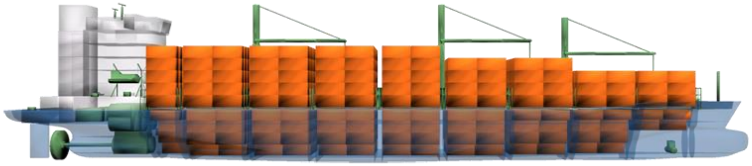
Cooling a waste heat recovery system: A study of hybrid cooling for a container ship navigating in the Arctic



Santiago Suárez de la Fuente, Ulrik Larsen, Rachel Pawling, Iván García Kerdan and Alistair Greig

15th September 2017

Contents

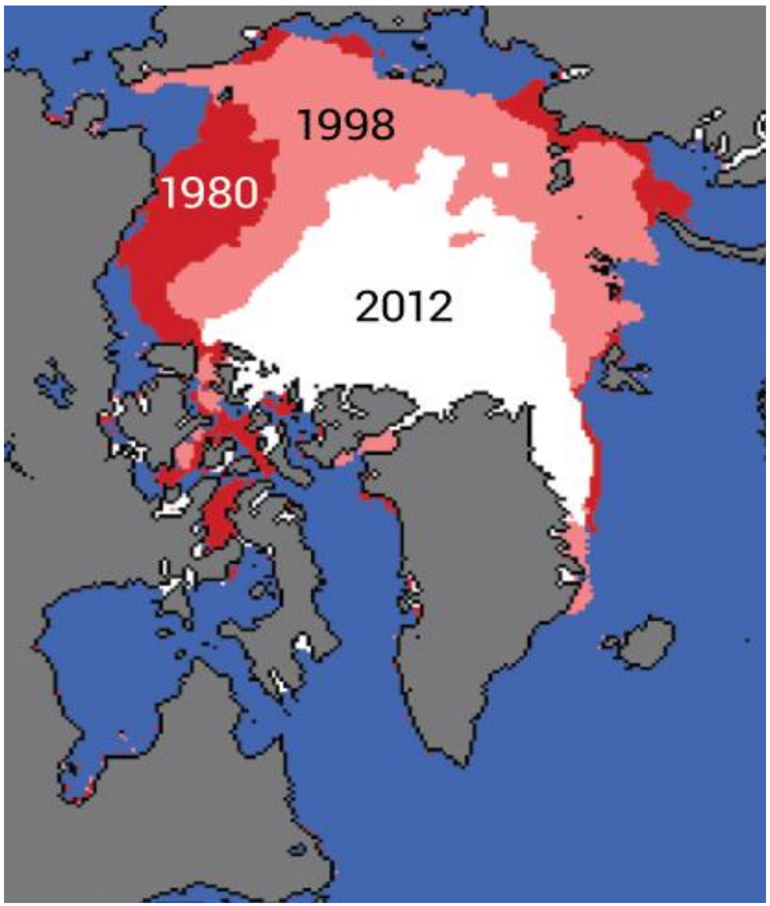
- Arctic and Waste Heat Recovery System an opportunity for shipping
- Objective
- Case Study
- Method
- Results
- Conclusions
- References

http://worldmaritimenews.com/archives/96297/danish-russian-cooperation-on-arctic-shipping/

Arctic Ice

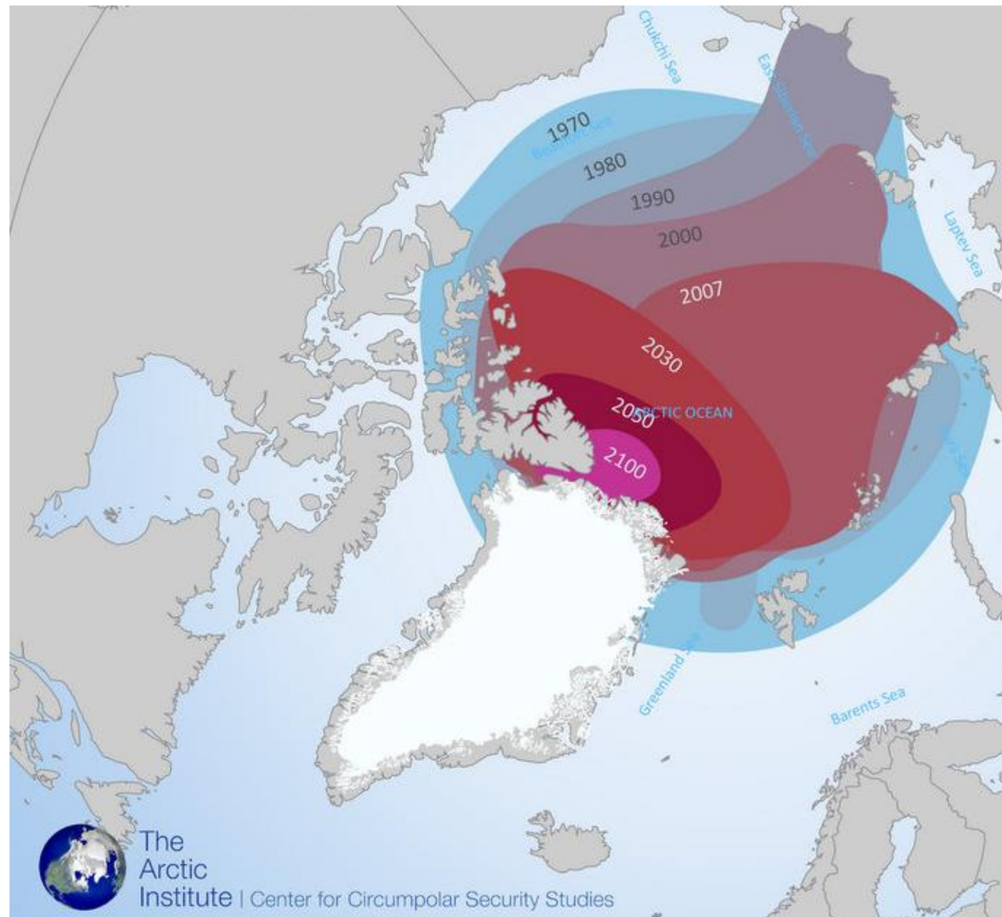
Arctic ice is reducing, we know that, but how does it looks?

Past (Summer)

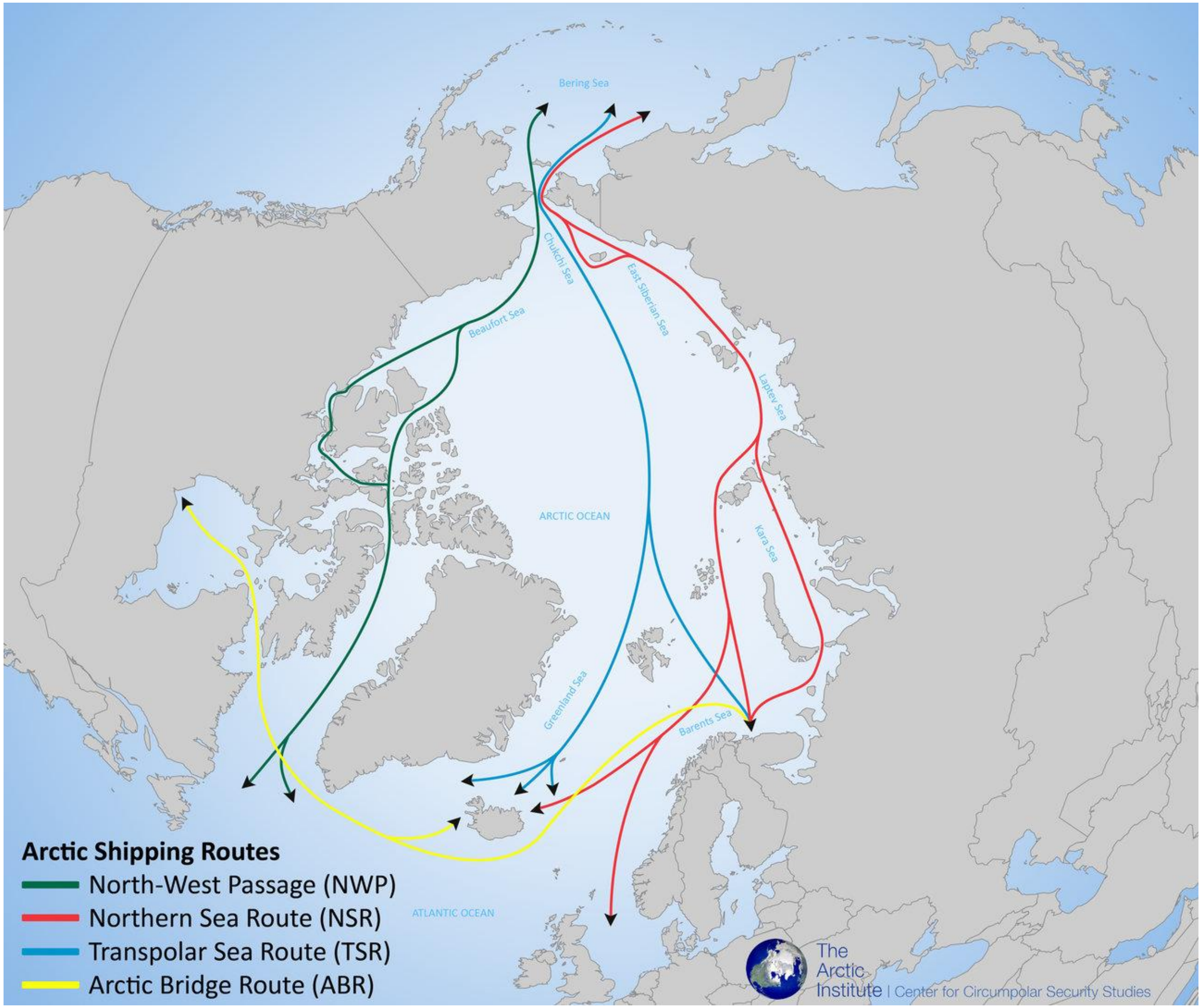


[1]

Future (Summer)



The Arctic as a Route

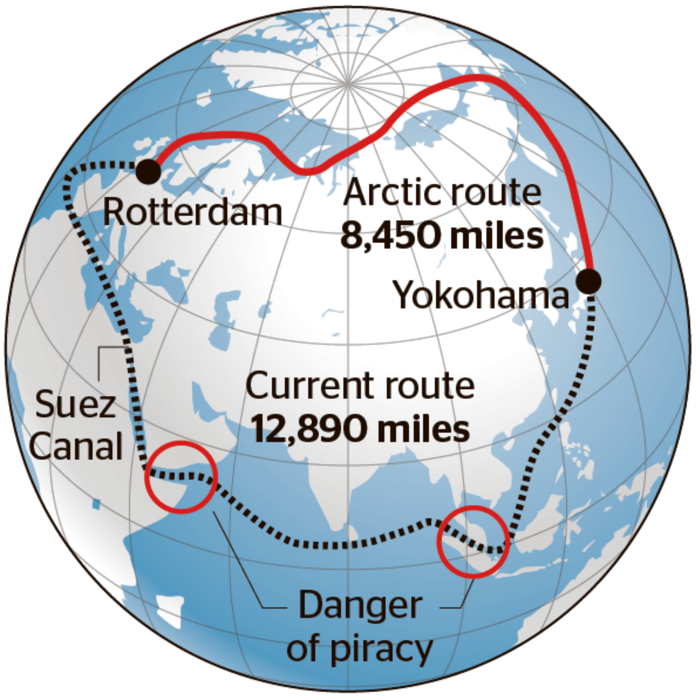


The Arctic as a Route

Pro

- Faster and cheaper shipping → At least a distance reduction of 22%, less global emissions
- Avoid slow and expensive canals → e.g. Suez and Panama (Average $180k per pass [1])
- Avoid piracy areas

Northwest passage



Northern sea route

[2]

The Arctic as a Route

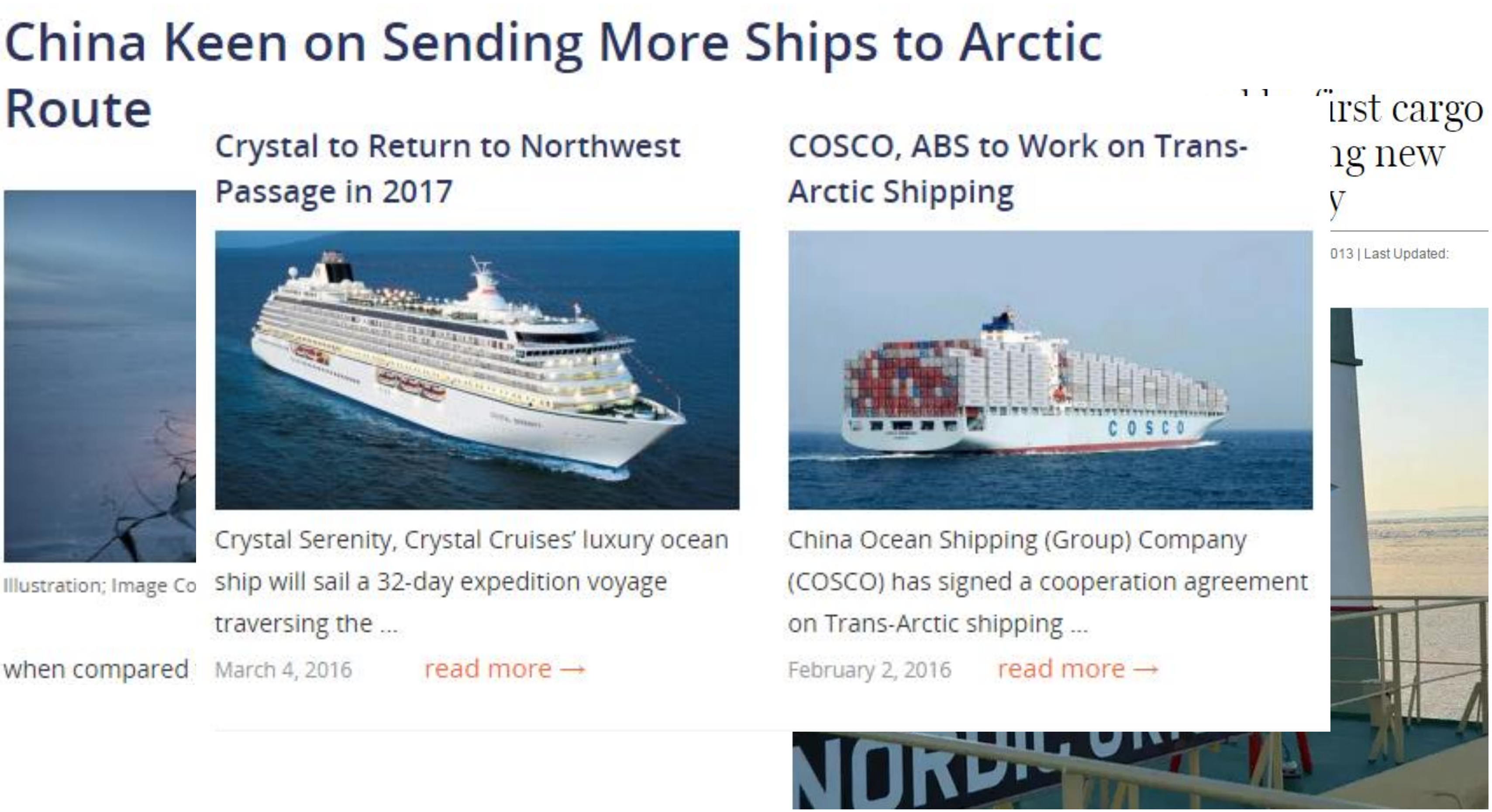
Con

- Seasonal route → Only available in summer/autumn months
- Sensible area to emissions → CO_2, NO_x, SO_x, soot, etc.
- Threat to wild life → noise, spills, etc.

[3]

The Arctic as a Route

Like it or not is already happening and quite quick!



China Keen on Sending More Ships to Arctic Route

Illustration; Image Co

when compared

Crystal to Return to Northwest Passage in 2017

Crystal Serenity, Crystal Cruises' luxury ocean ship will sail a 32-day expedition voyage traversing the ...

March 4, 2016 read more →

COSCO, ABS to Work on Trans-Arctic Shipping

China Ocean Shipping (Group) Company (COSCO) has signed a cooperation agreement on Trans-Arctic shipping ...

February 2, 2016 read more →

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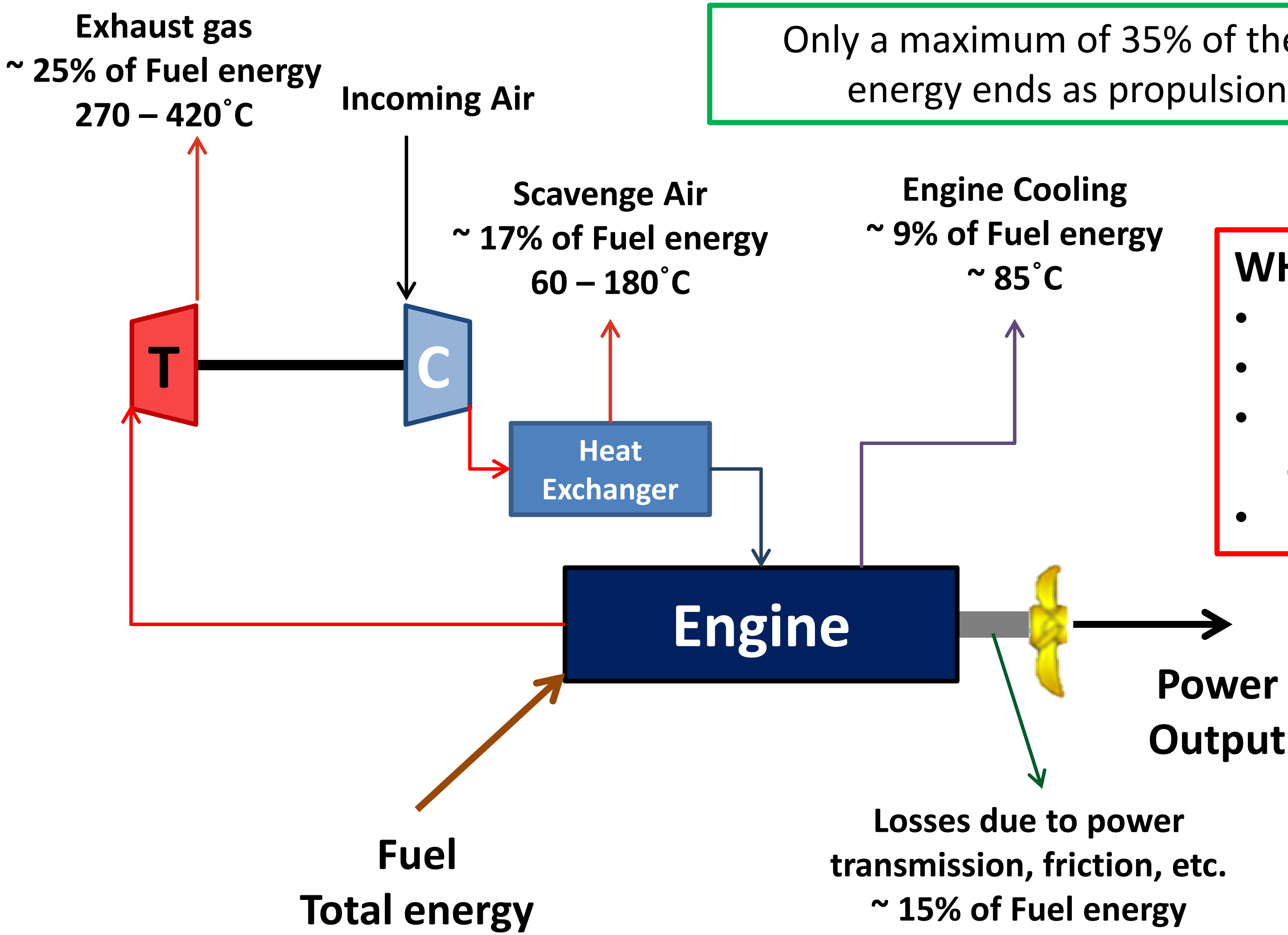
013 | Last Updated:

Waste Heat Recovery Systems

Only a maximum of 35% of the combustion energy ends as propulsion power [4]



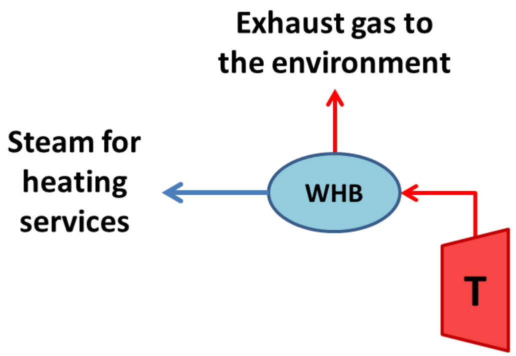
WHRS Benefits

- Fuel Savings
- Higher Efficiency
- Regulation compliance
- Lower emissions

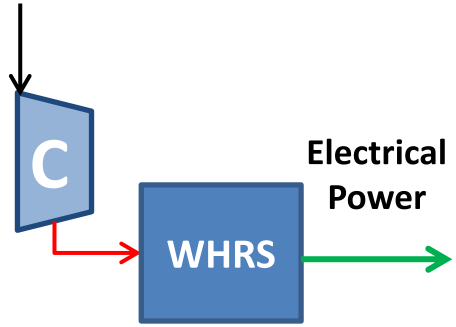
T - Turbocharger
C - Compressor

Another Consideration

Due to the low ambient temperature in the Arctic, the exhaust gas waste heat is normally used as the heating provider on-board



So the next best thing available to produce electrical power is the scavenge air waste heat



But also, lower temperatures mean better efficiency (Carnot Theorem):

$$\eta = 1 - \frac{T_L}{T_H}$$

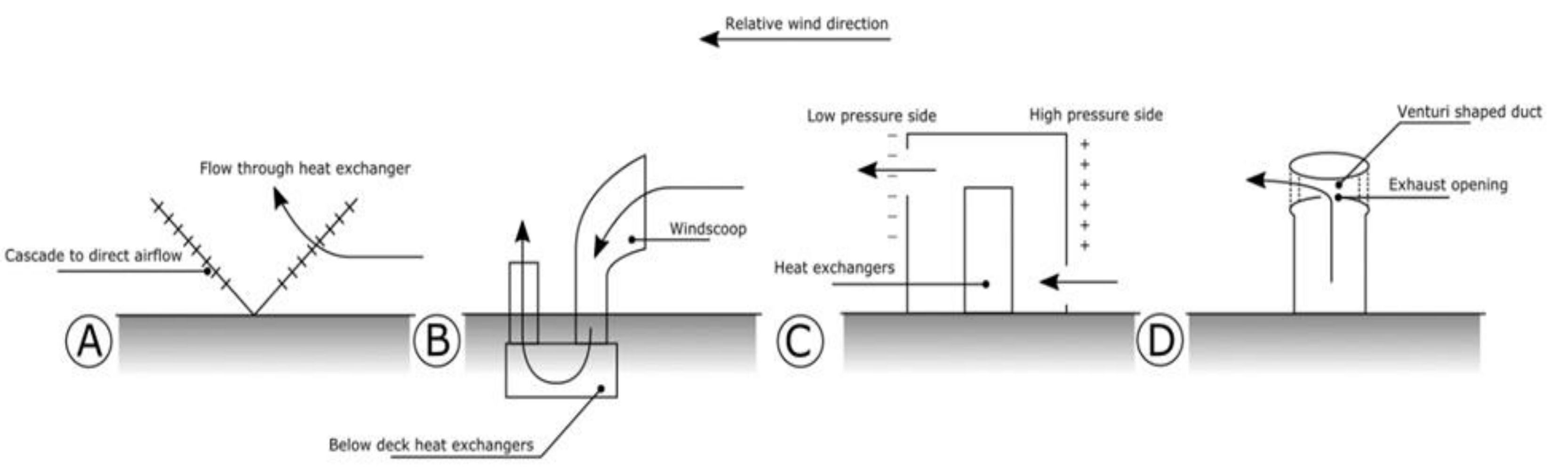
Another Consideration

Using ambient air as the WHRS coolant requires large :

- Coolant's mass flow rates, → Up to 4 times more compared to SW
- Power consumption, → Up to 10 times more compared to SW
- Volumes. → Up to 9 times more compared to SW

However, there exist potential in reducing the power consumption by:

- Using the ship's forward movement, and
- Passive ventilation (e.g. Venturi shaped ducts, density change).



Another Consideration

These methods are taken from ventilation practises in building and transportation:

https://www.quora.com/Why-do-nuclear-power-plants-have-such-wide-chimneys

http://www.canoekayak.com/kayakfish/kayakfish-news/hovercraft-runs-over-kayak-fisherman/

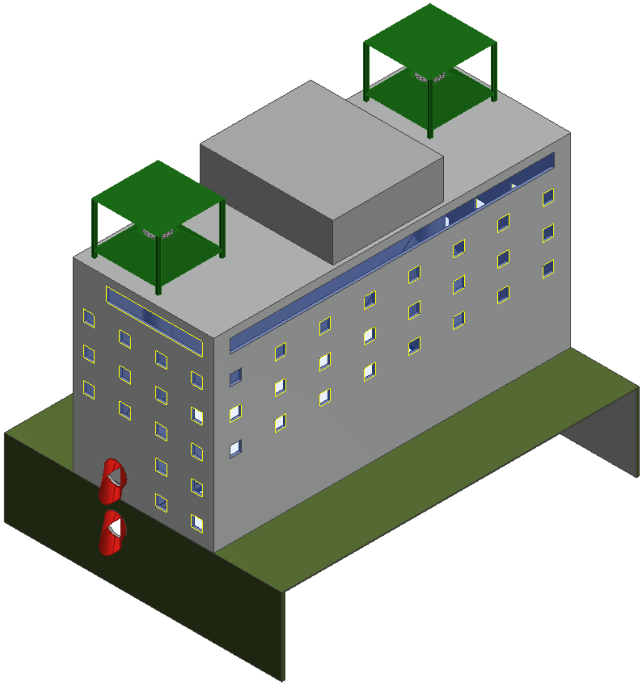
https://en.wikipedia.org/wiki/Postmodern_architecture

https://www.pinterest.com.mx/pin/592856738418521147/

http://cyrilhuzeblog.com/2012/04/13/jims-forceflow-cylinder-head-cooler/

Objective

- To quantify the annual benefit, in CO_2 emission reduction, when using a hybrid cooling approach for a marine WHRS unit using a container ship's scavenge air waste heat while navigating in the Arctic.



Container ship

Deadweight (t)	Length (m)	Beam (m)	Draught (m)	Design Speed (kn)
52,450	252	32.2	12.5	23.3

[5]

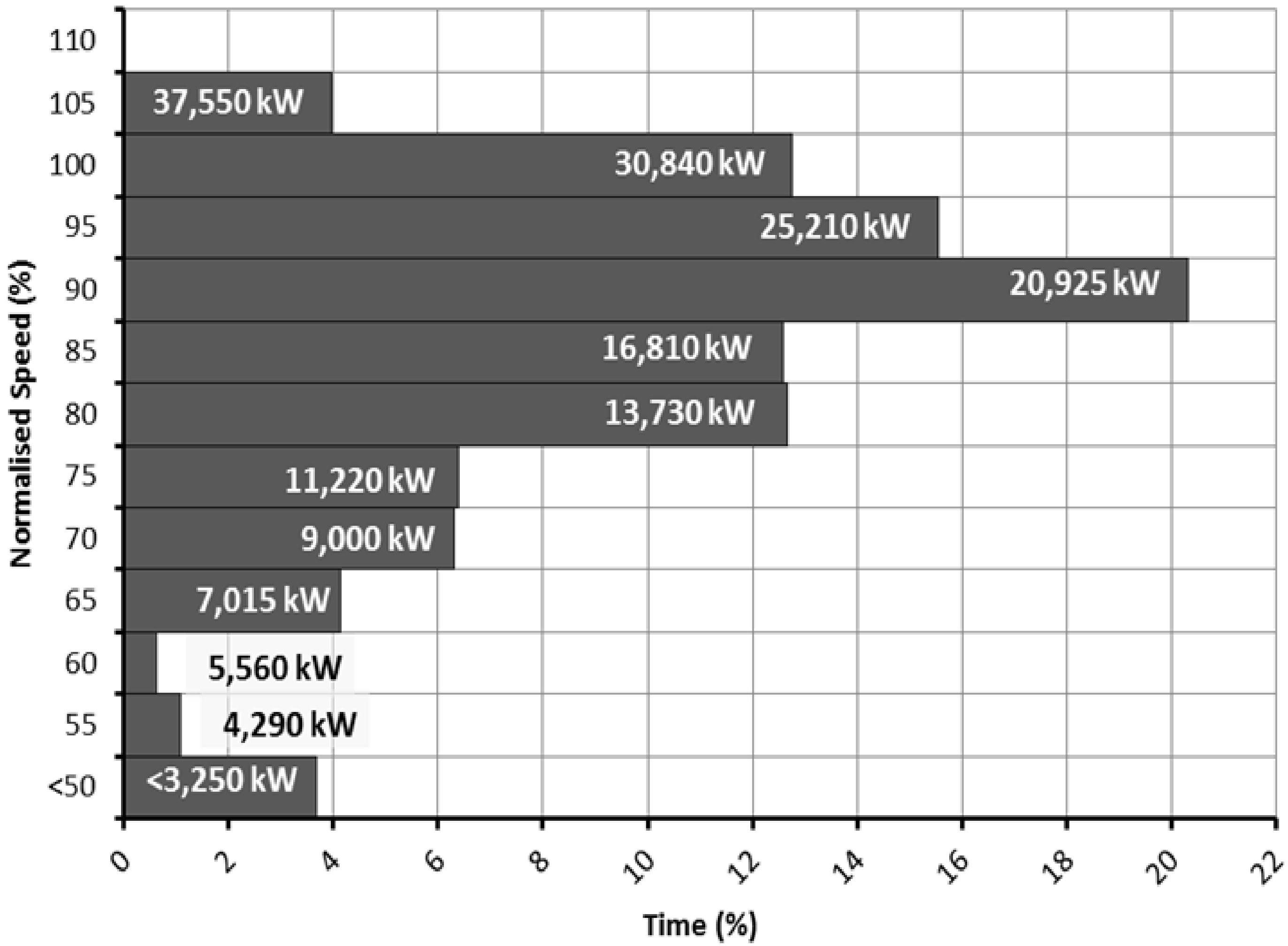
- Two-stroke slow speed diesel producing about 38,000 kW
- Electric demand = 1,390 kW_e [6]
- Auxiliary engine specific fuel consumption = 227 g/kWh (LS-MDO)

https://tugster.wordpress.com/tag/jpo-libra/

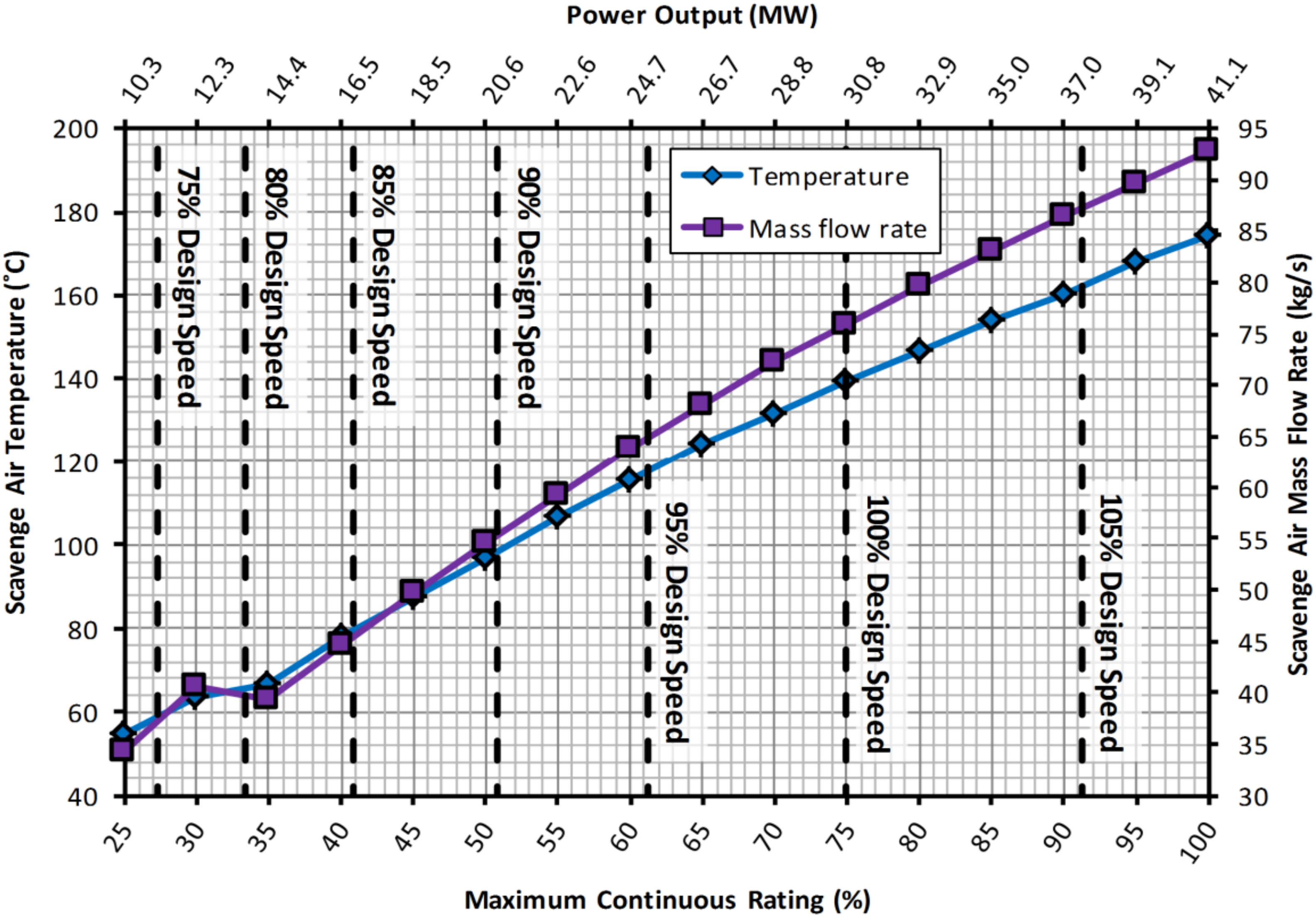
- 4,100 twenty feet container (TEU) in line = **24.8 km**
  - **1 TEU = 6.1 x 2.6 x 2.4 (m) ≈ 39 m^3**
- Ship can carry what **14,986** 3.5 tonne vans can
- Engine power is equal to:
  - **316** 3.5 tonne vans (assuming 120 kW engine)
  - **157** Hummer H2 (largest engine 242 kW)
  - **53** modern F1 cars (assuming 709 kW engine [7])

The Operating Profile

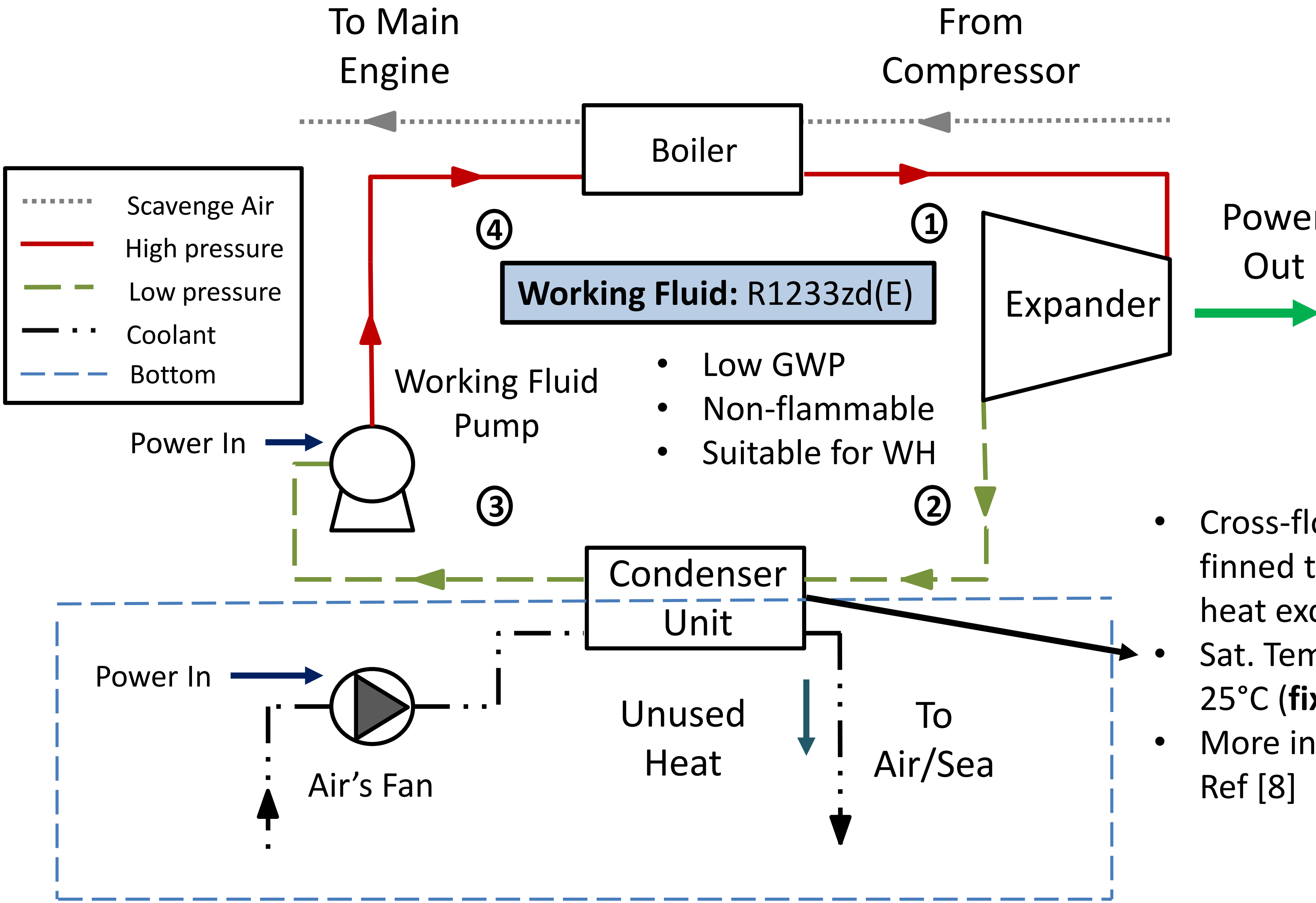
- Normalised to design speed → 23.3 kn (43.2 km/h)
- Taken from Automatic Identification System for a similar ship (2013)



The Operating Profile



Organic Rankine Cycle

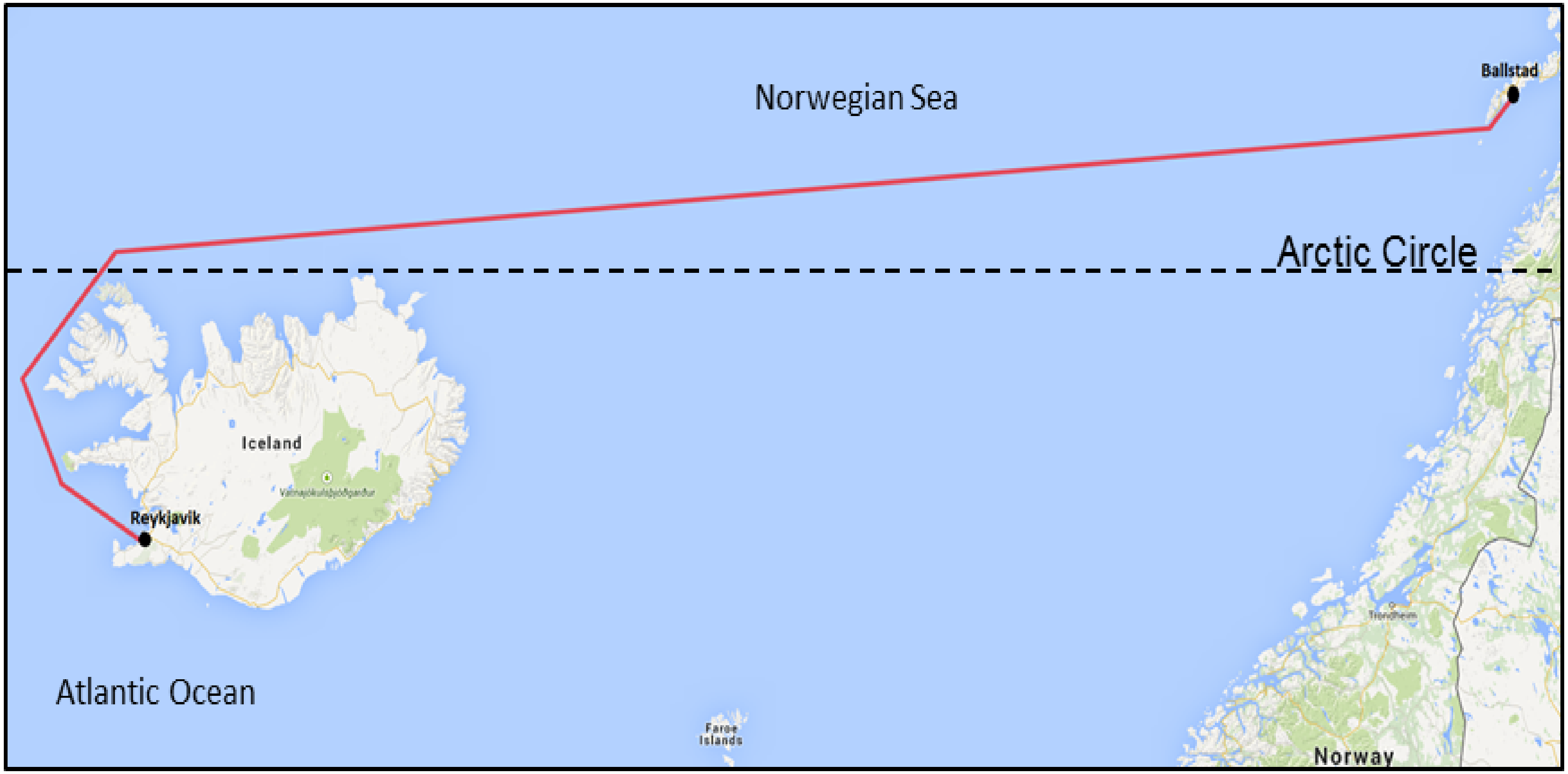


- Cross-flow finned tube heat exchanger
- Sat. Temp. = 25°C (**fix**)
- More info in Ref [8]

The Arctic Route

Ballstad - Reykjavik

- One Journey = **1,980 km**
- Around **9** single trips per month
- **104** trips per year



The Arctic Route

Monthly Ambient Air Temperature (˚C)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-1.7	-1.1	-0.9	1.0	4.0	5.4	7.3	7.3	7.4	4.1	1.4	-0.5

CRUTEM4 data set

- Data available between 1870 to 2013
- 5°N by 5°E
- Uncertainties considered

The Arctic Route

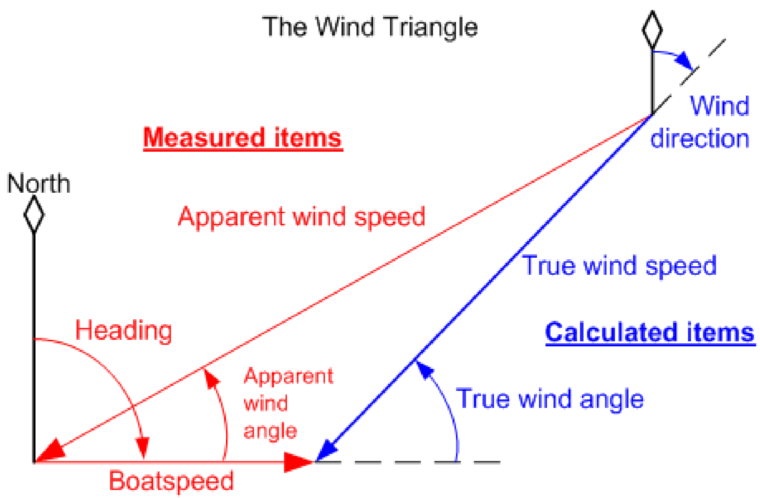
Monthly Ambient Air Temperature (˚C)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-1.7	-1.1	-0.9	1.0	4.0	5.4	7.3	7.3	7.4	4.1	1.4	-0.5

Wind Occurrence Probability

- Route discretised in 44 points, 500 observations over a 36 year period
- Given as True Wind Speed (TWS) and True Wind Angle (TWA)
  - Seen from the ship's bow
  - Apparent Wind is needed → Dependant on the direction and speed of ship
  - Provided by

University of Strathclyde



[8]

The Arctic Route

Monthly Ambient Air Temperature (˚C)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-1.7	-1.1	-0.9	1.0	4.0	5.4	7.3	7.3	7.4	4.1	1.4	-0.5

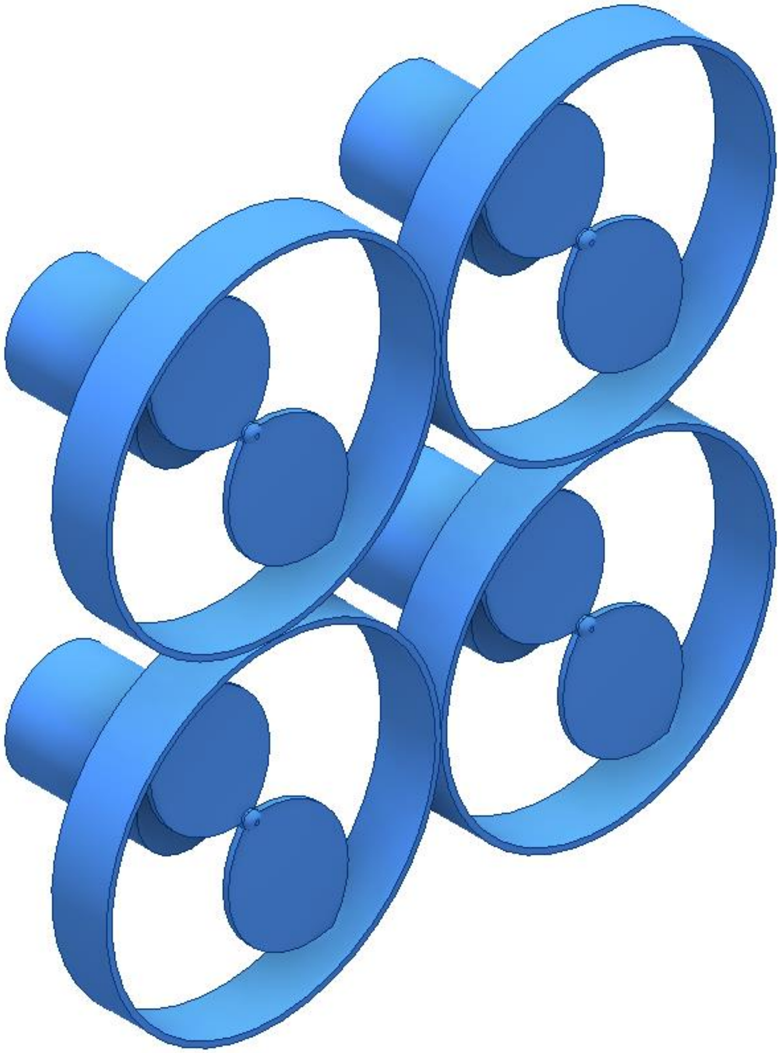
Wind Occurrence Probability

TWA (˚N)\TWS (m/s)	0	2	4	6	8	10	12	14
0	0.00%	1.26%	0.21%	0.42%	0.00%	0.00%	0.00%	0.00%
45	1.26%	5.03%	6.92%	2.10%	1.89%	0.00%	0.00%	0.00%
90	0.21%	7.34%	12.58%	7.13%	7.55%	2.10%	0.00%	0.00%
135	0.84%	6.71%	10.69%	5.24%	3.98%	1.89%	0.84%	0.63%
180	0.21%	3.14%	4.61%	2.31%	1.26%	1.05%	0.42%	0.21%

Hybrid Cooling Equipment

Fans (Forced cooling)

- **Efficiency** → 60% (constant)
- Sized as they are always operating



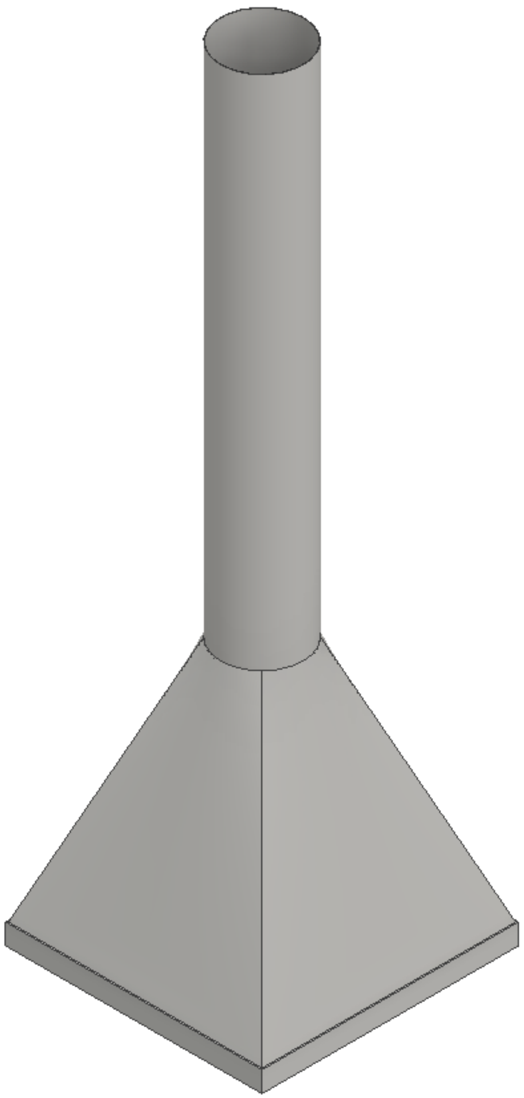
$\dot{Q}_f$ → Fan volumetric flow rate

Hybrid Cooling Equipment

Chimney (Passive cooling)

- **Height** → 19.6 m
- **Exit Diameter** → 2.0 m
- **Entry Box** → Dependant on the heat exchanger design
- **Material** → Aluminium
- Works by a change in air density (due to the heat absorbed from the ORC unit

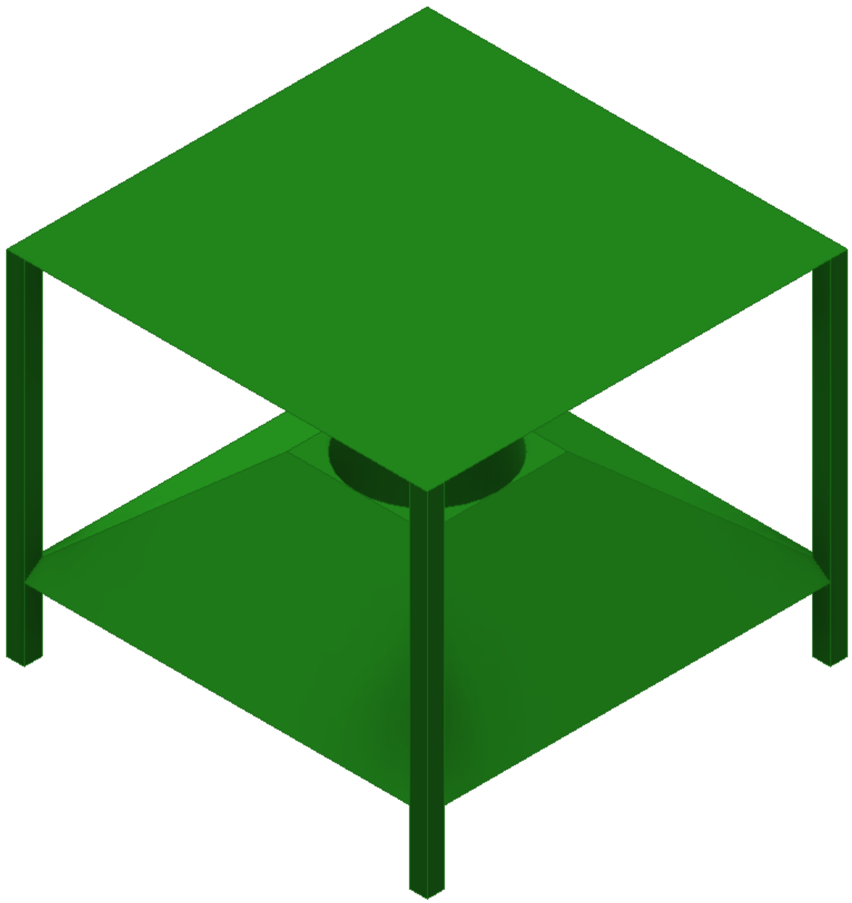
$\dot{Q}_s$ → Stack volumetric flow rate



Hybrid Cooling Equipment

Venturi-shaped roof (Passive cooling)

- **Contraction** → 2
- **Flow area** → 4.0 m^2
- **Pressure Coefficient** → -0.75
- **Material** → Aluminium
- Sits above the superstructure roof
- Works by creating a negative pressure at the chimney exit



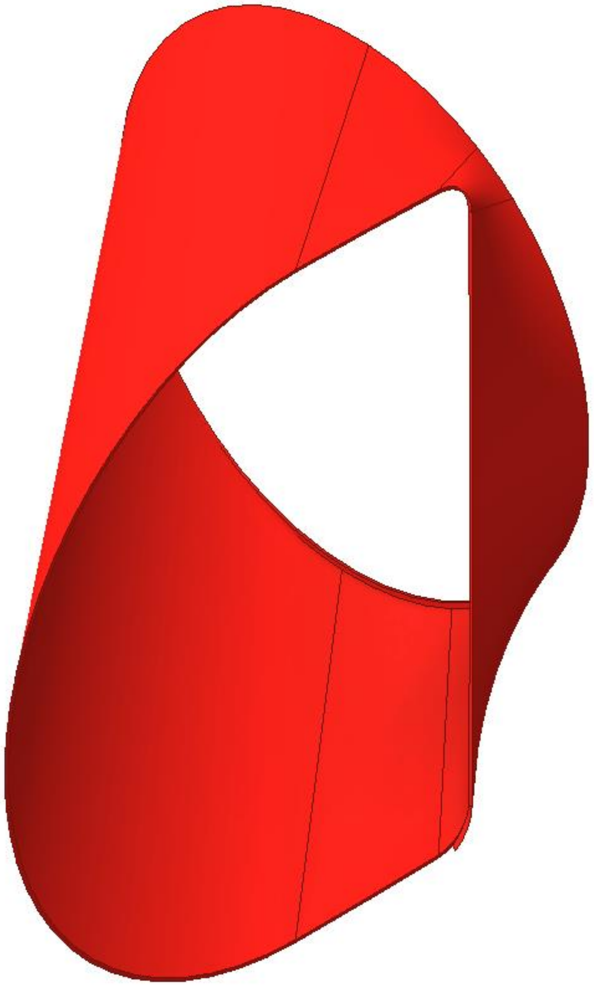
$\dot{Q}_{vr}$ → Venturi-shaped roof volumetric flow rate

Hybrid Cooling Equipment

Windscoops (Ship fwd movement)

- **Number of windscoops per side** → 2
- **Flow area** → 2.0 m^2
- **Opening efficiency** → 0.55
- **Material** → Aluminium
- Rotate along its central axis
- Works by channelling ambient air through the heat exchangers

$\dot{Q}_{ws}$ → Windscoops volumetric flow rate

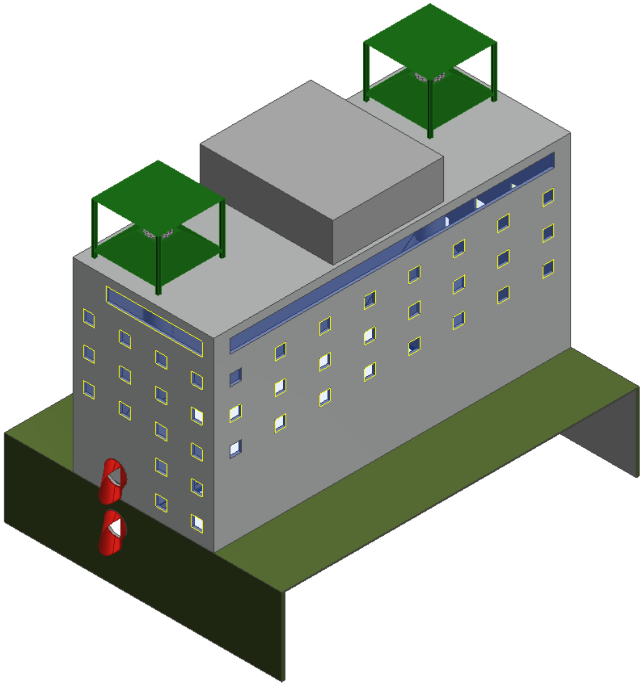


Hybrid Cooling Equipment

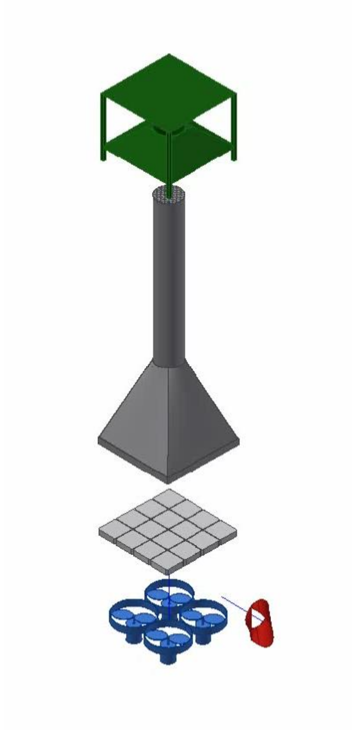
System

- Two set of equipment are installed to the ship superstructure
  - This increases the chances of using more wind
  - Increases system complexity and cost

- Total air cooling flow is given by:



$$\dot{Q}_T = \sqrt{\dot{Q}_s^2 + \dot{Q}_{ws}^2 + \dot{Q}_f^2 + \dot{Q}_{vr}^2}$$

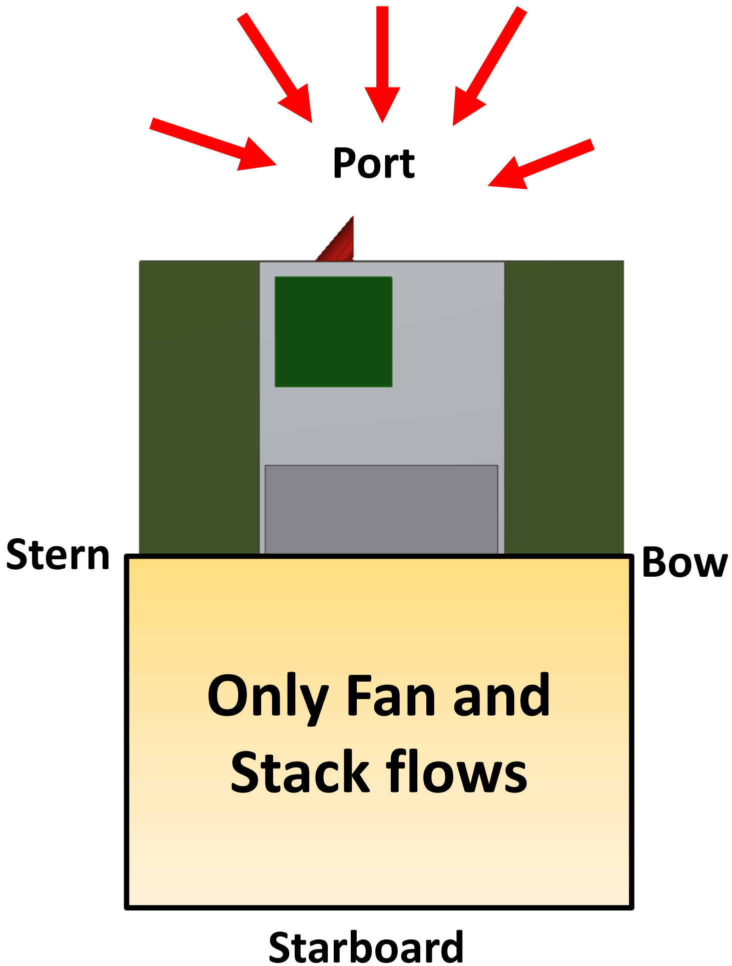


Method

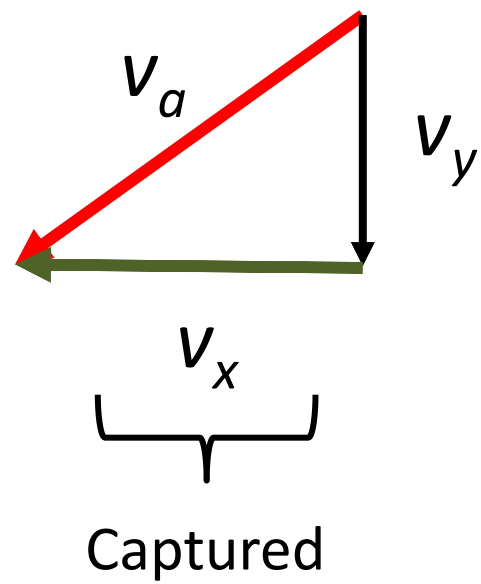
- Two-step single objective (Annual CO_2 reductions) optimisations:
  1. Particle Swarm Optimisation
  2. Pattern Search Optimisation
- **12** different variables analysed → *Heat exchanger characteristics, TC pressure, WHRS design point, etc.*
- Steady-state thermodynamic study
- It does not consider space implications and benefit of waste heat boiler

[9]

Rules of Engagement



For the Windscoop

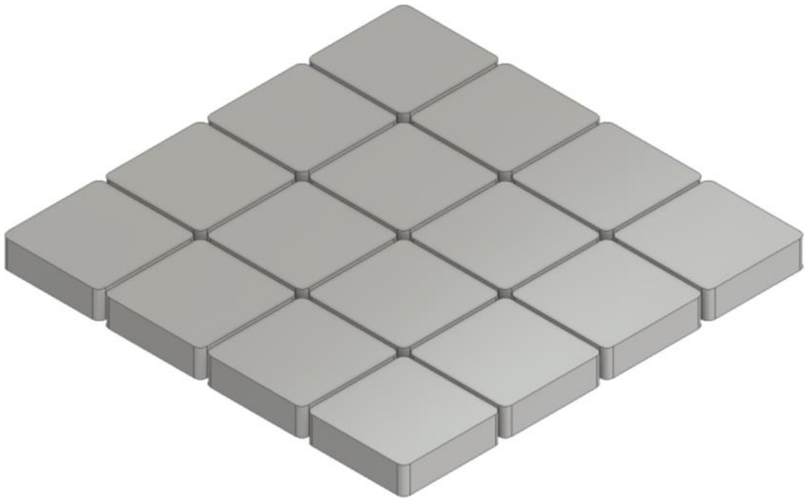


Ship's Forward Movement

Results

Optimal heat exchanger for one hybrid system at design speed

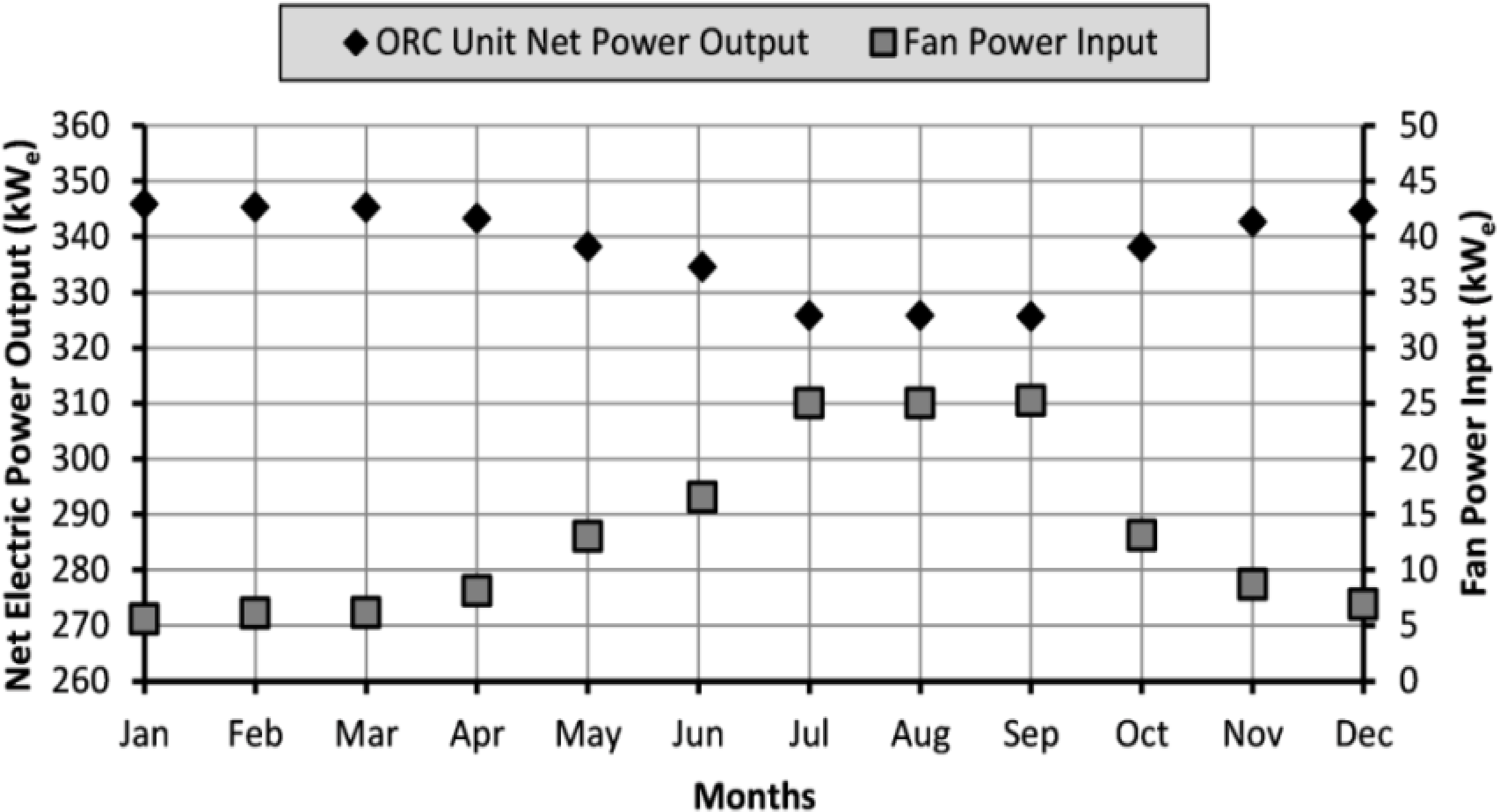
- Modules → 43
- Module width → 6.3 m
- Frontal area → 46.3 m^2
- Tube rows → 5
- Tube length → 7.3 m
- Heat rejected → 1649 kW
- Air requirement → 87.4 m^3/s



Due to the low waste heat temperature the ORC unit will not operate below **90%** of the **design speed** → **21.1 knots**

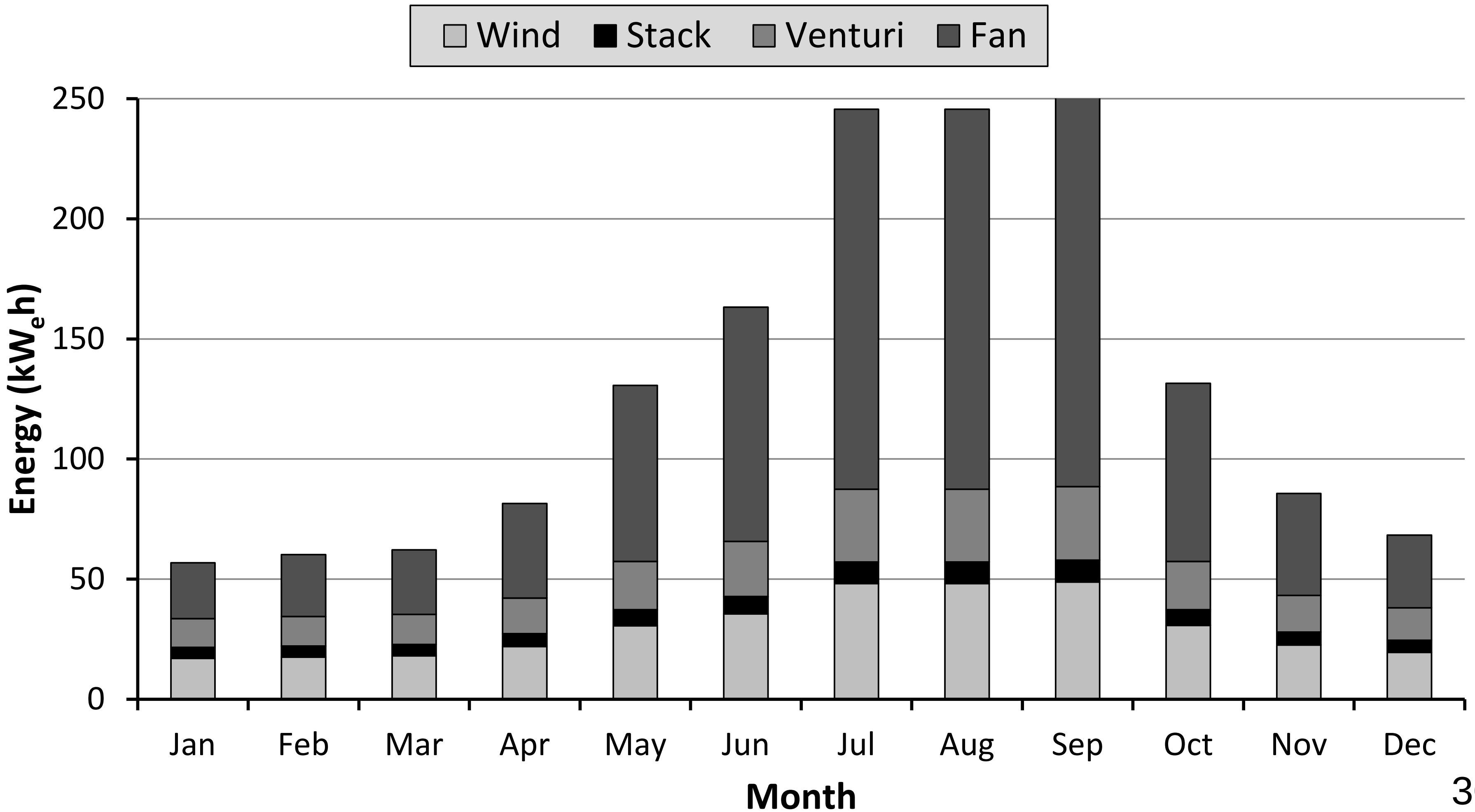
Results

ORC unit with **fan only→543** t of CO_2/year



Results

Monthly ORC power cooling energy consumption



Results

Wind and passive cooling save **4.9** t of CO_2/year

Represents **0.9%** increase in CO_2 savings

But, putting the number into context:

Plumbr. Thinking. Shipping 2012 http://plumbr.eu/blog/whats-your-overhead/thinking

Results

Fan-only operation → **6.2** t fuel/year

−

Wind and passive cooling → **1.6** t fuel/year

=

Hybrid cooling → **4.6** t fuel/year

↓

Represents a reduction of **25.7%**

Conclusions

- An ORC unit using the available waste heat from the scavenge air system of a container ship can reduce 543 t of CO_2/year
- A Hybrid system could reduce further the CO_2 emissions by 0.9%:
  - Largest contribution is by the Windscoop system
  - 25% reduction fan-related fuel consumption
- Further analysis has to be done to consider the friction, leak, ducting losses and how the wind behaves close to the ship superstructure

Thank you

Any Questions?

Contact Details

Email: santiago.fuente.11@ucl.ac.uk

Linkedin: Uk.linkedin.com/in/santiagosuarezdlf

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7. Mercedes: "No stopping" our engine gains for 2016. http://www.motorsport.com/f1/news/mercedes-no-stopping-our-engine-gains-for-2016-671911/
8. http://www.ockam.com/OldSite/truewind.html
9. Steve Boyes/Wild Bird Trust

Area of Opportunity

Marine WHRS are normally cooled by **seawater**, however in the Arctic the **air** temperature tend to be lower.

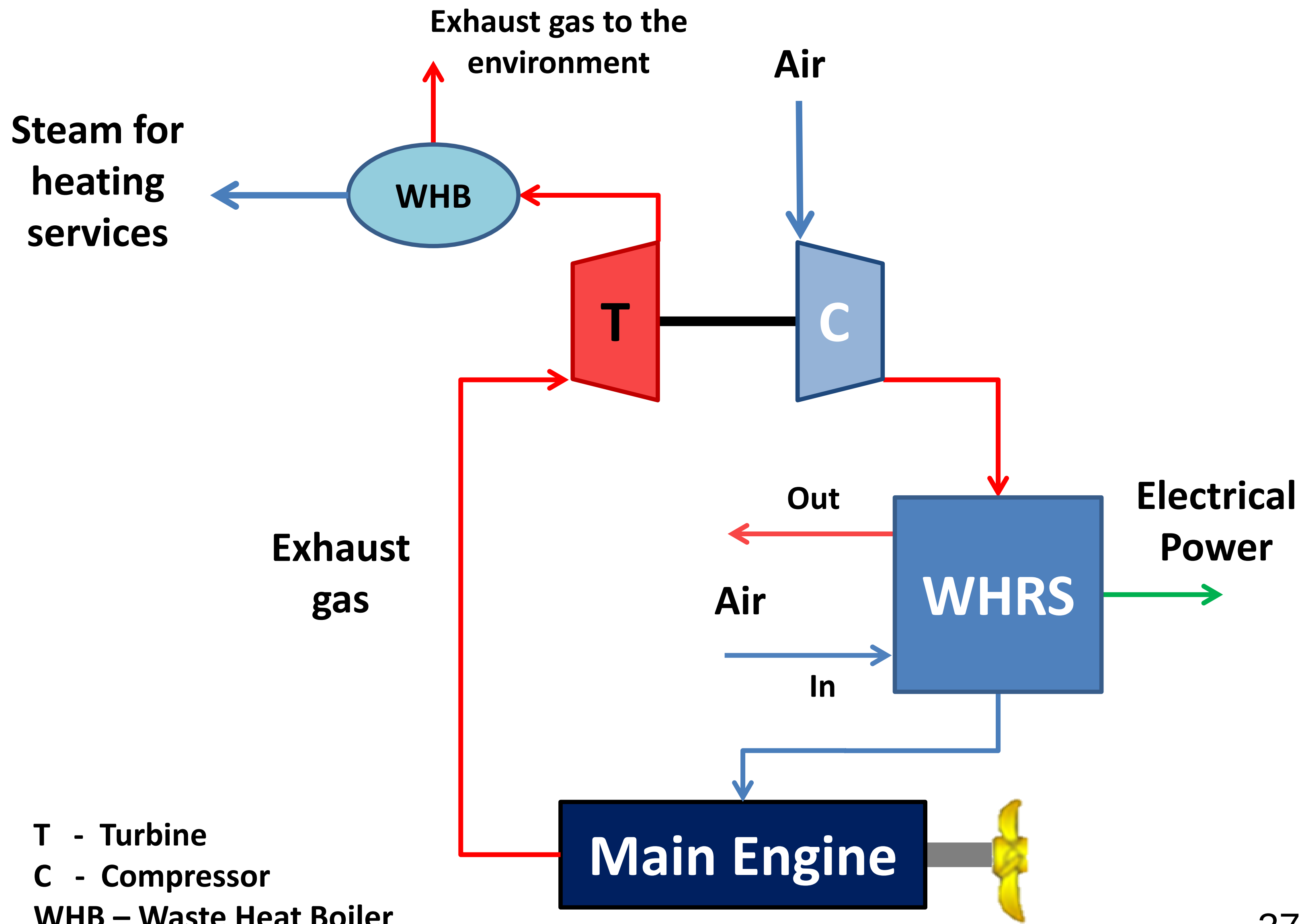
Monthly Average Difference (Negative = Air is cooler)

Longitude between -52˚E and 28˚E; latitude between 58˚N and 73˚N

Month	Average Temperature Difference
Jan	-8.82
Feb	-8.44
Mar	-7.66
Apr	-5.08
May	-2.25
Jun	-1.68
Jul	-1.63
Aug	-2.62
Sep	-2.89
Oct	-5.01
Nov	-7.04
Dec	-8.56
Average	-5.16

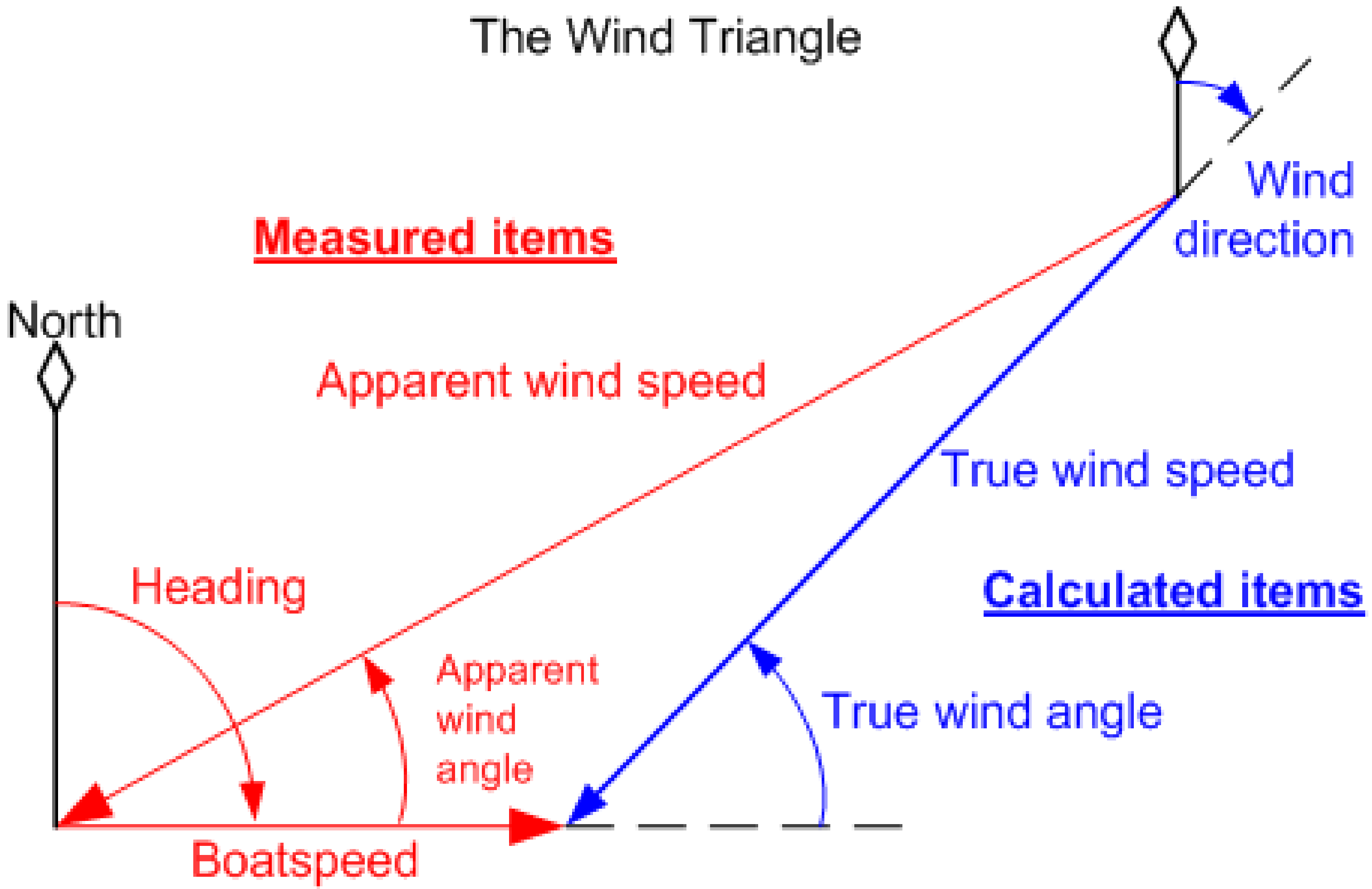
$$\eta = 1 - \frac{T_L}{T_H}$$

Marine WHRS



T - Turbine
C - Compressor
WHB – Waste Heat Boiler

True Wind



http://www.ockam.com/OldSite/truewind.html