The Delightful Frustration of Cruise Ship Power Plant Design

Rik van Hemmen, P. E.
Kyle Antonini
Contents

• Defining Cruise Ships
• Prime Movers, Fuels, and Propulsors
• Propulsion and Overall Power Design
• Design and Size Realities with Respect to Power
• Fuel Consumption, Space, and Weight
• Efficiency, Speed, and Itineraries
• Emissions Considerations with Different Fuels
• Technology, Power Failures, and Regulation
• Conclusions
What is a cruise ship?

- A passenger vessel whose features and amenities are as integral a part of the voyage as the various destinations, often beginning and ending at same port of call
- Cruise ships are predated by passenger liners and large private yachts
What is a cruise ship?

- German built Prinzessin Victoria Luise, launched in 1900, is credited as first purpose-built cruise ship (out-sizing the German royal yacht at the time)
- Sailed in Mediterranean, Baltic, and Caribbean Seas
- Passenger liner companies would run cruises on their ships during the winter months, when the North Atlantic passenger trade was light.
Cruise Ships versus Passenger Liners

- For passenger liners, speed sells.
- For cruise ships, destinations (and ship features) sell. May require speed, but often not.

Image sources: SS United States Conservancy; www.independent.co.uk
Cruise Ships versus Passenger Liners

- Hotel power demand (such as air conditioning) has gone up over time
- Nieuw Amsterdam air conditioned in public rooms only
- SS Rotterdam air conditioned throughout, with intermediate speed and one to two class conversion

SS Rotterdam
Image source: www.ssmaritime.com
Cruise Ships versus Passenger Liners

- As transatlantic air travel expanded, liners took up cruise services
- SS United States, the fastest liner, was a disaster in this regard
- Too big, purpose-designed interior, massive power plant, limited deck space, US crew

Image source: www.cbsnews.com
What defines a cruise ship?

“First” cruise ship had distinct requirements, thereafter shared by most cruise ships:

- One class
- Air conditioning
- Bathrooms in every cabin
- Lots of deck space
- Ship to shore transfers
- Low break doors
But we are here to discuss power...
A Quick Propulsion History

- Reciprocating steam: up to early 1900’s
- Steam turbines: early 1900’s to about 1975
- Medium speed diesels (diesel fuel) small passenger vessels: 1930 to 1975
- Slow speed diesels (HFO): 1975 to 1985
- Medium speed diesels (HFO): 1985 to today (advent of power plant concept)
- Gas turbines (diesel fuel): 1995 to ....... (still in contention because of emissions issues)
# Types of prime movers

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocating</td>
<td>• Oldest marine engine technology</td>
<td>• Less efficient and reliable than turbine (historically)</td>
</tr>
<tr>
<td>Steam</td>
<td>• Effective for slow-speed applications</td>
<td>• Space requirements</td>
</tr>
<tr>
<td></td>
<td>• Many applications for waste steam</td>
<td>• Requires more lubrication and maintenance</td>
</tr>
<tr>
<td>Steam Turbine</td>
<td>• No internal lubrication needed</td>
<td>• Less efficient than diesel</td>
</tr>
<tr>
<td></td>
<td>• Exhaust steam useful without oil contamination</td>
<td>• Best for constant-speed applications</td>
</tr>
<tr>
<td></td>
<td>• Higher power to weight ratio than reciprocating steam</td>
<td>• Requires gearing</td>
</tr>
<tr>
<td>Medium Speed</td>
<td>• Scalable power output without losing efficiency</td>
<td>• Fueling complexity</td>
</tr>
<tr>
<td>Diesel</td>
<td>• Higher power to weight ratio than steam</td>
<td>• Overhaul requirements</td>
</tr>
<tr>
<td></td>
<td>• Fuel hybrid (NG) options</td>
<td></td>
</tr>
</tbody>
</table>
# Types of prime movers

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Speed Diesel</td>
<td>• Higher power output than medium&lt;br&gt;• More efficient than medium</td>
<td>• Size&lt;br&gt;• Fuel complexity&lt;br&gt;• Reduced itinerary (speed) flexibility</td>
</tr>
<tr>
<td>Gas Turbine</td>
<td>• Less space required than steam turbine&lt;br&gt;• Few reciprocating parts&lt;br&gt;• Theoretically low overhaul requirements</td>
<td>• High temperatures&lt;br&gt;• High air exchange requirements&lt;br&gt;• Not heavy fuel capable&lt;br&gt;• Reduction gear requirement for propulsion</td>
</tr>
<tr>
<td>Sail</td>
<td>• Fuel costs negligible (zero if no onboard motor)&lt;br&gt;• Environmentally friendly&lt;br&gt;• Aesthetically pleasing</td>
<td>• At nature’s mercy&lt;br&gt;• Size limitations&lt;br&gt;• Speed&lt;br&gt;• Limited electricity production</td>
</tr>
<tr>
<td>Hybrid Concepts</td>
<td>• Deals with peak demands&lt;br&gt;• Saves on fuel consumption&lt;br&gt;• Reduced pollution</td>
<td>• Increased cost and complexity&lt;br&gt;• Operational/technology uncertainties&lt;br&gt;• Reduced itinerary flexibility</td>
</tr>
</tbody>
</table>
Steam vs Diesel

- Diesel provides higher power to weight ratio
- For years, steam plants were considered more reliable from a maintenance stand-point, but they also required more full-time monitoring
- Steam plant more flexible in balancing hotel and propulsion loads
- Currently, diesel wins out from a fuel consumption cost savings standpoint
## Types of fuel

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy Fuel Oils</td>
<td>• Low grade, cheap&lt;br&gt;• Product of distillation (“bottom of the barrel”)</td>
<td>• High viscosity requires preheating&lt;br&gt;• Onboard purifying&lt;br&gt;• Impurities, sulfur content&lt;br&gt;• Outlawed in polar operations</td>
</tr>
<tr>
<td>Diesel</td>
<td>• Cleaner than FO, low sulfur</td>
<td>• More expensive</td>
</tr>
<tr>
<td>Wind</td>
<td>• Renewable, Free</td>
<td>• Inconsistent availability</td>
</tr>
</tbody>
</table>

The present cutting edge....

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNG</td>
<td>• Cleaner emissions</td>
<td>• Cold storage and preheating</td>
</tr>
</tbody>
</table>

And possibly in the future....

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cells</td>
<td>• Clean emissions (water)</td>
<td>• Production and storage of hydrogen</td>
</tr>
<tr>
<td><strong>Ammonia</strong></td>
<td>• Clean emissions (nitrogen) &lt;br&gt; • Production from air and water</td>
<td>• Production inefficiencies&lt;br&gt;• Energy density versus hydrocarbons</td>
</tr>
<tr>
<td>Nuclear</td>
<td>• No refueling needed</td>
<td>• Stringent regulations&lt;br&gt;• Specialized manning required</td>
</tr>
</tbody>
</table>
# Types of Propulsors

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geared</td>
<td>• More adjustability between propeller and engine speeds.</td>
<td>• Costly manufacturing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Additional maintenance</td>
</tr>
<tr>
<td>Direct</td>
<td>• Optimized at slow speeds</td>
<td>• Little variability</td>
</tr>
<tr>
<td>Electric Drive (DC or AC)</td>
<td>• Prime movers can maximize efficiency</td>
<td>• Initial higher cost vs ICE prime mover</td>
</tr>
<tr>
<td></td>
<td>• Quiet</td>
<td>• Energy conversion loss</td>
</tr>
<tr>
<td></td>
<td>• Power plant approach</td>
<td></td>
</tr>
<tr>
<td>Controllable Pitch Propeller</td>
<td>• Fine-tuning of speed/efficiency/engine load</td>
<td>• Less efficient than optimized FPP design</td>
</tr>
<tr>
<td></td>
<td>• Gearing less necessary</td>
<td>• Maintenance issues</td>
</tr>
<tr>
<td></td>
<td>• Greater operating envelope</td>
<td></td>
</tr>
<tr>
<td>Podded Propulsors</td>
<td>• Maneuverability</td>
<td>• Capital cost</td>
</tr>
<tr>
<td></td>
<td>• Quiet</td>
<td>• Requires careful efficiency design</td>
</tr>
<tr>
<td></td>
<td>• Size</td>
<td>• Maintenance complexity</td>
</tr>
</tbody>
</table>
Fixed vs Controllable Pitch Propeller

- CPP efficient for full range of speeds, because pitch can be optimized.
- CPP can create faster accelerations and decelerations and improve maneuverability
- FPP is cheaper and more robust
- FPP more efficient for specific rotational speed and load condition
- CPP may not need reduction or reversing gears
- CPP is less necessary for electric drive

Image source: kamome-propeller.co.jp
Propulsion is sexy, but only a small piece of the power pie

- Cruise ships need power packages.
- Max power demand is top speed in hot weather
- Min power demand is alongside in cool weather
Propulsion is sexy, but only a small piece of the power pie

- In the old days, there were multiple boiler setups, in which boilers could be taken on and off line to suit power demand.
- Today, power plant concept can simultaneously provide propulsion and power
- Ship powering is almost always a power plant approach today

Titanic’s boilers prior to installation

Image Source: www.titanicpages.com
Design dynamics: who or what is the customer?

• The customer drives the power package
• The passenger and ship owner are both customers
• The passenger could not care less about power plants as long as they don’t fail, make noise, or leave soot on the decks (and aren’t nuclear powered).
• The ship owner could not care less as long as they don’t fail, make noise, leave soot on the deck, and cost the least as compared to their competitors
Importance of power in whole design

From the passenger’s point of view, the minimum standards for a good time are when:

• The air conditioning works
• The toilets flush
• The bar is open (and has ice)
• Food is plentiful
Importance of power in whole design

From ship owner’s point of view:

• A nuisance that should interfere with moneymaking as little as possible

• Ideal plant is super quiet, 100% reliable, 100% environmentally attractive, 100% capable of fulfilling any cruise itinerary choice (speed/range)

• Should only take up space not used for anything else

• Has lowest operational cost compared to competitors (purchase, fuel, crew, maintenance, etc.)
Importance of power in whole design

“Performance” is probably where the power plant sits.
Design Realities

Are owners unrealistic, spoiled brats?

Tell me what you really want.

Choose.

Tell me what is most important.

I really want all of that.

What do you mean choose?

All of it!

Design is a communication exercise, where designers listen to the spoiled brat and try to achieve as much as possible within technical constraints.
Sizing impacts of ever-larger cruise ships

- Old Panamax ship size limits: 965 ft long, 106 ft wide, 39.5 ft draft
- At least 65 largest cruise ships could not fit through the old Panama Canal
- New Panamax ship size limits: 1200 ft long, 160.7 ft wide, 49.9 ft draft
- At least 10 of current largest cruise ships still cannot fit
- Are their truly any limits?
Per passenger propulsion will decrease to a certain point.

“Harmony” accommodates >1500 more passengers than “Anthem,” but per-person propulsion still increases.

More passengers and/or longer itineraries require more amenities → require more space per passenger → bigger ship → more power.
Per passenger power requirements have decreased over time with increasing efficiencies, but there are limits.

Per passenger power versus year built for cruise ships built between 1988 and 2016.
Per passenger hotel power versus year built for cruise ships built between 1988 and 2016

Technical Constraints: Scaling Realities

- Seaborne Pride
- Crystal Symphony
- Queen Mary II
- Costa Fortuna
- Anthem of the seas
- Harmony of the seas
- Queen Elizabeth II
Fuel Consumption

- At maximum usage, Harmony of the Seas (the largest cruise ship) can burn up to 165,000 US gallons of fuel per day (though there are many efficiency standards in place to keep consumption down)
- Typical consumption of current 100,000 GT ships is up to 80,000 US gallons per day
- Repowering of QEII saved over 60,000 US gallons per day.
Transition from direct drive to electric drive (QE II Repowering)

QEII had largest conversion job in merchant shipping history, from steam turbine to diesel-electric plant

Requirements met:
1) Operating profile of ship and 32.2 knots maintained at 85% MCR
2) No increase in noise and vibration levels
3) Fully automated and unmanned engine room
4) Out of service no more than 7 months
Attempts at using gas turbines

• Common in warships and other naval applications since mid-20th century
• Excellent power-to-weight ratio, but more expensive fuel-wise (efficiency and high quality fuels)
• Impressive passenger-to-engine room volume ratio
• Waste heat recovery applications
• GE Turbines implemented in cruise ships in the 21st century
• Due to emissions issues, still a player
Exhaust Heat Recovery

Heat recovery systems use exhaust gases to power turbines and generate extra power from otherwise wasted energy.
Space requirements and weight considerations

• Power plant spaces probably are more effectively positioned low in the ship (stability and less desirable space)
• Power plants require intake air and exhaust air ducting which are generally positioned higher in the ship
• Generally requires uptake spaces in valuable passenger spaces
Space requirements and weight considerations

- SS Normandie integrated machinery spaces with passenger areas.
- First class dining hall was “largest room afloat.”
- Effectively used third “dummy” funnel for air conditioning machinery and additional storage.
Space requirements and weight considerations
Power Plant Sizing

• Sizing is related to passenger capacity and ship speed
• There is a slight variation with regard to vessel luxury level where larger per passenger volumes increase hotel requirements
• But maximum speed is the big driver
• What is the maximum speed you need?
EEDI (Energy Efficiency Design Index)

\[
EEDI \approx \frac{\sum (\text{Power} \cdot \text{CO}_2 \text{ Output} \cdot \text{Specific Fuel Consumption})}{\text{Gross Tonnage} \cdot v_{ref}}
\]

- The dirty trick is low speeds (less power and fuel consumption) get you better EEDI’s, but it makes your ship inflexible in itineraries.
- A large gross tonnage ship of low weight will result in a better EEDI. (Think Hindenburg)
- But will it have enough horsepower in a strong head wind?
- High-low mixes, large fleets, large cruise ship companies
EEDI (Energy Efficiency Design Index)

Symbols for plus (+) and minus (−) indicate CO₂ contribution to EEDI formula.
EEDI (Energy Efficiency Design Index)

Per Passenger Propulsion of Different GT cruise ships built between 1988 and 2016, with EEDI Reference Curve
Itinerary speeds

• With respect to EEDI, the best ship is the slowest ship you can get away with.
• Typical cruise itineraries fall in the lower 20 knot range.
• As long as enough onboard amenities abound, the speed is not as important. It’s about enjoying the journey, right?
• Ocean liners (QEII and QMII) obviously don’t follow this rule.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Service Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmony of the Seas (2016)</td>
<td>22</td>
</tr>
<tr>
<td>Anthem of the Seas (2015)</td>
<td>22</td>
</tr>
<tr>
<td>Carnival Destiny (1996)</td>
<td>20</td>
</tr>
<tr>
<td>Disney Magic (1998)</td>
<td>24</td>
</tr>
<tr>
<td>MV Minerva (1996)</td>
<td>15</td>
</tr>
<tr>
<td>Queen Elizabeth II (1969)</td>
<td>28.5</td>
</tr>
<tr>
<td>Queen Mary II (2003)</td>
<td>30</td>
</tr>
</tbody>
</table>
Itinerary speeds

Olympic Voyager, a slim monohull design, cruised up to 28 knots, in order to spend less time at sea, cover 3 continents, and allow more time to enjoy port stops.
Emissions

- CO$_2$ is related to type of fuel and needs to be reduced to prevent global warming and ocean acidification; don’t burn oil or switch to LNG or hydrogen or sail
- NOx is a highly reactive smog pollutant, produced in high combustion pressures and temperatures, more in high efficiency diesels than low efficiency diesels, less in gas turbines
- SOx is a smog pollutant related to acid rain, is a function of the fuel burned; zero-sulfur fuel $\rightarrow$ zero SOx
Emissions

- Reducing emissions is a deeply multivariable system evaluation.
- Using internal combustion will give you emissions, so it is a choice between evils.
- Hydrogen, nuclear, and sail remove all emission issues.
- Hydrogen and nuclear are perfect in theory.
- LNG is nice, but it is at best a transition fuel.
Emissions Present Approach

- Scrubber systems in the exhaust take care of NOx and SOx, but they are a consumables solution and have disposal issues.
- However, it is the present approach while using oil.

Image source: disneycruiselineblog.com
Present Approach with LNG

- NOx can be reduced by de-rating engines
- A less efficient engine will produce less NOx but more CO\textsubscript{2} per kW generated.
- You can pass present emissions standards with low efficiency LNG engines.
- You get to low CO\textsubscript{2} by nature of the fuel, CH\textsubscript{4}. 
LNG

- Currently the “environmentally friendly” hydrocarbon option
- Carnival’s largest ship to date (180,000GT) will be LNG (2020 delivery)
- Lower sulfur but prone to “methane slip” issues
- Requires both extreme cooling for storage and pre-warming → greater storage space requirements
- New IMO safety code requires specific training
- (Lack of) supply chain infrastructure
- Itinerary flexibility
Ideal Hydrogen

• Hence, H₂, if generated by sustainable methods (solar hydrolysis), is the best solution if we can store it.
• Prime movers could be low efficiency internal combustion, but possibly much more efficiently, fuel cells.
• From a systems point of view, this is a low efficiency system, but if the hydrogen is generated sustainably, it is perfect.
Ammonia

- Ammonia (NH₃) actually burns (and it is toxic and a perfect refrigerant)
- Stores easily as a liquid
- Has realistic applications as a long-term storage medium for hydrogen for fuel cells, pending the widespread adoption of new and more efficient production and conversion technologies
- At present ammonia/fuel mixtures can provide comparable performance with proportional reduction in greenhouse emissions
Yeah, but what about nuclear?

• Today’s nuclear power plants are inefficient, overweight, and unnecessarily complicated
• There are much better concepts out there with much lower risk
• But they still use radioactive fuels, and that scares the public more than the Hindenburg
• It would make a lovely passenger ship, though (steam plant with multiple generators and electric drive)
Sail

- E.g. Windstar and Club Med
- Very good if you can pull it off (very specific itineraries)
- Valid, but limited application

- [Roadmap for Sail Transport Engineering](#)

Image source: cruiseweb.com
Sail

But the aesthetics, though!

Stad Amsterdam

Maltese Falcon

Image source: sailmaster.com

Image source: burgessyachts.com
Design Wheels within Design Wheels

Performance
- Must fit “mission” (itinerary)
- Itinerary begets speed and power requirements
- Adjust speed and power to optimize efficiency
- Revisit itinerary based on speed and power
- Repeat
Effect of a new technology

• E.g. LED
• Uses 10 times less electricity (per lumen) and lasts 40 times longer than incandescent bulbs
• Occurred in only last 30 years
• Reduces power requirements, transmission weight (cabling), bulkhead penetration sizes, and deeper carry on effects (fixture weight)
• Ultimately will cost less to purchase
• New ship construction takes years and a ship leaves the yard with old bulbs but not old LEDs
• About 3 light bulb change crewmembers per passenger ship have lost their job
Cruise ship power failures

Carnival Splendor, 2010
• Engine Room fire resulted in lost power
• 4500 passengers stranded for 4 days

Carnival Triumph, 2013
• Engine room fire caused power failure
• 4000 passengers stranded for 4 days
• Infamous “poop cruise”

Real problem is stupid small emergency generators. Unsung heroes of disasters are the engineers (Titanic/Costa Concordia).
Powering Redundancies

• Own lifeboat and get home design
• As long as the air conditioner runs, toilets flush, and the bar is open, nobody cares
• New SOLAS passenger ship code – “Safe Return to Port”
• Distributed power
• Better Ship Electric Arrangements

Crew emergency escape chute

Image source: cruiselawnews.com
What did we learn?

• Things are changing very quickly (technology and regulations)
• The customer’s desires and reality are two different things
• Earning capacity, environment, sustainability, and efficiency push against each other
• Ship design is very complicated and power plant design is only a small piece of it.
• Design and construction is a communication exercise
• Itinerary, Itinerary, Itinerary!
Questions??
Transition to full power station concept

- Set of multiple engines and/or turbines provide electrical power to common busbar
- From busbar, power is distributed to propulsion mechanism and to hotel
- e.g. QEII used 9 MAN B&W diesel engines to provide power to electric propeller motors, hotel, and rest of systems
Podded Propulsors

- 360 degree azimuthal independent electric-driven motor
- Multiple pods can be situated and optimized for hydrodynamic performance and efficiency.
- Shown to be of higher efficiency than conventional engine propulsion
- Used in the Queen Mary 2

Image source: www.rolls-royce.com
Cruise ship power failures

Norwegian Dawn, 2015
• Ship ran aground on reef after temporary power loss off coast of Bermuda