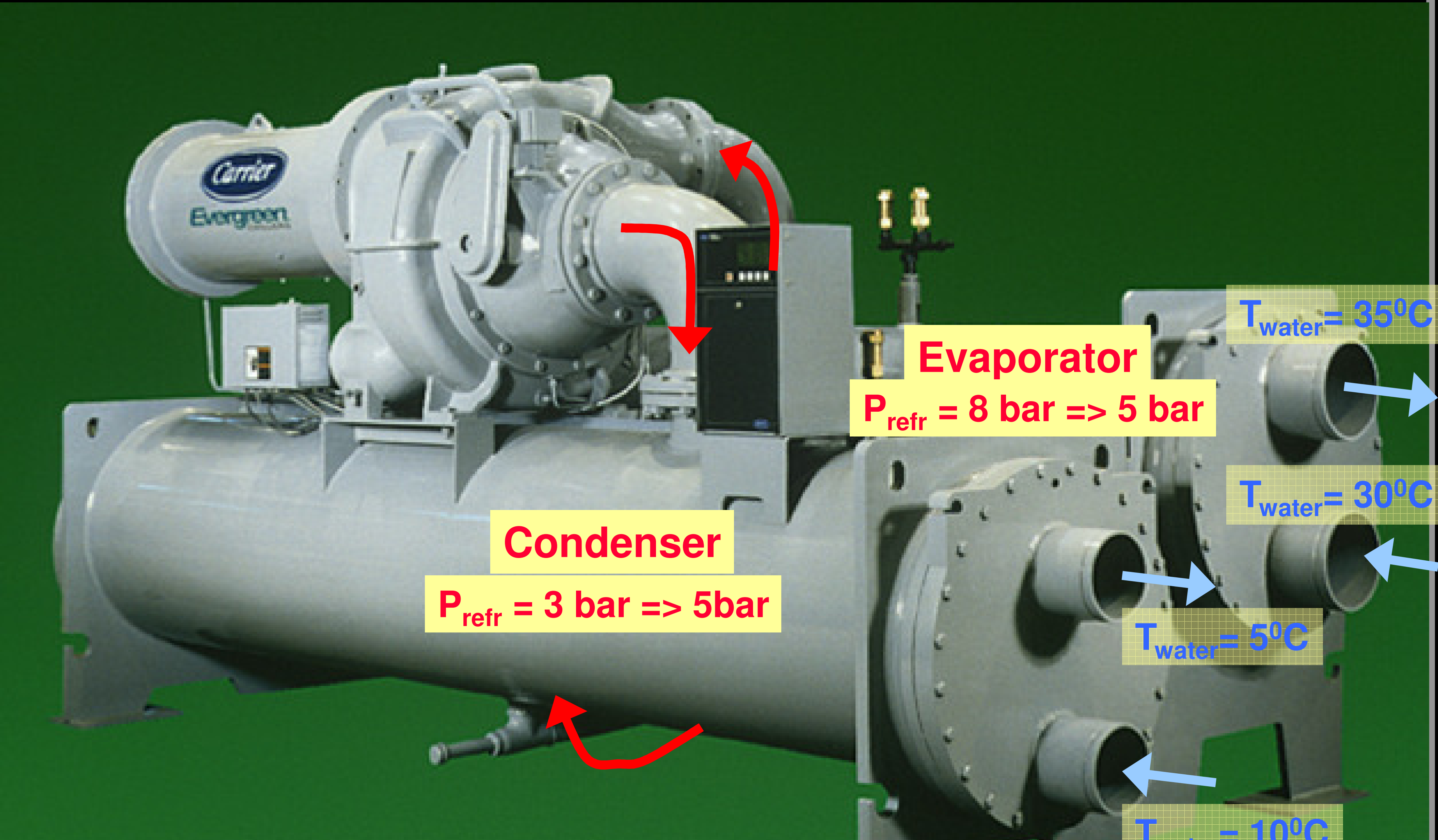
After power failure:

- **The liquid refrigerant in the condenser evaporates**
  - **incoming condenser water is being cooled**
- **The refrigerant vapor in the evaporator condenses**
  - **incoming chilled water is being heated**
- **The compressor rotates in reverse direction as a turbine**





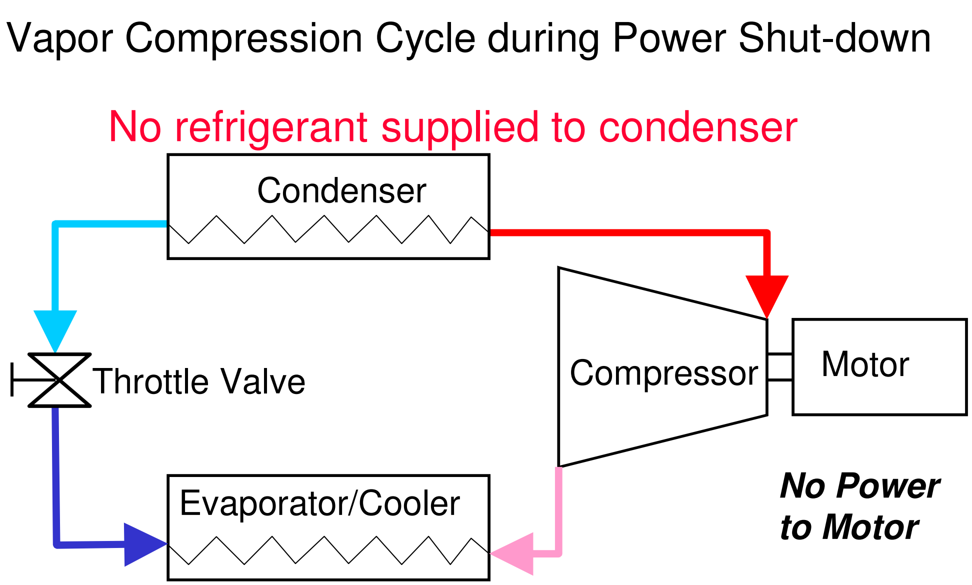
Compressor rotates temporarily at high speed in reverse direction

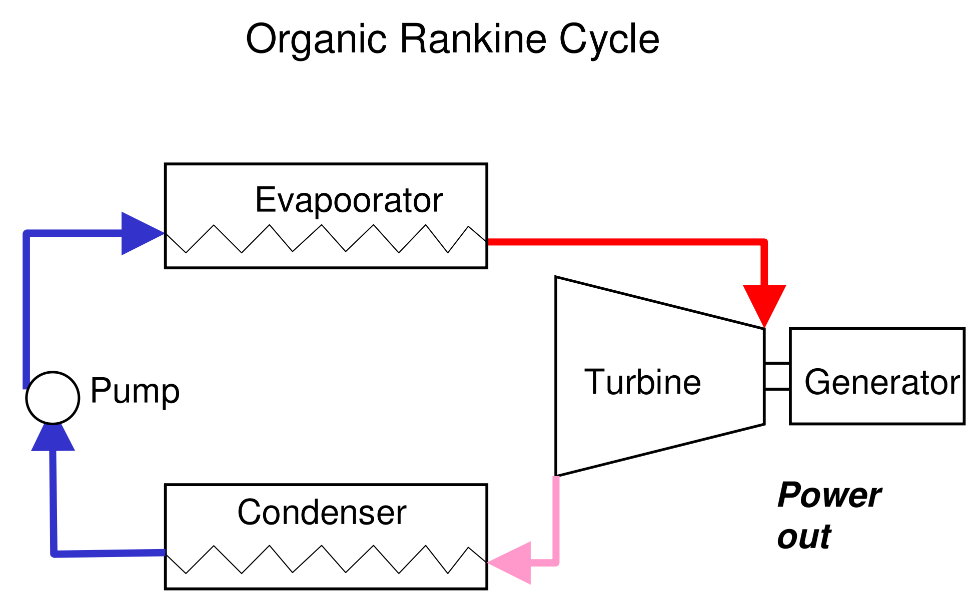


Pressure equalization occurs in about 20 seconds in an R-134a centrifugal chiller

In order to continue this reverse process refrigerant and heat have to be added continuously to the “condenser” and heat has to be removed from the “evaporator”, reversing their original roles.

Result: an ORC made from refrigeration equipment.



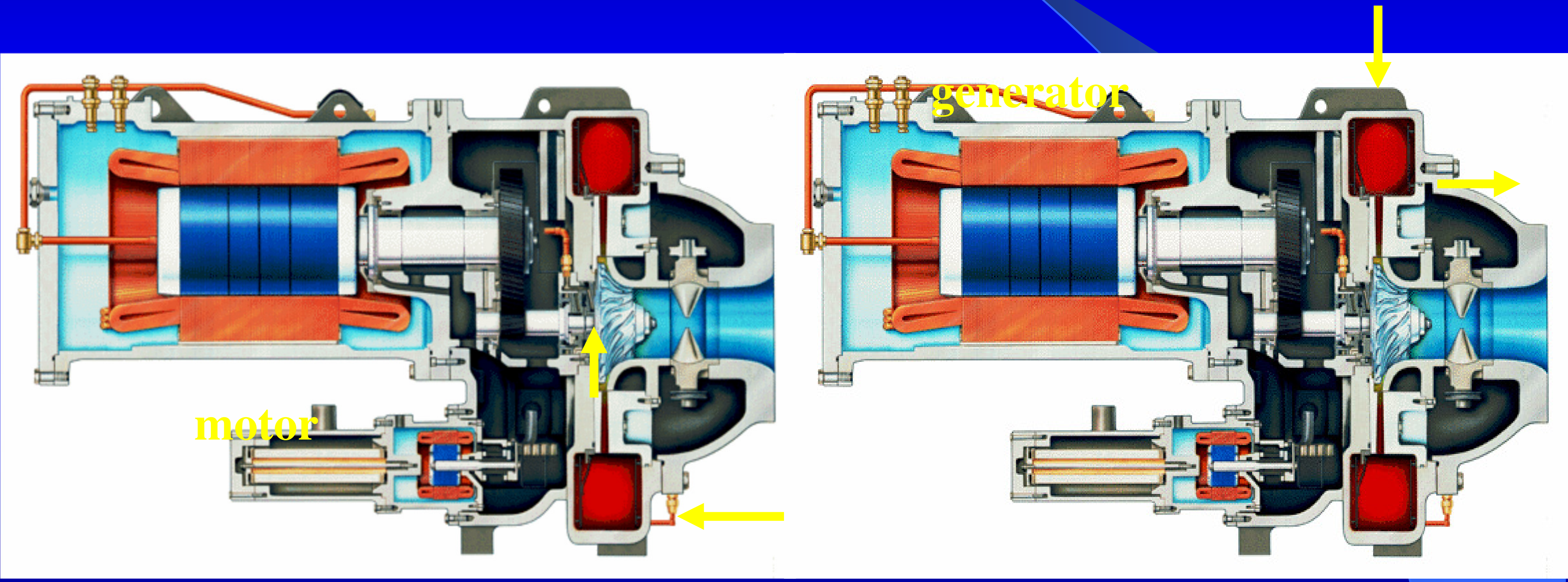


Warm-water heat source / Cold-water heat sink

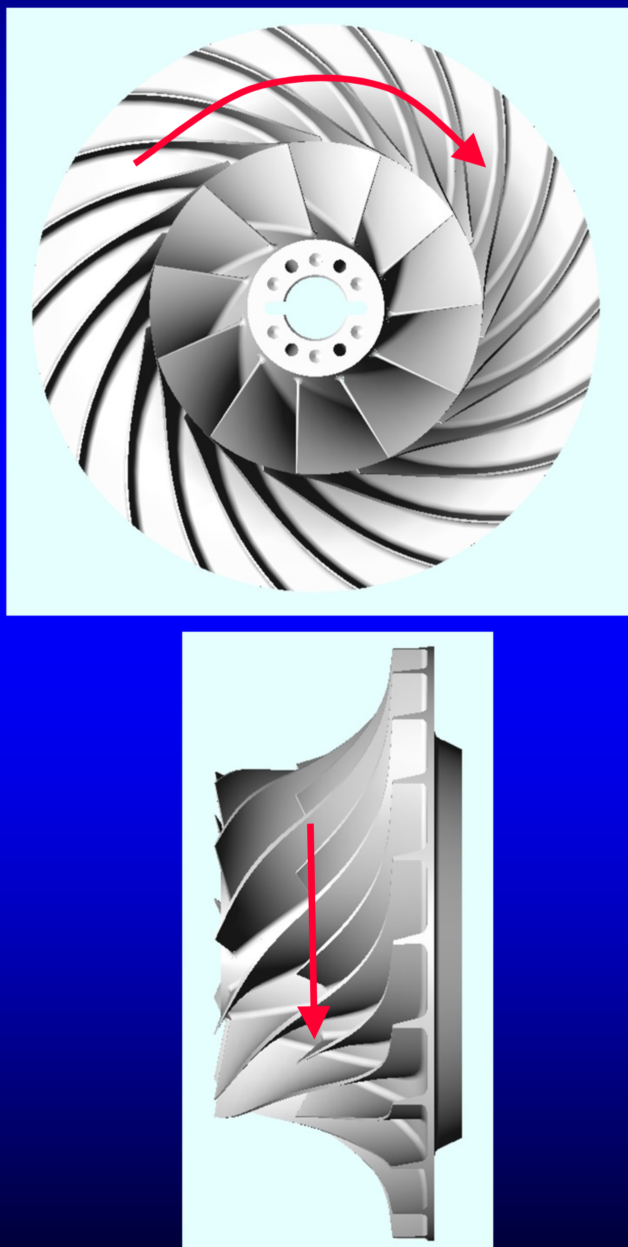
⇒ ORC looks like a centrifugal chiller on stilts

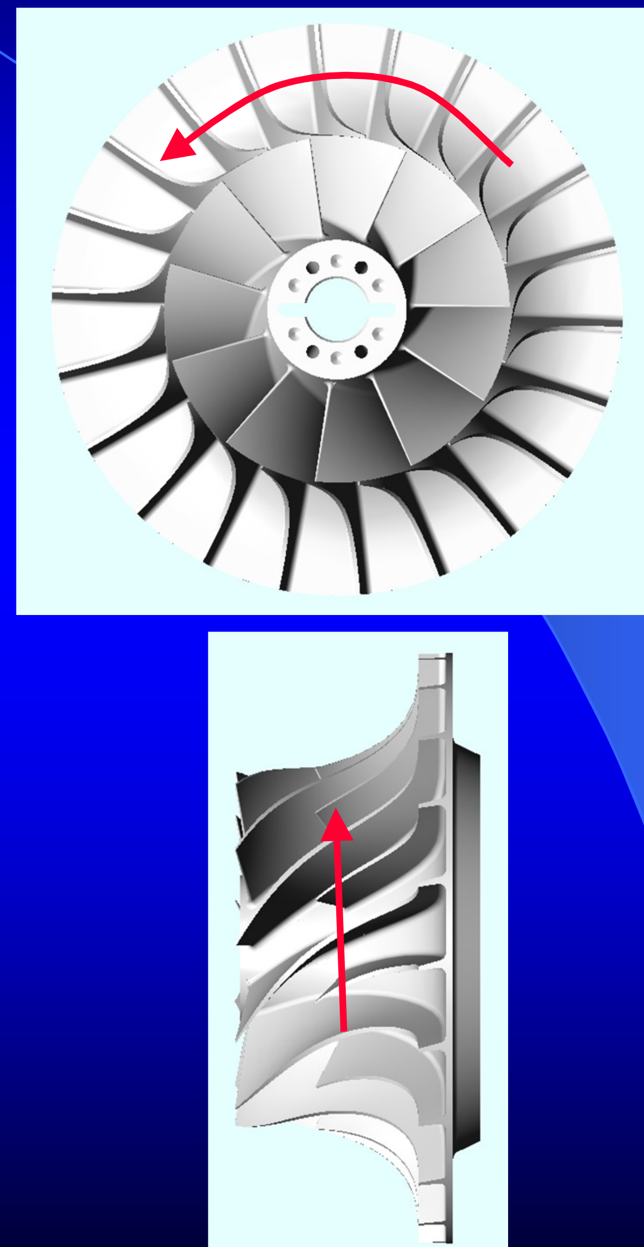
⇒ (The stilts were required to obtain the required NPSH for the pump)

Vapor Compressor versus Organic Rankine Cycle Turbine



Compressor Impeller versus ORC Turbine rotor





Low temperature / small capacity ORC system development based on HVAC equipment

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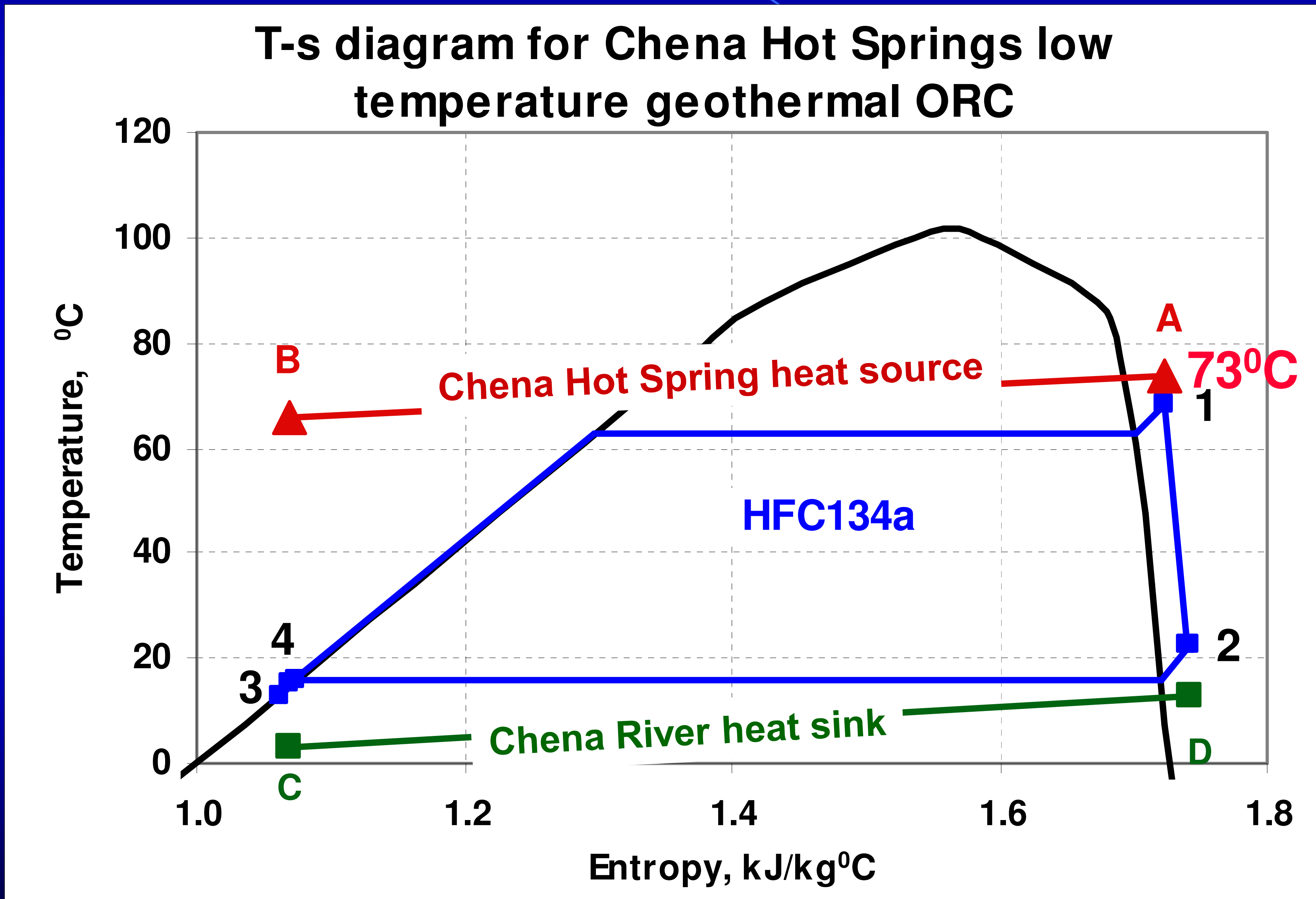
Electricity from warm water:

the water-cooled, warm-water driven ORC



The two 225kW ORC Units at Chena Hot Springs, AK

Electricity from 73 ^{0}C warm water

Warm water ORC in Chena Hot Springs, AK

Other reasons to visit the ORC at Chena Hot Springs, Fairbanks AK

CHENA
HOT SPRINGS
RESORT

Location for a future ORC conference?

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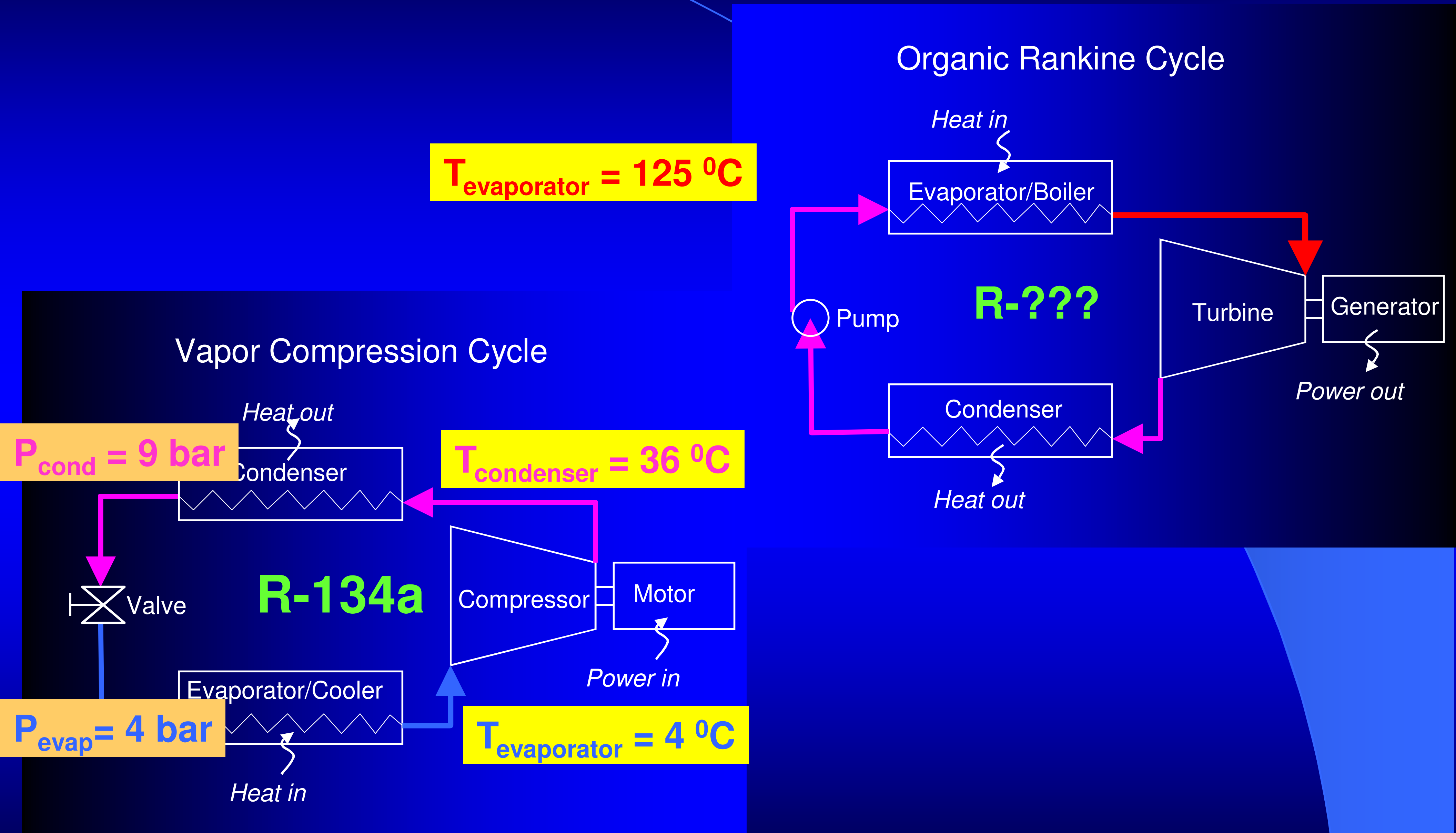
Vapor Compression Cycle versus Organic Rankine Cycle



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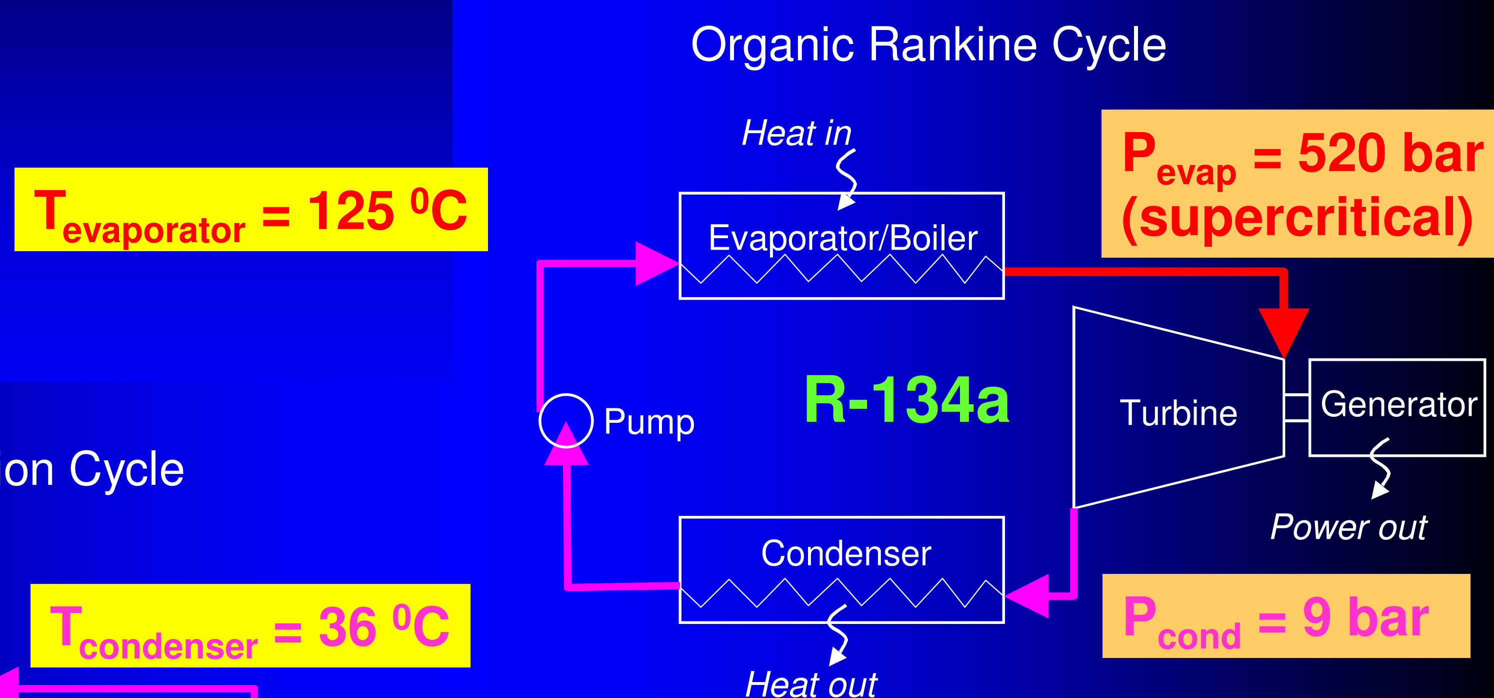
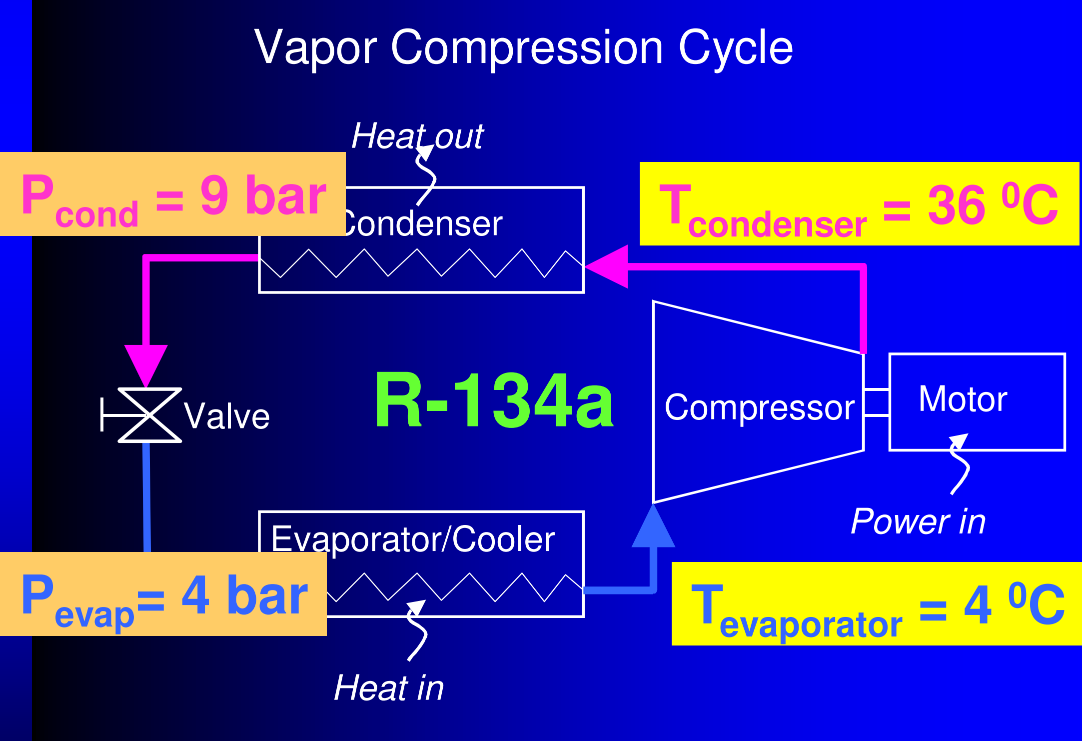


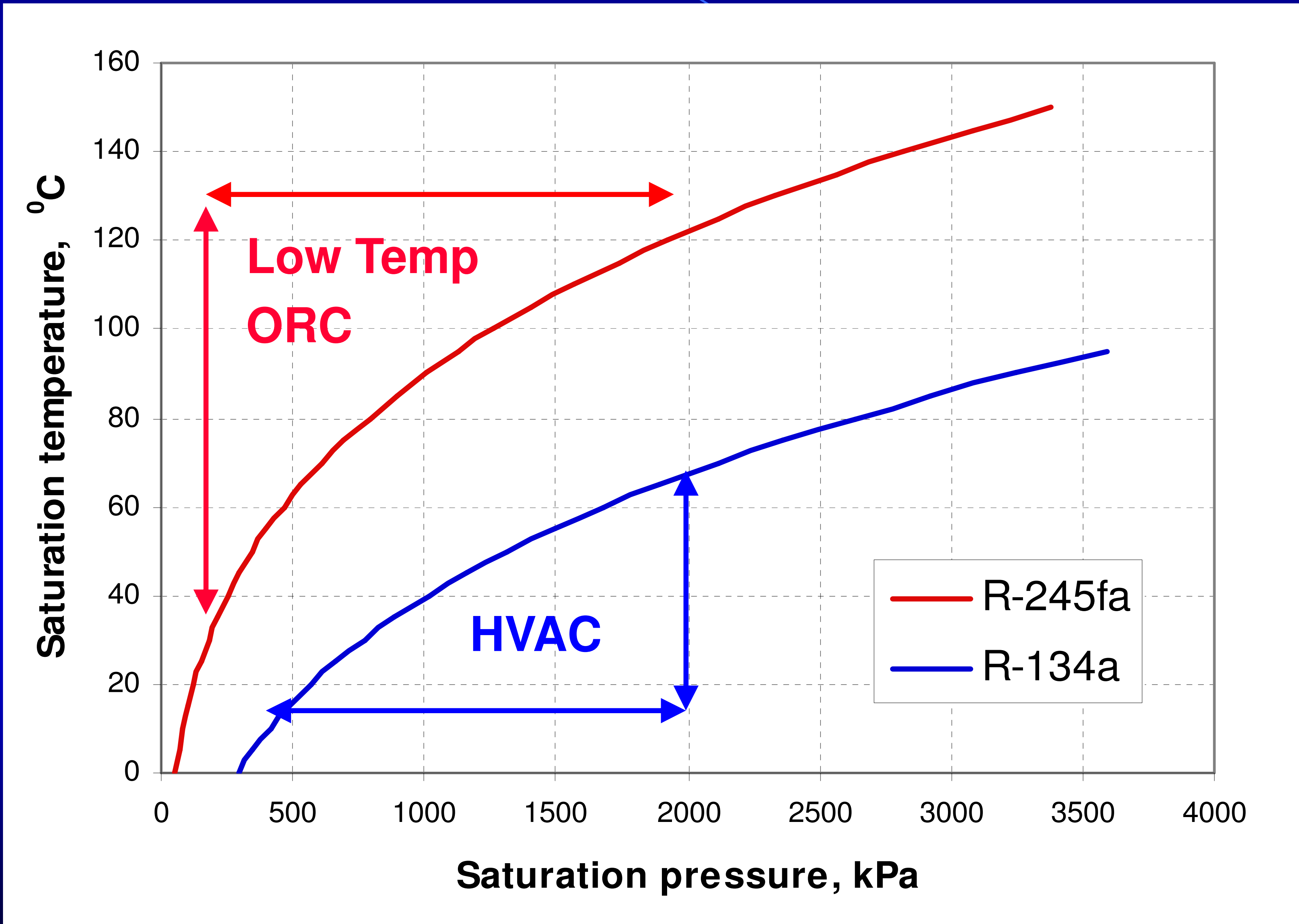


A new working fluid with lower pressure and a higher critical temperature is required

The known low pressure refrigerants are

- **CFC's (e.g. R11,R113,R114)**
- **HCFC's (e.g. R123)**
- **flammable/toxic (e.g. pentane or siloxane or toluene)**

R-245fa enables HVAC equipment operation at low temperature ORC conditions



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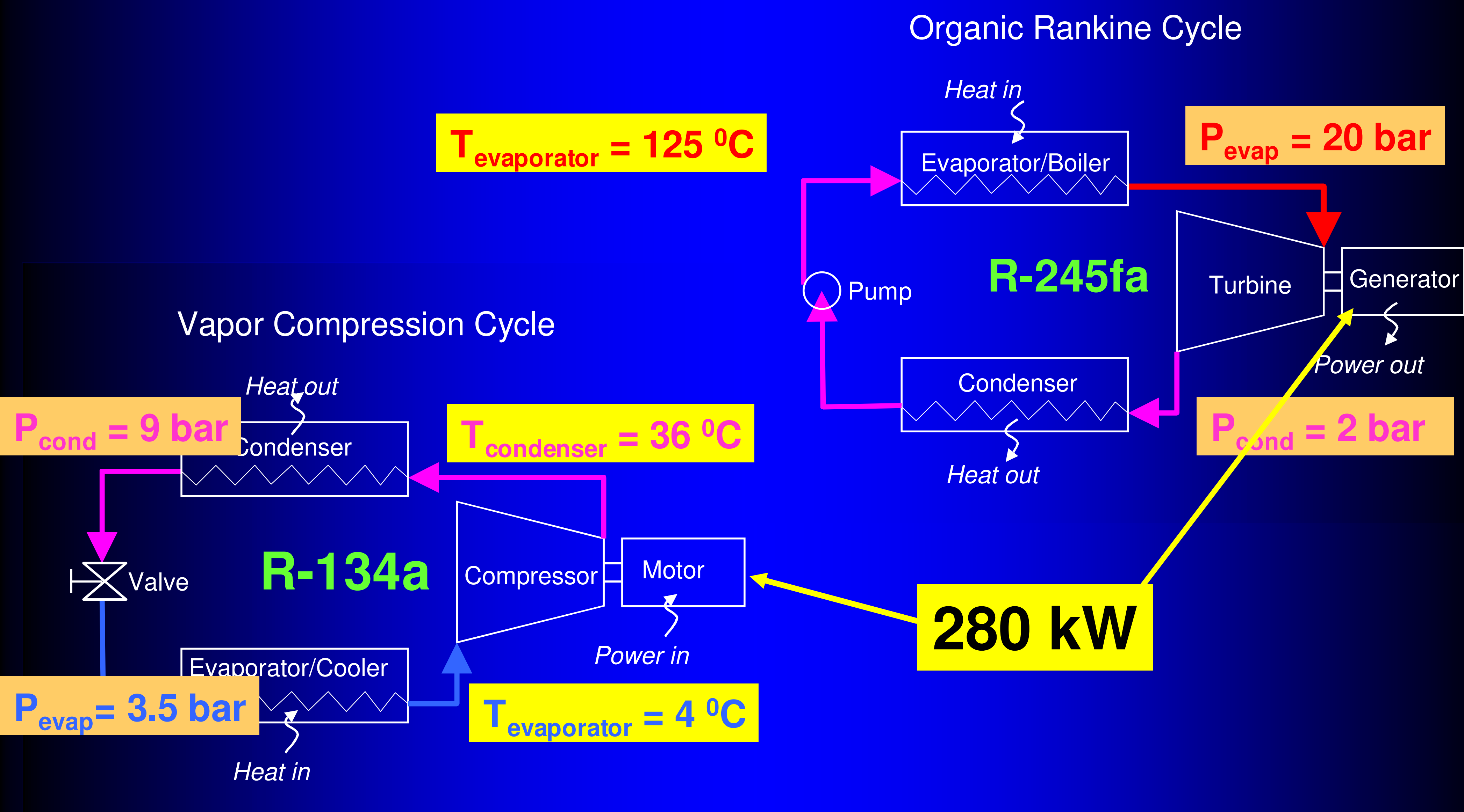
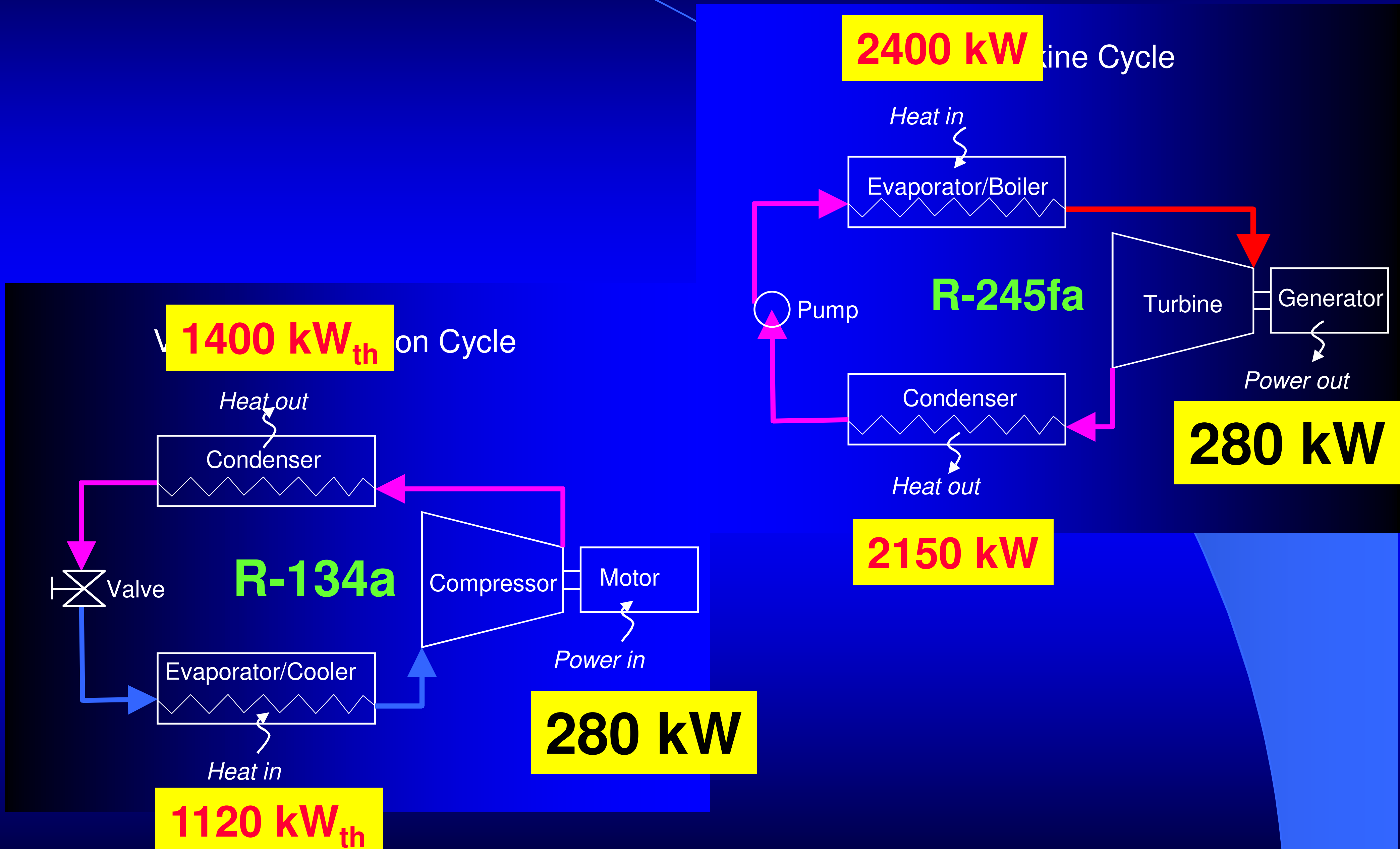


Heat exchanger size comparison for the same motor/generator power



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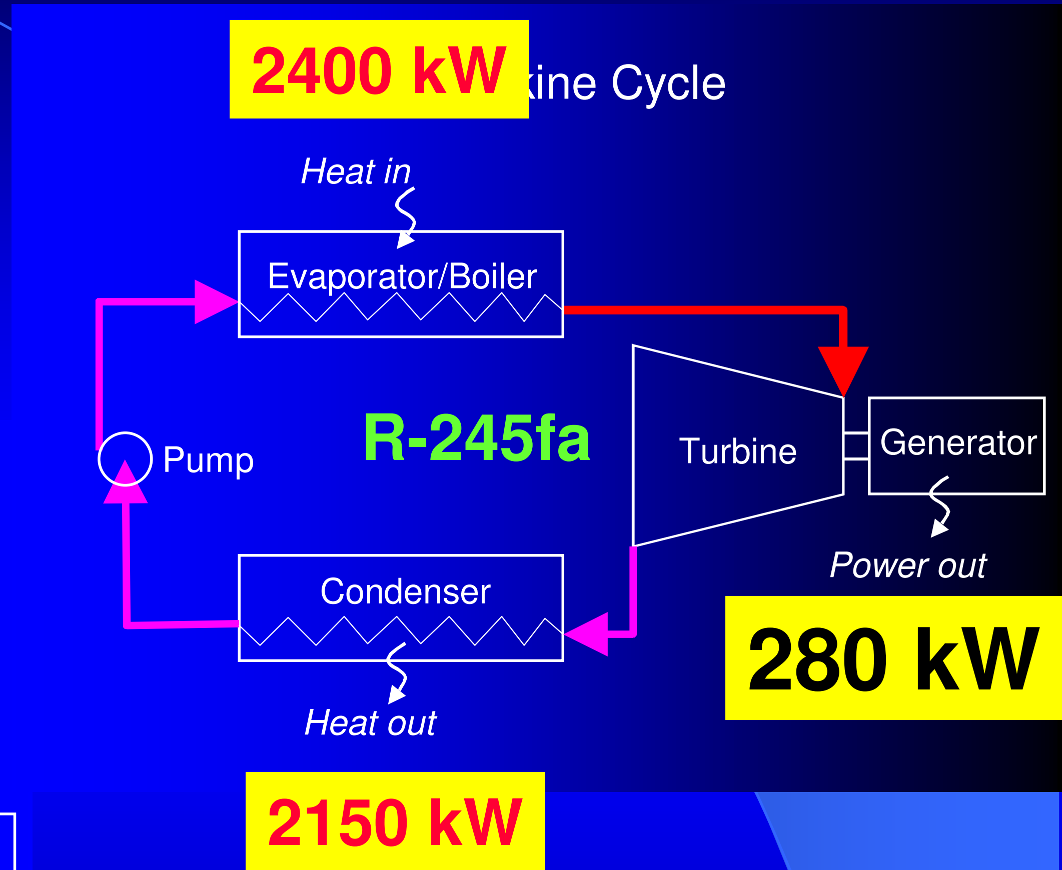

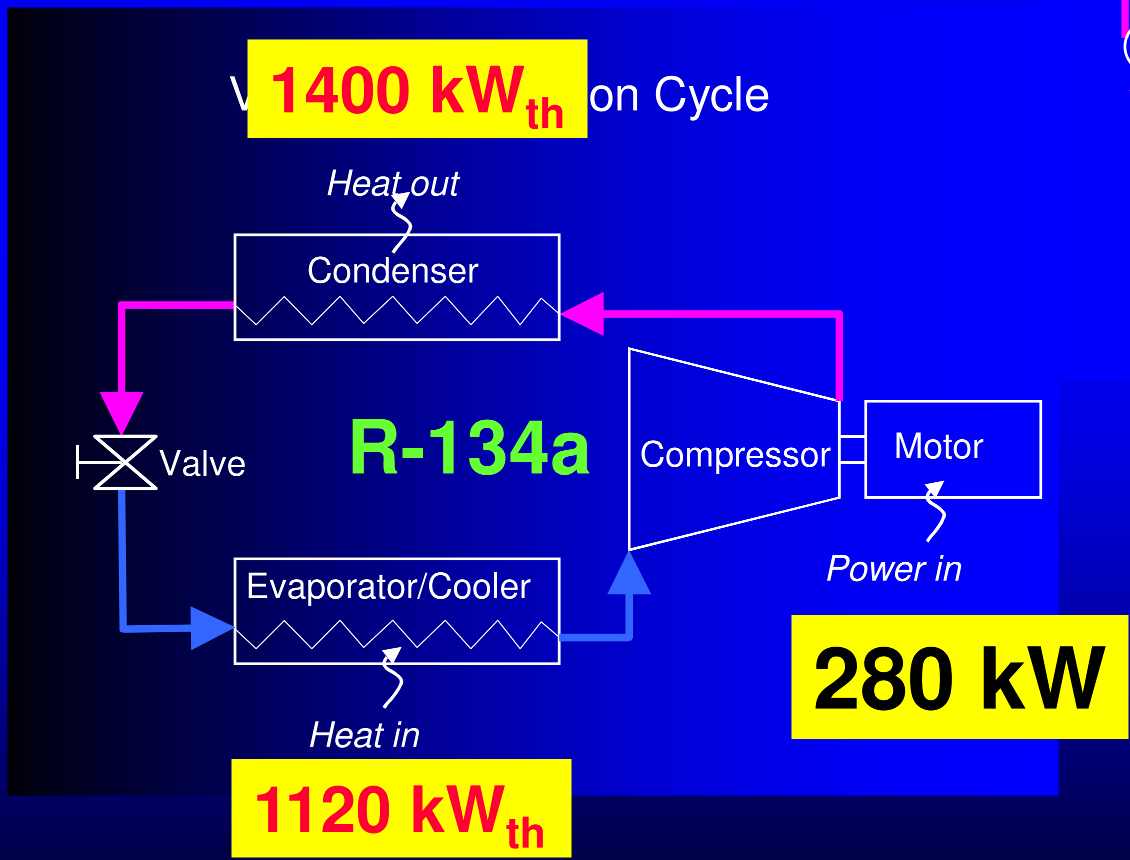

Heat Exchangers double in capacity relative to chillers using the same motor/generator size

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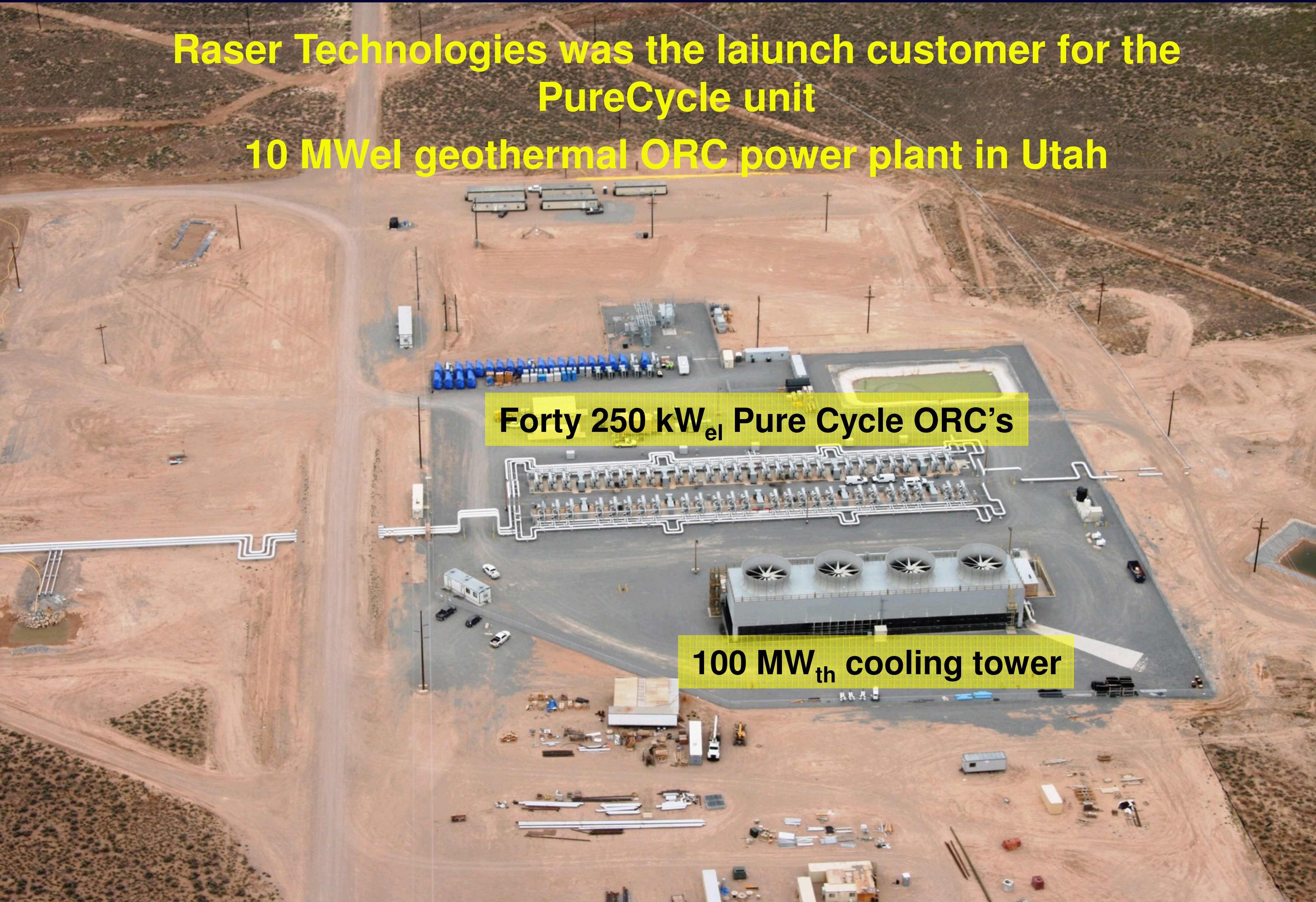
Transition from prototype to real product

Chena → Raser

PURECYCLE®

Raser Technologies was the laiunch customer for the PureCycle unit

10 MWel geothermal ORC power plant in Utah



Thermo-1, the 10 MWel geothermal ORC power plant in Utah


100 MW$_{th}$ cooling tower
Forty 250 kW$_{el}$ Pure Cycle ORC's

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Reduction in CO_2 emission from a 200 kW fuel-free ORC power plant

CO_2 emission of power generating equipment per area and the reduction in CO_2 emission by replacing 200 kW of generating equipment with a zero-emission ORC power plant

	$Emis_{gen}$ kg CO_2 / kWh	$E_{directORC}$ tons CO_2
US		
West	0.50	-12483
West-Central	0.67	-16727
East-Central	0.94	-23468
North-East	0.49	-12233
South-Central	0.74	-18475
South-East	0.62	-15479
Average	0.67	-16727
Europe		
Germany	0.64	-15978
Holland	0.61	-15229
France	0.13	-3246
Sweden	0.04	-999
Average	0.41	-10236

To put it in perspective: number of times we could loose the charge before adding to global warming

Number of times a complete loss of charge can occur during the 15-year ORC power plant life before adding to global warming

	HFC245fa	*HFC236fa*	*HFC134a*
US			
West	52	4	32
West-Central	70	6	43
East-Central	98	9	61
North-East	51	4	31
South-Central	77	7	48
South-East	65	6	40
Average	70	6	43
Europe			
Germany	67	6	41
Holland	64	5	39
France	13	1	8
Sweden	4	0	2
Average	43	3	26

Carbon footprint of ORC's with HFC's can be reduced

- Some of the recently developed low-GWP refrigerants for the HVAC industry, e.g.:
  - HFO-1234yf
  - HFO-1234ze
  - C6FK
  - C7FK
  - DR11
  - DR2

could become attractive ORC working fluids

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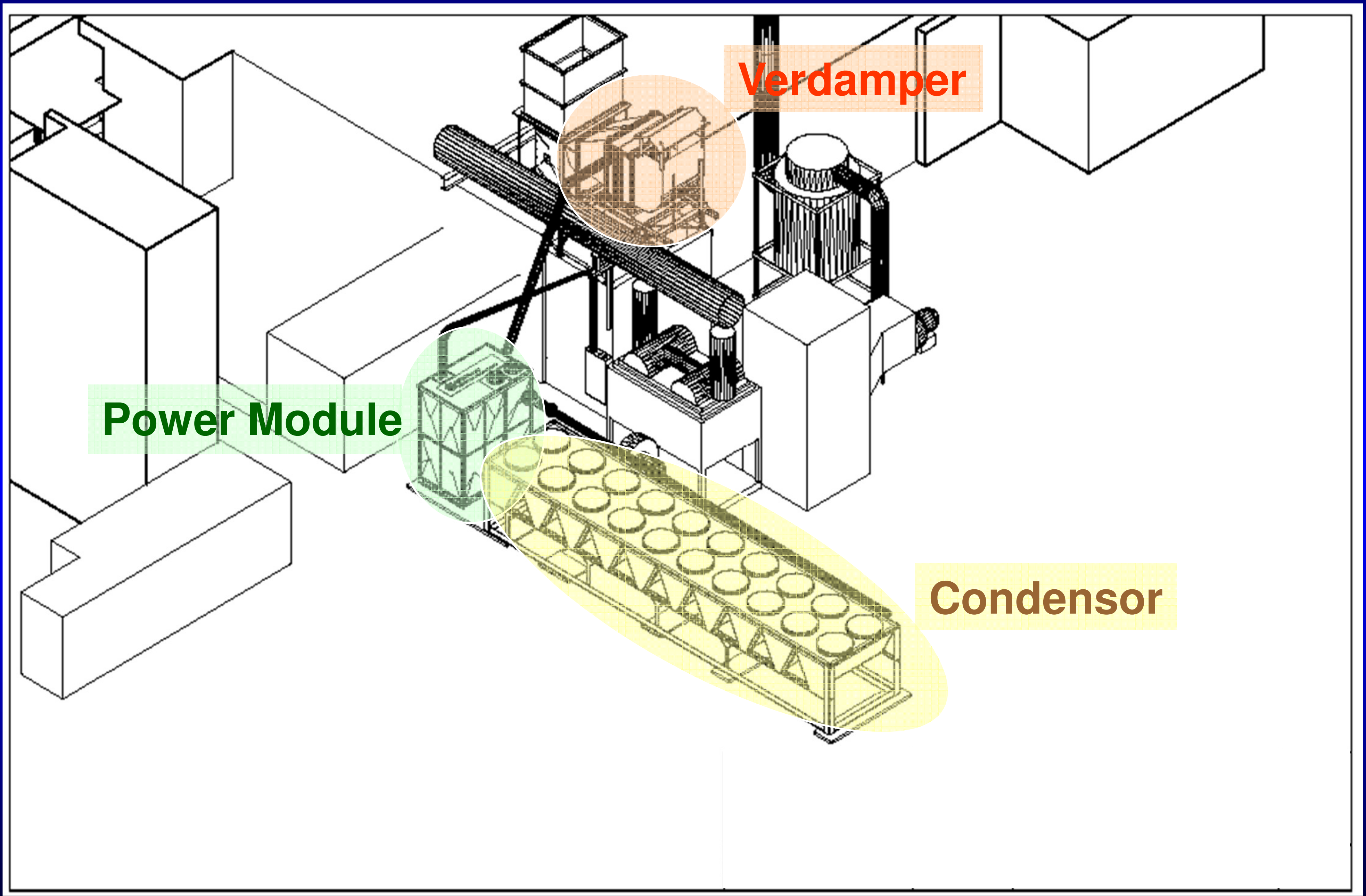
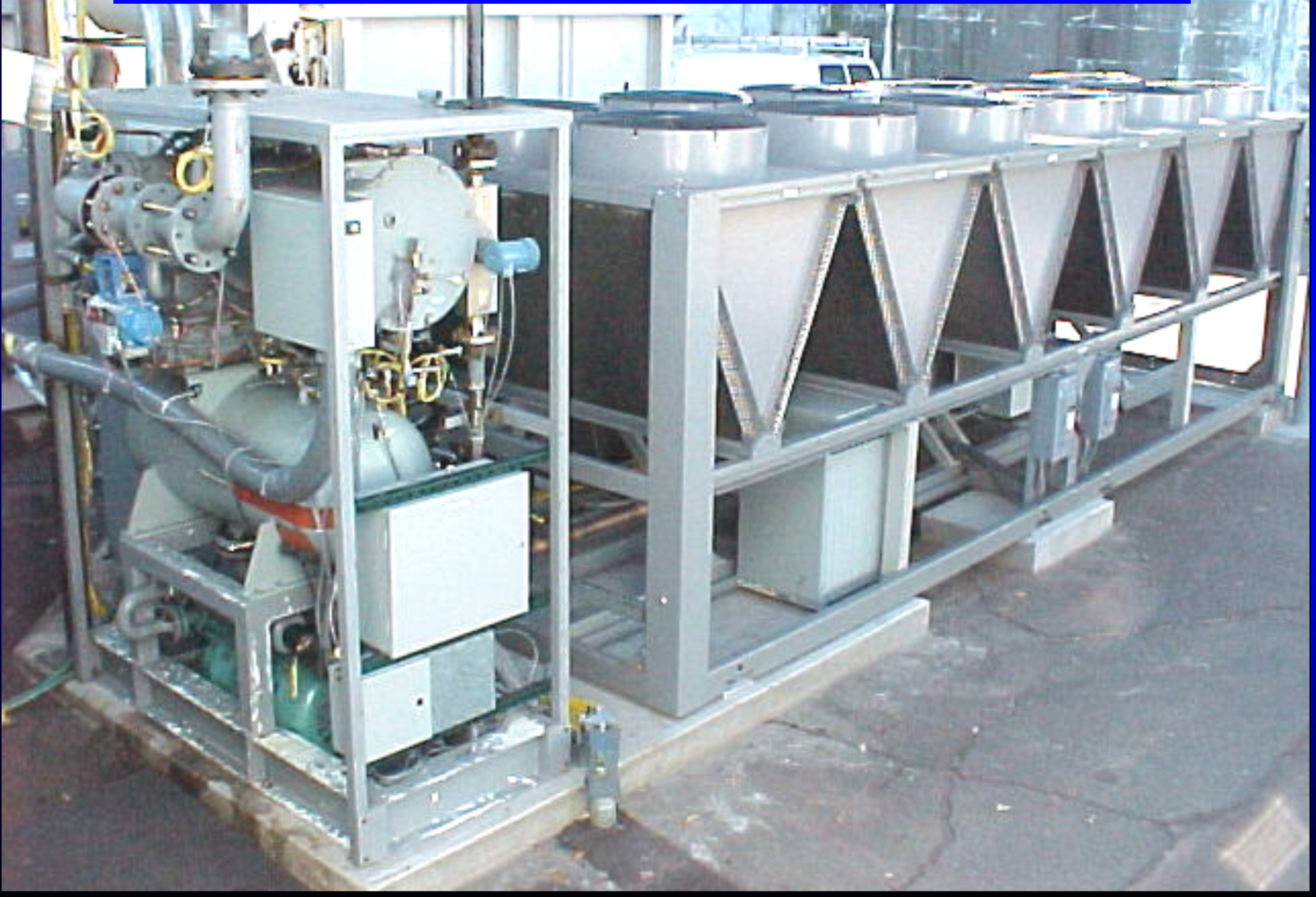
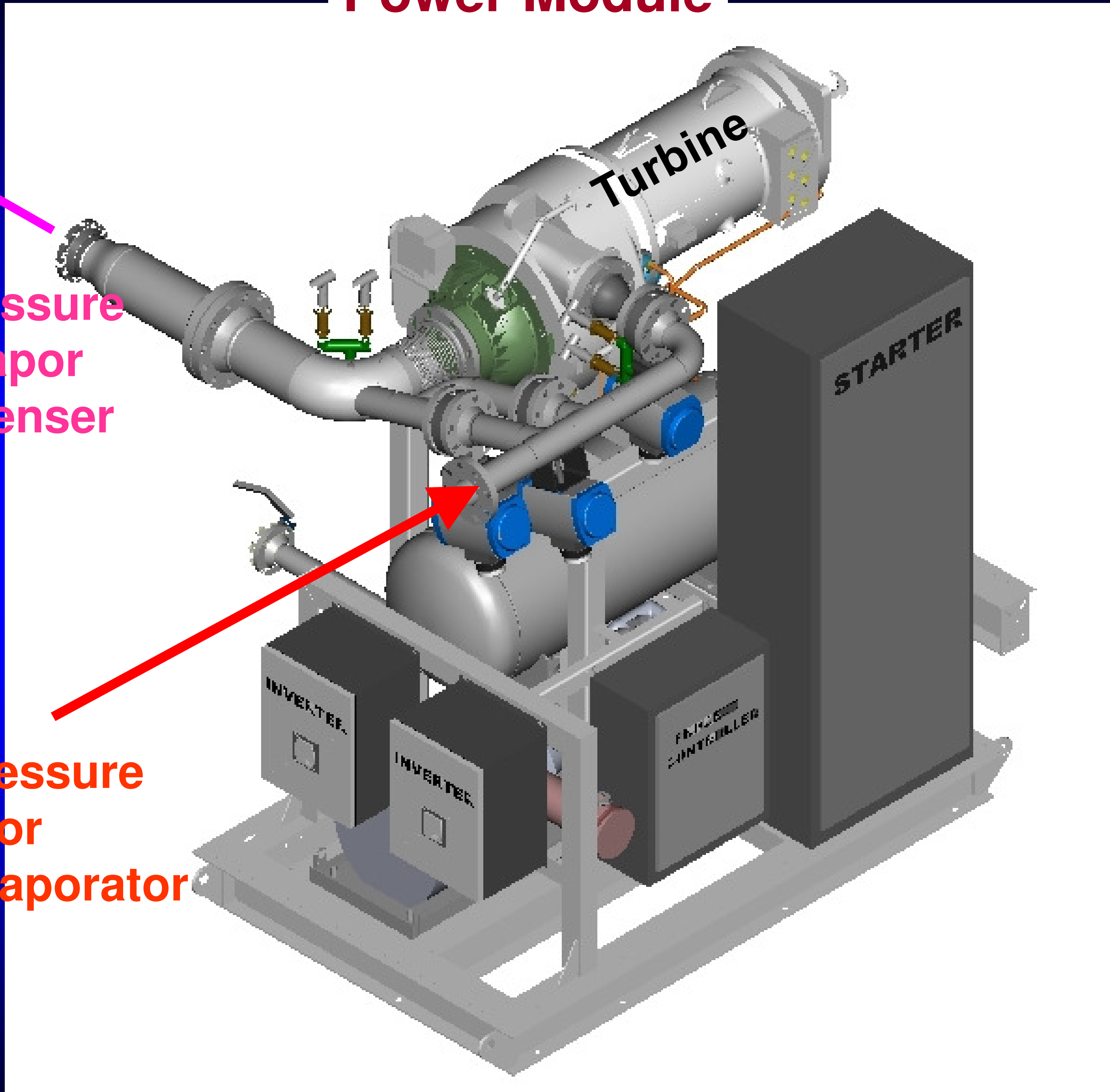
Split System Design with Remote Evaporator



100 kWel ORC development unit in Hartford, CT powered by gas turbine exhaust waste heat



Power Module



Low pressure warm vapor to condenser

High pressure hot vapor from evaporator

Demo Installations

Electrical power from waste heat with 200 kWel ORC units with air-cooled condenser and hot gas driven evaporator

Landfill Flare

Austin Energy (Austin, TX)

Landfill Recip Exhaust

US Energy (Danville, IL)

Gas Turbine

UTRC (Hartford, CT)

Being replaced by engines

250 kW ORC too large

250 kW ORC too small

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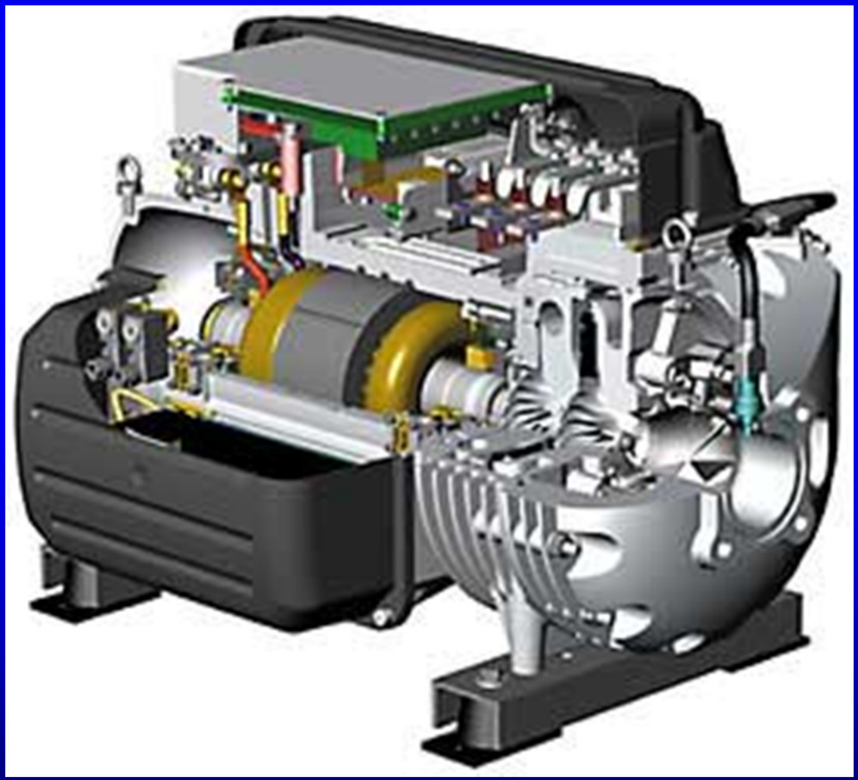
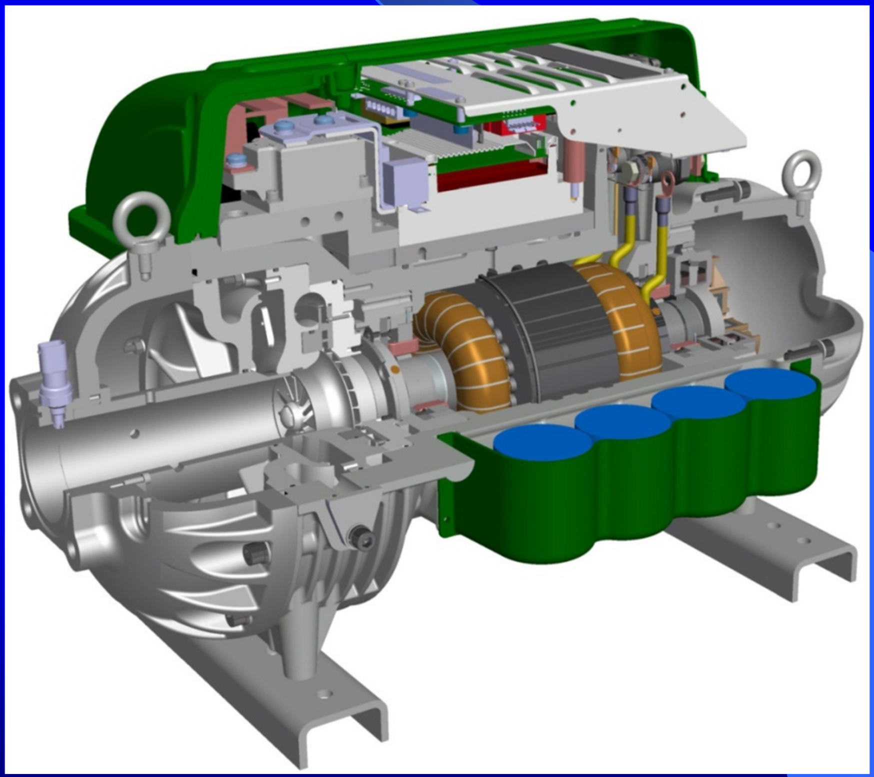
One 250 kW ORC demo needs exhaust heat from three Jenbacher engines

A 75 kW ORC matches an individual recip engine

Turbocor compressor



Verdicorp ORC



Two-stage centrifugal compressor => Single stage radial inflow turbine

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SUMMARY AND CONCLUSIONS

- The number of potential low temperature ORC applications seems endless and the interest is in the technology is overwhelming
- Low temperature ORC turbines/expanders - down to 50 kWel - are now commercially available
- Smaller capacity ORC systems with scroll expanders are emerging
- The biggest challenge faced by the ORC industry in general and by the low temperature small capacity ORC's in particular is cost (not efficiency).
- Taking advantage of the synergy between HVAC compressors/heat exchangers and ORC turbines/heat exchangers is the key to the development of cost effective low temperature ORC's