ASC Research Vessel Replacement Program
Power Systems Study

PREPARED FOR: Leidos, ASC Centennial, CO			BY: Reed Lillie, ENGINEER
1201 WESTERN AVENUE, SUITE 200 SEATTLE, WASHINGTON 98101-2953 T 206.624.7850 GLOSTEN.COM			CHECKED: Sean A. Caughlan, PE, SENIOR ENGINEER
			APPROVED: Timothy S. Leach, PE, PRINCIPAL-IN-CHARGE
DOC: 19136-000-03	REV: -	FILE: 19136.01	DATE: 8 July 2021

SEAN A.M. CAUGHLAN STATE OF WASHINGTON 42864 REGISTERED PROFESSIONAL ENGINEER
Digitally Signed 08-Jul-2021

References

1. *ASC Research Vessel Replacement Program Concept Design Report*, Glosten, Rev. –, 27 May 2020.
2. *Antarctic Support Contract Vessel Options Study*, Glosten, Rev. B, 6 March 2018.
3. *Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses*, The Obama Administration, White House Office of Management and Budget, Circular A-94, Appendix C, 2017.
4. *Annual Energy Outlook 2020, Table 3, Energy Prices by Sector and Source*, U.S. Energy Information Administration, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2020&cases=ref2020&sourcekey=0, accessed 28 January 2021.
5. *Advanced Clean Transit, Battery Cost for Heavy-Duty Electric Vehicles*, California Environmental Protection Agency, Air Resources Board, 14 August 2017.
6. *[NBP Specifications] Attachment B – Technical Requirements*, Raytheon Polar Services Company, Rev. 3, 15 November 2002.
7. *Green Ship Alternatives Study*, Glosten, Rev. -, 8 June 2021.
8. *Shipping 2020*, DNV, 2012.

Executive Summary

This study was conducted to determine if there are better alternatives to the baseline diesel electric power plant design for the Antarctic Research Vessel (ARV). Three systems of power generation and four different annual operating profiles were compared to determine the best solution. The three power generation systems were:

- Diesel electric (baseline).
- Hybrid diesel electric with batteries (hybrid).
- Diesel electric with variable speed generators (VSGs).

Diesel electric is considered the baseline architecture for the ARV (see Reference 1) due to its efficient operation across a variety of operating modes and commonality in similar vessels. Diesel electric provides full rated torque at low propeller speeds which is critical for an ice breaking vessel. *Hybrid diesel electric with batteries* adds battery storage to the diesel electric architecture, potentially enhancing efficiency, reliability, and emissions, in exchange for additional complexity and capital cost. *VSGs* have very similar architecture but offer potentially improved efficiency and emissions. Both hybrid and VSGs were considered more efficient ‘cousins’ of the already proven diesel electric and are growing trends within the industry.

30-year life cycle costs were calculated for each system and operating profile, including capital expenses (CapEx) and operating expenses (OpEx). Among these were the cost for new engines, new batteries, fuel, engine maintenance and periodic battery replacement. Performative and emissions factors were also considered. Alternative fuels were not considered in this study. For a discussion on alternative fuels, see the Reference 7.

A baseline operating profile (profile 1) and three other profiles were analyzed to better understand the sensitivity of the different activities on lifecycle costs. Each operating profile assumes 365 days of operation each year including in port days. Operating profile 2 assumes a 25% increase over the baseline in the number of days spent conducting open water transit. Operating profile 3 assumes a 25% increase over the baseline in the number of days spent on station, and operating profile 4 assumes a 25% increase over the baseline in the number of days spent in ice. Table 1 below details the activity breakdown of these four different operating profiles.

Table 1 Number of days spent conducting each activity annually, per operating profile

	Profile 1	Profile 2	Profile 3	Profile 4
Activity	Baseline	=Baseline +25% transit	=Baseline +25% on station	=Baseline +25% in ice
Open Water Transit	79	**99**	75	70
Icebreaking	29	27	27	**36**
On Station, DP	49	46	**61**	44
On Station	15	14	**19**	13
Deployment - Dredging & Trawling	17	16	16	15
Deployment - Towing Side Scan	10	9	9	9
Hotel Only (in port)	82	76	78	73
Ice Transit	84	78	80	**105**
TOTAL	**365**	**365**	**365**	**365**

Tables 2 through 5 detail the life cycle costs and CO_2 emissions for each power system and operating profile.

Table 2 Summary of comparative findings between different power systems for baseline operating profile (profile 1)

	Diesel electric	Hybrid – Diesel electric with battery	VSG - Diesel electric with variable speed generators
30-year Fuel Consumption (gal)	69,999,000	69,203,000	69,928,000
30-year CO2 Emissions (MT)	746,000	739,000	746,000
CapEx (USD)	$9,377,000	$9,743,000	$9,819,000
OpEx – Engine Maintenance (USD)	$3,726,000	$3,433,000	$3,860,000
OpEx – Battery Replacement (USD)	$ -	$878,000	$ -
OpEx - Fuel	$106,630,000	$105,418,000	$106,522,000
30-year Life Cycle Cost (USD)	**$119,733,000**	**$119,472,000**	**$120,201,000**

Table 3 Summary of comparative findings between different power systems for operating profile 2 (baseline + 25% transit)

	Diesel electric	Hybrid – Diesel electric with battery	VSG - Diesel electric with variable speed generators
30-year Fuel Consumption (gal)	73,211,000	72,309,000	73,106,000
30-year CO2 Emissions (MT)	780,000	773,000	780,000
CapEx (USD)	$9,377,000	$9,743,000	$9,819,000
OpEx – Engine Maintenance (USD)	$3,727,000	$3,569,000	$3,925,000
OpEx – Battery Replacement (USD)	$ -	$878,000	$ -
OpEx - Fuel	$111,523,000	$110,148,000	$111,364,000
30-year Life Cycle Cost (USD)	**$124,627,000**	**$124,338,000**	**$125,108,000**

Table 4 Summary of comparative findings between different power systems for operating profile 3 (baseline +25% on station)

	Diesel electric	Hybrid – Diesel electric with battery	VSG - Diesel electric with variable speed generators
30-year Fuel Consumption (gal)	70,481,000	69,732,000	70,428,000
30-year CO2 Emissions (MT)	751,000	745,000	751,000
CapEx (USD)	$9,377,000	$9,743,000	$9,819,000
OpEx – Engine Maintenance (USD)	$3,720,000	$3,438,000	$3,814,000
OpEx – Battery Replacement (USD)	$ -	$878,000	$ -
OpEx - Fuel	$107,364,000	$106,223,000	$107,283,000
30-year Life Cycle Cost (USD)	**$120,461,000**	**$120,282,000**	**$120,916,000**

Table 5 Summary of comparative findings between different power systems for operating profile 4 (baseline + 25% in ice)

	Diesel electric	Hybrid – Diesel electric with battery	VSG - Diesel electric with variable speed generators
30-year Fuel Consumption (gal)	69,665,000	68,891,000	69,600,000
30-year CO2 Emissions (MT)	742,000	736,000	743,000
CapEx (USD)	$9,377,000	$9,743,000	$9,819,000
OpEx – Engine Maintenance (USD)	$3,733,000	$3,395,000	$3,810,000
OpEx – Battery Replacement (USD)	$ -	$878,000	$ -
OpEx - Fuel	$106,121,000	$104,942,000	$106,023,000
30-year Life Cycle Cost (USD)	**$119,231,000**	**$118,958,000**	**$119,652,000**

For each operating profile the hybrid system incurs slightly less cost over the service life of the vessel as the other systems, it is the least polluting, dramatically decreases engine operating hours, allows for quiet operations, and provides instantaneous power when needed. Based on this analysis, the hybrid system is the recommended power system for the ARV.

Power Systems Compared

Baseline - Diesel Electric

The diesel electric power system baseline assumption for the ARV is based on the Concept Design Report (Reference 1).

- Twin 5.5MWe motors with azimuthing propellers
- Selected engines are EPA Category 3 engines with per cylinder volume greater than 30 liters per cylinder. Emissions meet EPA/IMO Tier III levels with Selective Catalytic Reduction using urea. Only one commercial engine is known that can meet lower emissions levels (EPA Tier 4) without urea but it has a higher fuel consumption and is not available in appropriate power levels for this vessel.
- 16.8MW installed mechanical power w/additional harbor generator for hotel loads only. :
    - 2 x 4.80MW Engines (MAN8L32/44CR)
    - 2 x 3.60MW Engines (MAN6L32/44CR)
    - 1 x 1.32MW Engine (MAN6L21/31)
- 16.2MWe installed electrical power w/additional harbor generator for hotel loads only:
    - 2 x 4.632 MWe generator sets (MAN 8L32/44CR)
    - 2 x 3.474 MWe generator sets (MAN 6L32/44CR)
    - 1 x 1.280 MWe generator sets (MAN6L21/31)
    - Medium voltage propulsion bus, 6.6kV

Hybrid – Diesel Electric with Battery

Hybrid systems add energy storage to the propulsion bus, allowing the engines to operate more efficiently. Normally a combination of diesel generators is brought online (automatically or manually) to *follow* the load that is on the bus (i.e., the generators need to provide as much power as is being demanded by the ship). This often means that the generators are operating outside their best efficiency point (typically about 85% of maximum continuous rating). A hybrid system uses the batteries to 'balance' the supply-demand equation by allowing the generator to operate at or very near its best efficiency whenever it is online, and the battery will either be charged or discharged to make up the difference. In practice this means reduced operating hours for the generators, which reduces maintenance. In addition to reducing the hours on the engines, batteries allow them to be run at peak efficiency nearly all the time, saving on fuel. Operating at the best efficiency is also better for the engines, which also contributes to lower maintenance.

Hybrid systems have been used successfully on existing research vessels including the *Sir David Attenborough* (SDA). Batteries offer many unique advantages for polar research vessels, such as periodically operating with zero emissions (if sized accordingly), reducing underwater radiated noise (URN), and providing instantaneous power. The generator sets are major contributors to URN, even when isolated with resilient mounts. A hybrid system could allow operation for short periods on batteries alone, which could significantly reduce noise and be an advantage for scientific researchthat relies on the use of transducers. Another interesting efficiency advantage of hybrid systems is the ability to recover energy from other electric devices used for braking. For example, a common application on most research vessel is the use of CTDs. When lowering

CTDs to great depths, braking resistors are required to ‘dump’ the excess heat generated when slowing their descent. Instead of resistors, batteries could be charged during descent, and the stored energy could be used when pulling the CTD back to the surface. Energy recovery or regeneration is appropriate for very large loads, but not necessarily cost effective for smaller loads.

Batteries are expensive, take up extra space, and require additional auxiliary equipment for cooling. Batteries must also be installed in a dedicated space with a fire boundary and have a fire suppression system (very similar to an engine room). However, once installed the batteries require almost no maintenance. Although initially more costly and complex than the baseline diesel electric system, a hybrid system may recoup these added costs over the life of the vessel by saving on fuel and maintenance (see Findings section below).

Modular batteries installed in a shipping container with all auxiliary equipment included (such as fire suppression, cooling, power conversion, etc.) have become a trend in the offshore industry. There could be advantages for this modular design, including the benefits of standardization, but it was not specifically evaluated in this report. The disadvantage of the modular approach for the ARV would be that it would likely require two 20-foot ISO containers to provide the required capacity. As deck space is at a premium, this approach would have to be carefully considered due to the significant space penalty.

The hybrid system modeled for comparison uses a 2350kWh bank of batteries (see Battery Replacement section below) in tandem with the same four fixed speed diesel electric generators used in the baseline system. When operating with hotel load only, it is assumed that a single engine will continue to run at its peak efficiency point while any excess power is stored in the batteries. Once charged, the batteries will provide all power to meet the hotel load, allowing the engine to be shut off until the batteries require charging again. Thus, the hybrid system was modeled *without* a harbor generator.

In the Vessel Options Study (see Reference 2) larger batteries were considered:

- 4,477kWh: 4 hours silent operation (800kW average load, 1MW peak) plus peak shaving
- 8,954kWh: 8 hours silent operation (800kW average load, 1MW peak) plus peak shaving

These larger batteries were also based on a 10-year life, but their size was driven primarily by the requirements for silent operation. As fisheries research and silent operation has not been identified as a primary design driver, these larger battery variants are not recommended due to added cost, weight, and spaces penalties incurred.

Batteries would provide some potential safety and operational advantages in addition to efficiency. Having a large amount of energy storage connected to the propulsion bus would allow nearly instantaneous transfer of power to the batteries if the plant went offline. If properly designed, a battery could feed both sides of a split bus for added redundancy. In such a configuration, temporary propulsion and even auxiliary power could be maintained while the plant is brought back online, or while emergency power is started. If the ARV specifications require a hybrid propulsion system, this capability should be required. However, such a battery would not be appropriate for typical uninterruptible power supply (UPS) service such as for scientific operations as its primary function is ship's power. Conversely, if something were to happen to the batteries, the vessel operation would not be affected since the diesel engines are sized to provide full power. In this way, batteries and diesel electric systems work very well to enhance safety and operations.

VSG – Diesel Electric with Variable Speed Generators

Medium voltage, variable speed generators (VSGs) may not be commercially available today but, based on conversations with vendors, they are expected to be available in the next several years. It is assumed that the technology will be available by the time the ARV is constructed.

VSGs produce constant voltage AC power at a variable frequency. The system includes rectifiers to produce DC power, which is fed into a common DC bus. Because the power from the generators is converted to constant voltage DC, the alternator does not need to maintain a constant synchronous speed, as is required for maintaining the frequency in parallel operation of synchronous AC generators.

The DC power is then converted to clean AC power with power conversion equipment. The larger motor loads, such as propulsion motors, can be fed directly from the power conversion equipment, eliminating the need for phase shifting transformers and additional electrical drive equipment. 60 Hz AC power is fed to a 480 VAC ship's service switchboard serving the smaller motor loads and house loads. With advances in digital electronics, the conversions between AC and DC power happen far more efficiently than in the past.

Compared to constant speed engines, variable speed operation offers a much broader range of operating points, each with its own specific fuel consumption value. The engine's control system can select an operating point for both speed and power that maximizes the efficiency of the engine and reduces fuel consumption. The largest benefit comes when operating below 50% loading, because this is an area where constant speed generators are very inefficient. This can also result in reduced air emissions. Wear on the engine is reduced at lower operating speeds, so VSGs can result in lower maintenance costs.

VSGs , have a history in industrial applications but are a recent development in the marine industry. Development and adoption of marinized VSG technology for ship electrical power generation is ongoing.

The system modeled for comparison assumes four VSGs. Similar to the baseline diesel electric system, this includes two 3.6MW engines and two 4.8MW engines. Because VSGs can operate efficiently at low loads, there is no need for a harbor generator. Thus, the VSG system was modeled *without* a harbor generator.

A VSG battery hybrid system was not considered. The success of the hybrid system relies on the ability to always operate the engines at peak efficiency which occurs at 85% maximum continuous rating (MCR). The success of the VSG system relies on the ability to operate the engines efficiently at all loads, even at 25% MCR. To combine these two systems would be redundant, resulting in no greater fuel savings and higher cost than any of the other systems.

Methodology

Life cycle costs were calculated for three different systems of power generation under four operating profiles (each totaling 365 days). Unless stated otherwise, the tables in this report only show the results from the baseline operating profile. See Appendix B for a complete list of life cycle costs for the other operating profiles.

Life Cycle Cost

Assumptions

All Power Systems

- Intermediate values of specific fuel consumption & emissions were found by linear interpolation from manufacturer provided fuel consumption numbers (Appendix A).
- Service life of power plant: 30 years.
- Base price of MDO in constant 2021 dollars: USD$1.50/gallon (based on ~$470/MT Americas average MGO for Sept 24th, 2020, Reference 4). Results were also generated for an assumed fuel cost of USD$4.15/gallon (based on ~$1300/MT). The change in relative difference of life cycle costs was insignificant (Reference 8).
- Real, 30-year discount rate: 0.7% (Reference 3).
- Constant, annual escalation rate of fuel: 0.80% (Reference 4 for transportation diesel).
- United States Dollar to Euro conversion rate: 1.19:1.
- Constant, annual escalation rate of energy storage: -2.5% (professional estimate).
- Total Installed Mechanical Power: 16,800MW (excludes harbor generator)
- Total Installed Electrical Power: 16,212MWe (excludes harbor generator)

Baseline Power System

- Harbor generator maintenance costs are proportionately scaled from average maintenance costs of four main engines by ratio of average installed powers.

Hybrid Power System

- Battery Life: 10-year replacement cycle.
- Battery size: 2,350kWh.
- Depth of discharge (DoD) of battery: 40%.
- Minimum battery life (cycles): 24,000 based on NMC battery chemistry with 40% DoD.
- Overall charge & discharge efficiency of batteries: 92%
(99% battery x 96% transformer x 96% converter).
- Battery cost at time of construction: USD$300/kWh (see Reference 5).
- Replacement batteries based on annual escalation rate of -2.5% from first cost.

Variable Speed Generator

- Fuel curves based on MAN propulsion engine operating on combinator curve (Appendix A).
- VSG estimated reduction in cost per periodic service event vs. fixed speed: 15%.

Capital Expenses

Capital expenses for engines and batteries were estimated for each power system. Generator set prices were obtained from MAN, an industry leading manufacturer. It is expected that the costs for comparable engines from other manufacturers are similar to those quoted by MAN. The capital cost for the four generator sets was provided as a single value in Euros (Appendix A). It was assumed at the time of this report that one Euro is equivalent to USD$1.19.

Assuming a battery size of 2350kWh, (See Battery Replacement) the capital cost of the batteries and auxiliary equipment (power electronics, cooling equipment, ventilation, fire suppression, etc.) was determined to be USD$1.2M. These capital costs are summarized in Table 6 in constant 2021 dollars.

Table 6 Summary of capital expenses

Item	Diesel electric	Hybrid – diesel electric with battery	VSG - Diesel electric with variable speed generators
Cost of Engine 1 (USD)	$2,439,000	$2,439,000	$2,805,000
Cost of Engine 2 (USD)	$2,439,000	$2,439,000	$2,805,000
Cost of Engine 3 (USD)	$1,830,000	$1,830,000	$2,104,000
Cost of Engine 4 (USD)	$1,830,000	$1,830,000	$2,104,000
Cost of Harbor Gen. (USD)	$839,000	$ -	$ -
Cost of Batteries (USD)	$ -	$705,000	$ -
Cost of Batteries: Aux. Equip. (USD)	$ -	$500,000	$ -
TOTAL	$9,377,000	$9,743,000	$9,818,000

Operating Expenses for Baseline Operating Profile

The baseline operating profile, consisting of eight activities, is presented in detail in Table 7. The maximum expected electrical power demand for each activity was estimated as a percent of total installed mechanical power. A demand factor was applied to these values to account for the fact that the load will not always be at the maximum. For example, while the maximum on station DP load may be 60% of installed power, or ~10MW, the demand factor would bring this load down to around 6MW as a more typical value appropriate for fuel consumption calculations. Similarly, the icebreaking load may be as high as 13-14 MW, a more typical value would be closer to 8MW when considering fuel consumption over many days. In terms of how the generator are actually loaded, the loading will vary depending on may factors and the number and size of generators needed can also vary. The demand factor is a tool used to ‘flatten’ this variation and allow a reasonable estimate for calculating fuel consumption.

Calculations for the required power during open water transit assumed a speed of 11 knots including an allowance for hotel loads (10% of total installed mechanical power excluding the harbor generator), a 1.6 times multiplier to account for added resistance in wind and waves, a 97% motor efficiency, and 97% drive efficiency.

Table 7 Baseline Operating Profile (Reference 6)

Activity	Speed (kt)	Days	Required % of Installed Mechanical Power	Demand Factor	Required Power w/Demand Factor (KWe)
Open Water Transit	11	79	n/a	n/a	7,271
Icebreaking	3	29	80%	0.60	8,064
On Station DP	0	49	60%	0.60	6,048
On Station	0	15	30%	0.60	3,024

Activity	Speed (kt)	Days	Required % of Installed Mechanical Power	Demand Factor	Required Power w/Demand Factor (KWe)
Deployment – Dredging & Trawling	1 - 3	17	50%	0.60	5,040
Deployment – Towing Side Scan	1 – 3	10	50%	0.60	5,040
Hotel Only	0	82	10%	0.60	1,008
Ice Transit	<= 6	84	30%	0.60	3,024
TOTAL DAYS		**365**			

The amount of power needed to perform each activity was scaled based on the installed power and the endurance calculations presented in Reference 1. Table 8 below lists the engine loads necessary to meet the power demands of each activity for the diesel electric and VSG power systems for the baseline operating profile. These loads are listed as a percent of each engine's MCR. See Appendix B for a complete list of these values for the other three operating profiles.

Table 8 Engine loads as % of MCR: diesel electric & VSG for baseline operating profile

Activity	Eng. 1 (4,800kW)	Eng. 2 (4,800kW)	Eng. 3 (3,600kW)	Eng. 4 (3,600kW)	Harbor Gen (1,320kW)
Open Water Transit	78.5%	78.5%	0.0%	0.0%	0.0%
Icebreaking	46.5%	0.0%	85.0%	85.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%	0.0%
On Station	0.0%	0.0%	87.0%	87.0%	0.0%
Deployment – Dredging & Trawling	0.0%	0.0%	72.5%	72.5%	0.0%
Deployment – Towing Side Scan	0.0%	0.0%	72.5%	72.5%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	0.0%	0.0%

This table applies to both the fixed and variable speed power systems since the generators for both are of equal size. As noted above, there may be times when more generators are needed to respond to the load. For example, during icebreaking there may be times when all four generators are needed, but on average the load can be met with fewer. It is assumed that loads and operating times are split evenly between engines 1 & 2 and engines 3 & 4. The loads were determined through an optimization analysis to minimize fuel consumption while simultaneously considering performative factors, such as needing reserve power when station keeping or icebreaking. Because their speed can be reduced at lower loads, the VSGs are more efficient than the fixed speed generators. The resultant fuel savings are listed in Tables 2-5.

Table 9 and Table 10 list the engine loads for the hybrid system for the baseline operating profile. Table 9 shows how the engines are used when charging the battery, while Table 10 shows how the engines are used when discharging the battery. See Appendix B for a complete list of these values for the other three operating profiles.

Table 9 Engine loads as % of MCR: hybrid – diesel electric with battery (charging) for baseline operating profile

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	85.0%	0.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	85.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	85.0%	0.0%
Hotel Only	0.0%	0.0%	85.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

Table 10 Engine loads as % of MCR: hybrid – diesel electric with battery (discharging) for baseline operating profile

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	0.0%	85.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	0.0%	0.0%
Deployment – Towing & Side Scan	85.0%	0.0%	0.0%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

For all operating profiles, the engines in the hybrid system operate at their best efficiency point (BEP) of 85% MCR nearly all the time. At the BEP the engines burn less fuel than at any other load. These fuel savings are summarized in Tables 2-5.

Because no operating load requires exactly 85% of MCR, the engines (when operating at BEP) will produce an excess or deficit of power. Excess power is used to charge the batteries. When there is a deficit of power, it is made up for by discharging the batteries. For all operating profiles, an analysis was conducted to determine the optimal balance between time spent charging the batteries, discharging the batteries, and not using the batteries at all, such that fuel consumption was minimized. It is worth noting that for icebreaking the hybrid system is operating on two generators compared with three generators for the diesel electric and VSG systems. The rationale for this is that the batteries are able to absorb the additional power surges whereas without the battery an additional generator is needed to ensure adequate power is available.

After determining engine loads for each system, activity, and operating profile, data was collected from MAN on the specific fuel consumption (SFC) of both the fixed and variable speed engines. These SFC values, in grams/kWh, are summarized in Figure 1 and Figure 2. The figures show the benefit of lower fuel consumption at lower loads for the variable speed vs. the constant speed engines. It is expected that the VSG curve will be significantly 'flatter' (better) at lower load when a product is commercially available. Similar curves from other manufacturers with VSG products show more significant fuel savings at lower loads.

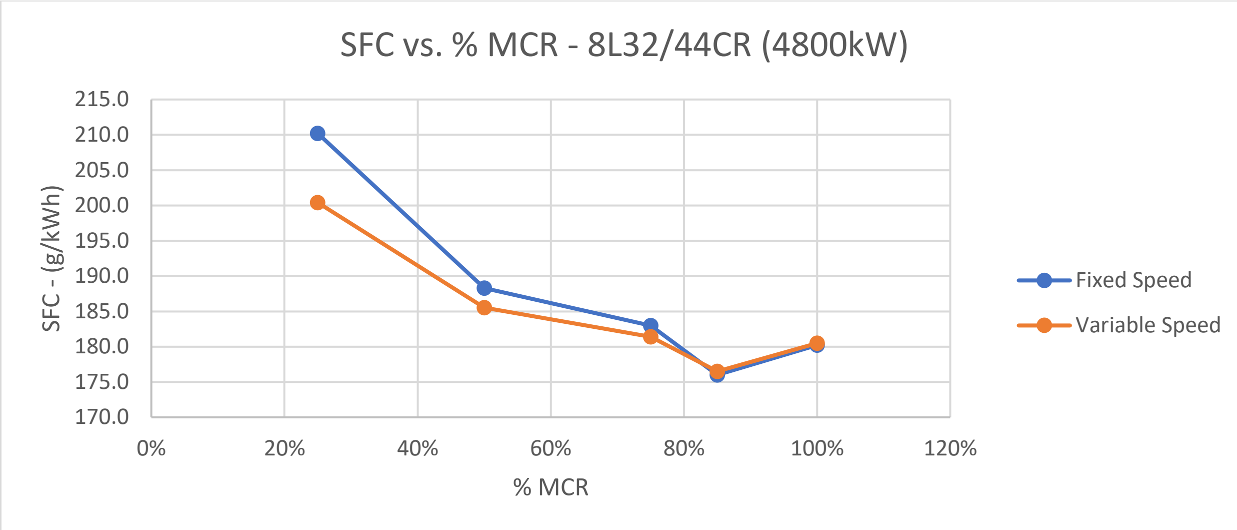


Figure 1 Specific fuel consumption (SFC) of fixed and variable speed 8L32/44CR MAN engine

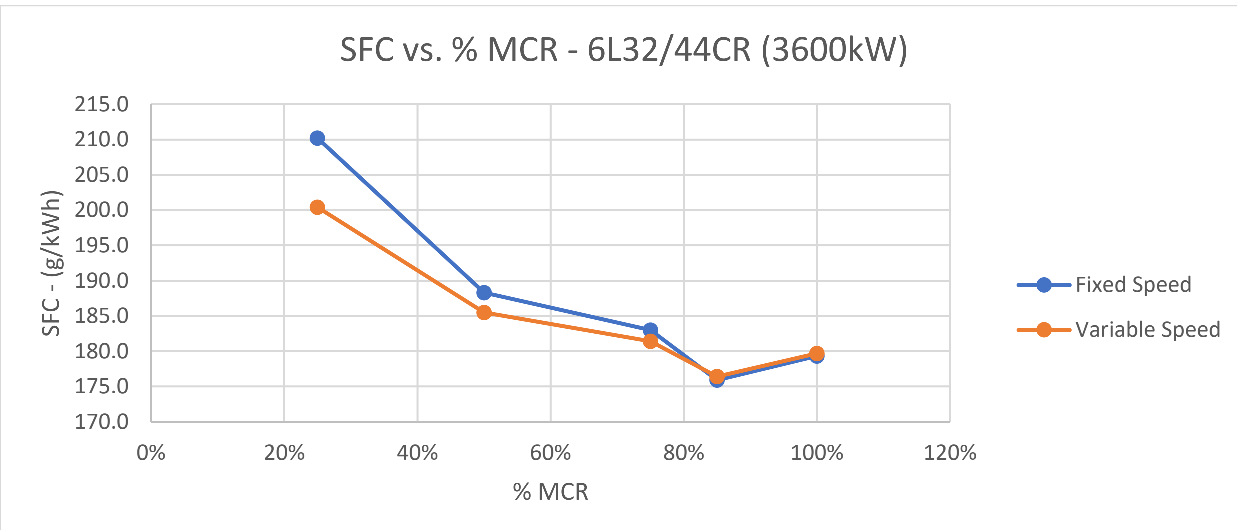


Figure 2 Specific fuel consumption (SFC) of fixed and variable speed 6L32/44CR MAN engine

These data points were used to determine the SFC of each engine at the loads shown in Table 8, Table 9, and Table 10 in order to calculate the annual fuel consumption for each power system and operating profile. Intermediate values were linearly interpolated.

The 2021 constant dollar price of MDO was assumed to be USD$1.50/gallon. This price was then time adjusted using a 30-year, uniform present value (UPV) factor. This accounted for the escalation in fuel prices over time, and the discounting of these future prices to adjust for the time value of money. A real, 30-year discount rate of 0.7% was used. The UPV factor, equating to 30.47, was multiplied by the base price of USD$1.50/gallon and the annual fuel consumption (in gallons) to arrive at the 30-year, 2021 constant dollar cost of fuel for each system. These life cycle costs are summarized in the Executive Summary for all four operating profiles.

For all operating profiles, the hybrid system consumes the least amount of fuel. For the baseline operating profile, the hybrid system saves approximately USD$1.2M over the 30-year life of the vessel compared to the baseline diesel electric system, and USD$1.1M compared to the VSG system.

Engine Maintenance

MAN was contacted to obtain maintenance schedules for the engines to determine the recommended periodicity of service items such as lube oil changes, minor overhauls, major overhauls, and alternator replacements (Appendix A). The annual run time, in hours, was calculated for each engine and power system and each operating profile. These times are summarized below in Table 11 for the baseline operating profile. See Appendix B for a complete list of these values for the other three operating profiles.

Table 11 Annual run time (in hours) of engines for each system for the baseline operating profile

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Run Time (hr) - Engine 1	2,244	2,372	2,244
Run Time (hr) - Engine 2	2,244	2,372	2,244
Run Time (hr) - Engine 3	3,708	3,414	4,692
Run Time (hr) - Engine 4	3,708	3,414	4,692
Run Time (hr) – Harbor Generator	1,968	0	0
TOTAL	**13,872**	**11,572**	**13,872**

These annual operating hours were compared against the maintenance schedule to determine the frequency (in years) of each service. An estimate was made for the one-time cost of these services in constant 2021 dollars. Maintenance periods and costs for each engine, system, and operating profile are summarized below in Table 12 and Table 13.

Table 12 Maintenance costs (2021 USD) for all operating profiles: harbor generator & engines 1 - 4

Service Item	Diesel Electric (Harbor Gen. Only)	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Lube Oil Change				
One time cost (USD)	$1,788	$11,375	$11,375	$9,669
Service period (hr)	4,000	4,000	4,000	4,000
Minor Overhaul				
One time cost (USD)	$10,175	$64,750	$64,750	$55,038
Service period (hr)	8,000	8,000	8,000	8,000
Major Overhaul				
One time cost (USD)	$66,550	$423,500	$423,500	$359,975
Service period (hr)	30,000	30,000	30,000	30,000
Alternator Overhaul				
One time cost (USD)	$7,857	$50,000	$50,000	$42,500
Service period (yr)	10	10	10	10

Table 13 Maintenance periods (yrs) (2021 USD) for all operating profiles: harbor generator & engines 1 - 4

Service Item	Diesel Electric (Harbor Gen. Only)	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Lube Oil Change				
Operating Profile 1	2.03	1.34	1.38	1.15
Operating Profile 2	2.19	1.30	1.33	1.13
Operating Profile 3	2.14	1.33	1.36	1.15
Operating Profile 4	2.28	1.33	1.39	1.16
Minor Overhaul				
Operating Profile 1	4.07	2.69	2.77	2.31
Operating Profile 2	4.39	2.60	2.67	2.26
Operating Profile 3	4.27	2.66	2.72	2.30
Operating Profile 4	4.57	2.66	2.78	2.32
Major Overhaul				
Operating Profile 1	15.24	10.08	10.37	8.65
Operating Profile 2	16.45	9.75	10.00	8.49
Operating Profile 3	16.03	9.96	10.21	8.62
Operating Profile 4	17.12	9.96	12.76	8.70

The dates of all future maintenance were calculated from the period of each service item. The single present value (SPV) of the future cost for each of these services was calculated to account for the time value of money, bringing each cost into constant 2021 dollars. These costs were summed over the life of the vessel for each engine, power system, and operating profile. The life cycle costs for the engine maintenance of each system are summarized below in Table 14 for the baseline operating profile. See Appendix B for a complete list of these values for the other three operating profiles.

Table 14 30-year maintenance costs for each power system for baseline operating profile

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Lube oil change	$473,000	$430,000	$436,000
Minor overhaul	$1,339,000	$1,167,000	$1,192,000
Major overhaul	$1,585,000	$1,521,000	$1,917,000
Alternator replacement	$329,000	$315,000	$315,000
TOTAL	**$3,726,000**	**$3,433,000**	**$3,860,000**

For all operating profiles, the hybrid system incurs the least maintenance costs. For the baseline operating profile, the hybrid system saves approximately USD$293,000 over the service life of the plant compared to the diesel electric system, and USD$427,000 compared to the VSG system. These savings are directly attributable to the 16.6% decrease in run time on the engines for the hybrid system compared to either the fixed or variable speed systems. The cost of maintenance for the VSG system is higher due to the need for one extra major overhaul of the engines. This results from the VSG system lacking either a harbor generator or battery bank to provide power at lower loads. Rather, even lesser loads must be met by running at least one of the four engines, resulting in more run time and greater maintenance costs.

Battery Replacement

It was assumed that the batteries have a service life of 10 years. This number was based on 24,000 cycles at 40% depth of discharge (DoD). The DoD of a battery represents the percent of its total capacity that will be discharged before recharging the battery. The shallower the DoD, the longer the battery will last (more cycles it can survive). One cycle is defined as discharging the battery by its DoD and then re-charging it by the same amount. Based on these assumptions, the vessel's mission profile, and the engine loads from Table 9 and Table 10, it was determined that a 2,350kWh battery is needed. For the baseline operating profile, a battery this size would need replacing about once every 10.06 years, or twice over the service life of the power plant.

It was assumed that at the time of construction, when the first set of batteries will be purchased, the price of energy storage will be USD$300/kWh and will decrease 2.5% each year. The uniform present values of the future costs of replacing the batteries at years 10.06 and 20.13 were thus calculated with an escalation rate of -2.5%, and a real discount rate of 0.7%. The life cycle costs, in constant 2021 dollars, for replacing the batteries are summarized in Table 15 for all operating profiles.

The cost benefits of using a larger battery were also estimated. While incurring greater capital expense, a larger battery needs to be replaced only once over the life of the vessel. Glosten found no appreciable difference in the life cycle costs between a larger or smaller battery bank. However, a smaller battery bank saves on space and allows for installation of new battery technology twice over the life of the vessel instead of just once.

Table 15 Constant 2021-dollar cost of periodic battery replacement for hybrid system for all operating profiles

Service Item	Time of Service (years)	Single Present Value of Future Cost
Operating Profile 1		
Battery Replacement	10.06	$509,000
Battery Replacement	20.13	$368,000
Total		**$877,000**
Operating Profile 2		
Battery Replacement	10.14	$508,000
Battery Replacement	20.28	$366,000
Total		**$874,000**
Operating Profile 3		
Battery Replacement	10.64	$500,000
Battery Replacement	21.28	$355,000
Total		**$855,000**
Operating Profile 4		
Battery Replacement	11.32	$489,000
Battery Replacement	22.64	$340,000
Total		**$829,000**

Emissions

Emissions for each power system and operating profile were compared. Data showing the relationship between engine load and pollutants were collected from MAN for both the fixed and variable speed generators (Appendix A). These values are summarized for each engine and power system below in . Values for NO_x (oxides of nitrogen), SO_2 (sulfur dioxide) and $C0_2$ were available across the full load band. However, values for PM (particulate matter) were not available for all loads for all engines, therefore a comparison was not possible.

Table 16 Emissions data (grams/kWh) for fixed and variable speed engines as function of load

Load (%)	Eng. 1&2 (g/kWh)	Eng. 3&4 (g/kWh)	VSGs 1&2 (g/kWh)	VSGs 3&4 (g/kWh)	Harbor Generator (g/kWh)
CO_2					
100	602.9	600.3	603.8	601.3	653.1
85	588.8	588.7	590.4	590.1	647.5
75	612.7	612.7	607.2	607.2	647.4
50	629.9	629.9	620.6	620.6	664.9
25	703.1	703.1	669.7	669.7	734.1
NO_X					
100	11.01	11.2	10.87	11.0	9.56
85	13.40	13.4	13.20	13.2	10.23
75	9.14	9.1	11.00	11.0	10.18
50	10.82	10.8	14.17	14.2	10.42
25	15.00	15.0	15.49	15.5	11.53
SO_2					
100	1.90	1.89	1.91	1.90	2.06
85	1.86	1.86	1.86	1.86	2.04
75	1.93	1.93	1.92	1.92	2.04
50	1.99	1.99	1.96	1.96	2.10
25	2.22	2.22	2.12	2.12	2.32

Intermediate values between loads were linearly interpolated. Using these data, the mission profile, and the generator loads, the annual metric tons (MT) of pollutants were calculated for each engine, power system, and operating profile. These values are summarized in for the baseline operating profile. See Appendix B for a complete list of these values for the other three operating profiles.

Table 17 Annual metric tons of emissions for each power system for baseline operating profile

Emissions	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
CO_2 – (MT)	24,294	24,019	24,267
NO_X – (MT)	473	540	508
SO_2 – (MT)	77	76	77
TOTAL	**24,844**	**24,635**	**24,852**

For all operating profiles, the hybrid system produced the least amount of total pollutants. This is directly attributable to the decrease in run time on the engines in the hybrid system compared to the fixed and variable speed systems (see Table 11). It should be noted, however, that the hybrid system produced higher NO_x emissions than the others. It is suspected that this is attributable to the fact that NO_x production is temperature-dependent and the hybrid always operates at a higher load (even if less time).

Findings

For all four operating profiles the hybrid system has the lowest lifecycle cost of the three power systems, produces the least total emissions, dramatically decreases engine operating hours, allows for quiet operations, and provides instantaneous power when needed. The hybrid system also negates the need to purchase and operate a separate harbor generator. This makes the hybrid power plant the best overall solution for the ARV.

It should be noted that this analysis was done based on static operating profiles (Table 1 and Table 7). These static operating profiles assume that the loads will always be static during a particular operation. Each load in the operating profile represents an estimated average and therefore the process cannot capture the dynamic load changes that will actually occur during operation. In a hybrid system the battery will respond to the dynamic load changes and allow the diesel generators to operate at their best operating point. In the conventional diesel electric system, the diesel generators will have to 'follow' the load as required and therefore it will not always be sitting at the loads shown in the profiles. Therefore in actual operation a hybrid system in will likely have lower fuel consumption and lifecycle cost than calculated in this report.

The benefits of a hybrid system should be present regardless of the type of propulsion system that is selected. See the Executive Summary for the life cycle costs and CO_2 emissions for each power system and operating profile.

Specification Changes

Recommended Changes

Based on the findings of this study, it is recommended that a hybrid power plant be specified for the ARV. Modifications to Sections 201, 301, and 311 are recommended.

Required Owner Decisions

There are no required owner decisions other than approving or disapproving of the above recommended specification changes.

Appendix A MAN Power Systems Information

Quotation

MAN Energy Solutions
Future in the making

Customer
Glosten ship design

Customer reference
Icebreaker

Application
Icebreaker

MAN quotation number
4306887-01-A001

Date
2020-04-15

MAN Energy Solutions

Main Generating Sets

MAN Energy Solutions
Elvis Ettenhofer
Dept. SESMM
Phone +49 821 322 4397
elvis.ettenhofer@man-es.com

Dear Sirs,

We thank you for your enquiry and are pleased to quote as follows, subject to confirmation:

SCOPE OF SUPPLY

2	Generating sets 8L32/44CR incl. alternators	4.800 kW per engine at 720 rpm
2	Generating sets 6L32/44CR incl. alternators	3.600 kW per engine at 720 rpm

Extent of delivery in accordance with the attached technical specification(s) 4306887-01-A001 dated 2020-04-15.

PRICE

Total price for above scope of supply per shipset : **7.175.000 EUR**

This price is a firm fixed price, strictly net, sea packed, FOB Northern European Main Seaport, according to Incoterms 2010, based on a delivery not later than 2021-12.

PAYMENT CONDITIONS

Our quotation is based on the following payment conditions:

- 15% down payment
- 25% at mid of contractual delivery time
- 60% on notification of readiness for dispatch

TIME OF DELIVERY

The present ex-works delivery time is approx. 12 months from the date of fully clarified order, subject to prior sales.

VALIDITY OF QUOTATION

This quotation is valid until 2020-05-31.

SOURCING

The supply will be delivered and warranted by MAN Energy Solutions, and the origin of the engines will be at the supplier's decision.

WARRANTY PERIOD

12 months from approved sea trial or 24 months after readiness of dispatch of the equipment, whichever period expires first.

CONFIDENTIALITY

This quotation is confidential. It may be shared with third parties only who have a need-to-know for the realization of this project under the prerequisite of confidentiality. Under no circumstances, it may be shared with MAN Energy Solutions' competitors.

GENERAL CONDITIONS

In addition to this quotation the MAN Energy Solutions General Conditions for the Supply of Marine Products shall apply. They are attached on the following pages and available for download on the Internet under:
www.mandieselturbo.com/marinesalesconditions

We trust, our quotation will be of interest to you and are available for any further information you may require.

Yours faithfully

MAN Energy Solutions

gez. i.V. Elvis Ettenhofer

Sales Manager Marine
Medium Speed

Four-Stroke Marine

gez. i.V. Udo Ziegler

Manager Tendering Marine
Medium Speed

Four-Stroke Marine

Planning data

Operating data - Marine Plants

4306887 - Ice Breaker

Engine configuration: MAN 6L32/44CR B5, Electric propulsion, 3600kW, 600kW/Cyl., 720rpm, ECOMAP 1 = Standard engine map
Fuel and emission: MDO, Tier II, E2 - cycle
Reference according to ISO 3046-1; ISO 15550
MAN SCR: SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)
Exhaust gas temperature control: 320°C (load ≥ 5 %)

Reference conditions

Air temperature	°C			25		
Relative humidity	%			30		
Air pressure	mbar			1,000		
CW temperature before CAC (LT stage)	°C	25	25	25	25	25
Glycol concentration HT string	Vol%			0		
Glycol concentration LT string	Vol%			0		

Engine performance

Engine output	%	100	85	75	50	25
Engine output	kW	3,600	3,060	2,700	1,800	900
Speed	1/min	720	720	720	720	720
Fuel oil consumption 1) (NCV = 42,700 kJ/kg)	g/kWh	179.3	175.9	183.0	188.3	210.2

Heat to be dissipated 2) 4)

Charge air							
Charge air cooler (HT stage)	$\dot{V}_{cw}$ = 42.0 m^3/h	kW	875	605	585	246	0
Charge air cooler (LT stage)	$\dot{V}_{cw}$ = 66.0 m^3/h 7)	kW	429	320	313	195	102
Lube oil cooler 6)	$\dot{V}_{cw}$ = 66.0 m^3/h 5)	kW	369	352	341	304	259
Jacket cooling	$\dot{V}_{cw}$ = 42.0 m^3/h	kW	294	265	249	210	154
Compressor wheel casing cooling	$\dot{V}_{cw}$ = 1.4 m^3/h	kW	13	11	10	7	3
Nozzle cooling	$\dot{V}_{cw}$ = 1.0 m^3/h	kW	0	0	0	0	0
Heat radiation (engine) (based on engine room temp. 35°C)		kW	144	131	123	101	74

Air data

Temperature of charge air						
at compressor outlet	°C	241	210	208	154	87
at charge air cooler outlet	°C	40	40	40	40	40
Air flow rate	kg/kWh	6.31	6.26	6.95	7.55	8.48
Charge air pressure (abs.)	bar	5.05	4.28	4.15	2.83	1.64

Exhaust gas data 3)

Mass flow	t/h	23.4	19.7	19.3	13.9	7.8
Exhaust gas temperature control active	-	Yes	Yes	Yes	No	No
Exhaust gas temperature at turbine outlet	°C	320	320	320	323	342
Heat content (190 °C)	kW	909	766	748	552	355
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50				

Footnotes

1) Tolerances (fuel consumption): +5%; Fuel: MDO; NCV = 42,700kJ/kg (measured NCV of fuel analysis); Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1
2) Tolerances (heat to be dissipated): +8 % for rating coolers, +6 % for central cooler (HT-, LT- and lube oil system), -12 % for heat recovery from HT- or LT- or lube oil system
3) Tolerances (exhaust gas data): ±5 °C/±15 °C for temperature at turbine outlet (control active/control not active), ±6 %/±4 % for flow quantity (control active/control not active)
4) Lube oil volume flow through engine: $\dot{V}_{LO}$ = 105 m^3/h

Specific lube oil consumption of the engine (related to reference full load from heading): 0.5 g/kWh +20 %

5) If charge air cooler (LT stage) and lube oil cooler are connected in series
6) Addition required for separator heat (e.g. 30 kJ/kWh)
7) Nominal CW-flow – the actual CW-flow may vary for control purposes

Last change of engine base data (ID: 32_44CR_600kW_TIER2_E2_ECO1): 2020-01-22

Planning data

Operating data - Marine Plants

4306887 - Ice Breaker

Engine configuration:	**MAN 8L32/44CR B5, Electric propulsion, 4800kW, 600kW/Cyl., 720rpm, ECOMAP 1 = Standard engine map**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO 3046-1; ISO 15550	
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C			25		
Relative humidity	%			30		
Air pressure	mbar			1,000		
CW temperature before CAC (LT stage)	°C	25	25	25	25	25
Glycol concentration HT string	Vol%			0		
Glycol concentration LT string	Vol%			0		

Engine performance

Engine output	%	100	85	75	50	25
Engine output	kW	4,800	4,080	3,600	2,400	1,200
Speed	1/min	720	720	720	720	720
Fuel oil consumption 1) (NCV = 42,700 kJ/kg)	g/kWh	180.2	176.0	183.0	188.3	210.2

Heat to be dissipated 2) 4)

Charge air							
Charge air cooler (HT stage)	$\dot{V}_{cw}$ = 56.0 m^3/h	kW	1,112	796	773	326	0
Charge air cooler (LT stage)	$\dot{V}_{cw}$ = 88.0 m^3/h 7)	kW	563	435	424	261	136
Lube oil cooler 6)	$\dot{V}_{cw}$ = 88.0 m^3/h 5)	kW	499	470	455	406	345
Jacket cooling	$\dot{V}_{cw}$ = 56.0 m^3/h	kW	405	354	332	280	205
Compressor wheel casing cooling	$\dot{V}_{cw}$ = 1.4 m^3/h	kW	18	15	13	9	5
Nozzle cooling	$\dot{V}_{cw}$ = 1.4 m^3/h	kW	0	0	0	0	0
Heat radiation (engine) (based on engine room temp. 35°C)		kW	192	174	164	135	98

Air data

Temperature of charge air						
at compressor outlet	°C	239	210	208	154	87
at charge air cooler outlet	°C	40	40	40	40	40
Air flow rate	kg/kWh	6.16	6.25	6.95	7.55	8.48
Charge air pressure (abs.)	bar	4.95	4.28	4.15	2.84	1.64

Exhaust gas data 3)

Mass flow	t/h	30.5	26.3	25.7	18.6	10.4
Exhaust gas temperature control active	-	Yes	Yes	Yes	No	No
Exhaust gas temperature at turbine outlet	°C	320	320	320	323	342
Heat content **(190 °C)**	kW	1,186	1,020	997	736	473
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50				

Footnotes

1) Tolerances (fuel consumption): +5%; Fuel: MDO; NCV = 42,700kJ/kg (measured NCV of fuel analysis); Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1

2) Tolerances (heat to be dissipated): +8 % for rating coolers, +6 % for central cooler (HT-, LT- and lube oil system), -12 % for heat recovery from HT- or LT- or lube oil system

3) Tolerances (exhaust gas data): ±5 °C/±15 °C for temperature at turbine outlet (control active/control not active), ±6 %/±4 % for flow quantity (control active/control not active)

4) Lube oil volume flow through engine: $\dot{V}_{LO}$ = 124 m^3/h

Specific lube oil consumption of the engine (related to reference full load from heading): 0.5 g/kWh +20 %

5) If charge air cooler (LT stage) and lube oil cooler are connected in series

6) Addition required for separator heat (e.g. 30 kJ/kWh)

7) Nominal CW-flow – the actual CW-flow may vary for control purposes

Last change of engine base data (ID: 32_44CR_600kW_TIER2_E2_ECO1): 2020-01-22

Planning data

Operating data - Marine Plants

4307041 - Ice breaker - Glosten

Engine configuration:	**MAN 6L32/44CR B6, Mechanical propulsion CPP, 3600kW, 600kW/Cyl., 750rpm, ECOMAP 1 = Standard engine map, recommended combinator curve**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO	**3046-1; ISO 15550**
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C			25		
Relative humidity	%			30		
Air pressure	mbar			1,000		
CW temperature before CAC (LT stage)	°C	25	25	25	25	25
Glycol concentration HT string	Vol%			0		
Glycol concentration LT string	Vol%			0		

Engine performance

Engine output	%	100	85	75	50	25
Engine output	kW	3,600	3,060	2,700	1,800	900
Speed	1/min	750	750	731	674	587
Fuel oil consumption [1] (NCV = 42,700 kJ/kg)	g/kWh	179.7	176.4	181.4	185.5	200.4

Heat to be dissipated [2] [4]

Charge air							
Charge air cooler (HT stage)	$\dot{V}_{CW}$ = 42.0 m^3/h	kW	879	612	546	202	-10
Charge air cooler (LT stage)	$\dot{V}_{CW}$ = 66.0 m^3/h [7]	kW	430	322	289	183	85
Lube oil cooler [6]	$\dot{V}_{CW}$ = 66.0 m^3/h [5]	kW	370	353	340	304	258
Jacket cooling	$\dot{V}_{CW}$ = 42.0 m^3/h	kW	295	265	246	210	153
Compressor wheel casing cooling	$\dot{V}_{CW}$ = 1.4 m^3/h	kW	13	11	10	7	3
Nozzle cooling	$\dot{V}_{CW}$ = 1.0 m^3/h	kW	0	0	0	0	0
Heat radiation (engine) (based on engine room temp. 35°C)		kW	91	85	81	70	53

Air data

Temperature of charge air						
at compressor outlet	°C	242	211	205	144	81
at charge air cooler outlet	°C	40	40	40	40	40
Air flow rate	kg/kWh	6.32	6.27	6.56	7.24	7.18
Charge air pressure (abs.)	bar	5.05	4.31	4.08	2.67	1.52

Exhaust gas data [3]

Mass flow	t/h	23.4	19.8	18.2	13.4	6.6
Exhaust gas temperature control active	-	Yes	Yes	No	No	No
Exhaust gas temperature at turbine outlet	°C	320	320	322	321	369
Heat content **(190 °C)**	kW	911	768	720	521	357
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50				

Footnotes

1) Tolerances (fuel consumption):	+5%; Fuel: MDO; NCV = 42,700kJ/kg (reference NCV for SFOC comparison); Attached pumps: lube oil: **1 resp. 2**; HT-water: **1**; LT-water: **1**
2) Tolerances (heat to be dissipated):	+8 % for rating coolers, +6 % for central cooler (HT-, LT- and lube oil system), -12 % for heat recovery from HT- or LT- or lube oil system
3) Tolerances (exhaust gas data):	±5 °C/±15 °C for temperature at turbine outlet (control active/control not active), ±6 %/±4 % for flow quantity (control active/control not active)
4) Lube oil volume flow through engine:	$\dot{V}_{LO}$ = 105 m^3/h
Specific lube oil consumption of the engine (related to reference full load from heading):	0.5 g/kWh +20 %

5) If charge air cooler (LT stage) and lube oil cooler are connected in series
6) Addition required for separator heat (e.g. 30 kJ/kWh)
7) Nominal CW-flow – the actual CW-flow may vary for control purposes

Last change of engine base data (ID: 32_44CR_600kW_TIER2_CPP_Curve_ECO1): 2020-10-01

Planning data

Operating data - Marine Plants

4307041 - Ice breaker - Glosten

Engine configuration:	**MAN 8L32/44CR B6, Mechanical propulsion CPP, 4800kW, 600kW/Cyl., 750rpm, ECOMAP 1 = Standard engine map, recommended combinator curve**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO	**3046-1; ISO 15550**
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C			25		
Relative humidity	%			30		
Air pressure	mbar			1,000		
CW temperature before CAC (LT stage)	°C	25	25	25	25	25
Glycol concentration HT string	Vol%			0		
Glycol concentration LT string	Vol%			0		

Engine performance

Engine output	%	100	85	75	50	25
Engine output	kW	4,800	4,080	3,600	2,400	1,200
Speed	1/min	750	750	731	674	587
Fuel oil consumption [1] (NCV = 42,700 kJ/kg)	g/kWh	180.5	176.5	181.4	185.5	200.4

Heat to be dissipated [2) 4)]

Charge air							
Charge air cooler (HT stage)	$\dot{V}_{CW}$ = 56.0 m^3/h	kW	1,117	804	722	268	-13
Charge air cooler (LT stage)	$\dot{V}_{CW}$ = 88.0 m^3/h [7)]	kW	565	436	392	246	114
Lube oil cooler [6)]	$\dot{V}_{CW}$ = 88.0 m^3/h [5)]	kW	499	471	453	406	344
Jacket cooling	$\dot{V}_{CW}$ = 56.0 m^3/h	kW	406	355	328	280	204
Compressor wheel casing cooling	$\dot{V}_{CW}$ = 1.4 m^3/h	kW	18	15	13	9	5
Nozzle cooling	$\dot{V}_{CW}$ = 1.4 m^3/h	kW	0	0	0	0	0
Heat radiation (engine) (based on engine room temp. 35°C)		kW	121	114	109	93	71

Air data

Temperature of charge air						
at compressor outlet	°C	239	211	206	144	81
at charge air cooler outlet	°C	40	40	40	40	40
Air flow rate	kg/kWh	6.17	6.25	6.56	7.24	7.18
Charge air pressure (abs.)	bar	4.96	4.30	4.08	2.67	1.52

Exhaust gas data [3)]

Mass flow	t/h	30.5	26.3	24.3	17.8	8.9
Exhaust gas temperature control active	-	Yes	Yes	No	No	No
Exhaust gas temperature at turbine outlet	°C	320	320	322	321	369
Heat content **(190 °C)**	kW	1,188	1,021	962	695	476
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50				

Footnotes

1) Tolerances (fuel consumption): +5%; Fuel: MDO; NCV = 42,700kJ/kg (reference NCV for SFOC comparison); Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1

2) Tolerances (heat to be dissipated): +8 % for rating coolers, +6 % for central cooler (HT-, LT- and lube oil system), -12 % for heat recovery from HT- or LT- or lube oil system

3) Tolerances (exhaust gas data): ±5 °C/±15 °C for temperature at turbine outlet (control active/control not active), ±6 %/±4 % for flow quantity (control active/control not active)

4) Lube oil volume flow through engine: $\dot{V}_{LO}$ = 124 m^3/h

Specific lube oil consumption of the engine (related to reference full load from heading): 0.5 g/kWh +20 %

5) If charge air cooler (LT stage) and lube oil cooler are connected in series

6) Addition required for separator heat (e.g. 30 kJ/kWh)

7) Nominal CW-flow – the actual CW-flow may vary for control purposes

Last change of engine base data (ID: 32_44CR_600kW_TIER2_CPP_Curve_ECO1): 2020-10-01

Exhaust gas emissions

Operating data - Marine Plants

4307041 - Icebreaker - Glosten

Engine configuration:	**MAN 6L32/44CR B6, Mechanical propulsion CPP, 3600kW, 600kW/Cyl., 750rpm, ECOMAP 1 = Standard engine map, recommended combinator curve**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO	**3046-1; ISO 15550**
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C	25
Relative humidity	%	30
Absolute humidity	g/kg	6.0
Air pressure	mbar	1000
Glycol concentration HT string	Vol%	0
Glycol concentration LT string	Vol%	0
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50
Oxygen reference value	%	15.0

Fuel type: MDO

Sulfur content S	wt%	0.50
Nitrogen content N	wt%	0.10
Oxygen content O_2	wt%	0.00
Carbon content C	wt%	86.24
Hydrogen content	wt%	13.14
Ash content	wt%	0.01
Water content H_2O	wt%	0.02
Density (15 °C)	kg/m³	865
Net calorific value	kJ/kg	42400

Exhaust gas emissions

Engine load	%	100.0	85.0	75.0	50.0	25.0
Engine output	kW	3600	3060	2700	1800	900
Speed	1/min	750	750	731	674	587
Charge air pressure (abs.)	bar	5.05	4.31	4.08	2.67	1.52
CW temperature before CAC (LT stage)	°C	25.0	25.0	25.0	25.0	25.0
Temperature of charge air at charge air cooler outlet	°C	40.0	40.0	40.0	40.0	40.0
Absolute humidity of combustion air	g/kg	6.0	6.0	6.0	6.0	6.0
Air flow rate	kg/kWh	6.3	6.3	6.6	7.2	7.2
Fuel oil consumption 4) (NCV = 42,400 kJ/kg)	g/kWh	180.9	177.6	182.7	186.8	201.9
Exhaust gas temperature at turbine outlet 6)	°C	320	320	322	321	369
Exhaust gas temperature control active	-	Yes	Yes	No	No	No
Exhaust gas volume flow 5)	m³/h	39912	33670	31186	22830	12257
Exhaust gas standard volume flow 5)	Nm³/h	18102	15271	14093	10344	5137
Exhaust gas mass flow 5)	kg/h	23429	19765	18240	13389	6649
O_2	g/kWh	812	812	862	1002	934
	Vol%, dry	12.05	12.13	12.31	12.94	12.19
CO_2	g/kWh	601.3	590.1	607.2	620.6	669.7
	Vol%, dry @ act. O_2	6.45	6.37	6.26	5.79	6.32
H_2O	g/kWh	260.16	255.79	263.82	272.81	290.87
	Vol% @ act.% O_2	6.00	5.94	5.86	5.50	5.91
NO_x 1)	g/kWh	11.02	13.22	11.00	14.17	15.49
	mg/Nm³, dry @ 15% O_2	1570*	1910*	1550*	1950	1970
	ppm, wet @ act.% O_2	1070	1295	1030	1205	1325
	ppm, dry @ act.% O_2	1140	1375	1095	1275	1410
CO	g/kWh	0.34	0.41	0.41	0.57	0.93
	mg/Nm³, dry @ 15% O_2	50*	60*	60*	80	120
	ppm, dry @ act.% O_2	55	70	65	85	140
HC	g/kWh	0.54	0.53	0.53	0.60	0.71
	mg/Nm³, dry @ 15% O_2	80*	80*	70*	80	90
	ppm, wet @ act.% O_2	175	170	165	170	200
	ppm, dry @ act.% O_2	185	185	175	180	215
SO_2 2)	g/kWh	1.90	1.86	1.92	1.96	2.12
	mg/Nm³, dry @ 15% O_2	270*	270*	270*	270	270
	ppm, dry @ act.% O_2	135	135	135	125	135
TSP 3) 7)	g/kWh	0.352	0.347	0.356	-	-
	mg/Nm³, dry @ 15% O_2	50*	50*	50*	-	-

Notes

All values only for guidance, not guaranteed, except values with addition *

Measuring instrument tolerance not chargeable upon MAN Energy Solutions SE

Standard reference conditions (standard cubic meter Nm³): 1013 mbar; 0 °C

O_2, NO_x, CO, HC measurement acc. to ISO-8178;

act. O_2 = actual O_2 concentration as stated above; dry = concentration corrected according to water content in exhaust gas.

Footnotes

1)Calculated as NO_2

2)The SO_2 content in the exhaust gas is valid for fuel with sulphur content of max. 0.005 wt% and lube oil with a sulphur content of max. 0.7 wt%

3)Total solid particulates (TSP) = soot + ash, without condensed or adsorbed water, hydrocarbons and sulfates; measurement acc. ISO 12141-1, in stack equivalent to PM, US EPA method 17. The TSP content in the exhaust gas is valid for fuel with an ash content as specified above

4)Tolerances (fuel consumption):
+5 %; Fuel: MDO;
NCV = 42,400 kJ/kg (measured NCV of fuel analysis);
Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1

5)Tolerances: ±6 %/±4 % for flow quantity (control active/control not active)

6)±5 °C/±15 °C for temperature at turbine outlet (control active/control not active)

7)Only valid for loadpoints without influence of exhaust gas temp. control

Last change of engine base data (ID: 32_44CR_600kW_TIER2_CPP_Curve_ECO1): 2020-10-01

Exhaust gas emissions

Operating data - Marine Plants

4307041 - Icebreaker - Glosten

Engine configuration:	**MAN 6L32/44CR B6, Electric propulsion, 3600kW, 600kW/Cyl., 720rpm, ECOMAP 1 = Standard engine map**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO 3046-1; ISO 15550	
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C	25
Relative humidity	%	30
Absolute humidity	g/kg	6.0
Air pressure	mbar	1000
Glycol concentration HT string	Vol%	0
Glycol concentration LT string	Vol%	0
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50
Oxygen reference value	%	15.0

Fuel type: MDO

Sulfur content S	wt%	0.50
Nitrogen content N	wt%	0.10
Oxygen content O_2	wt%	0.00
Carbon content C	wt%	86.24
Hydrogen content	wt%	13.14
Ash content	wt%	0.01
Water content H_2O	wt%	0.02
Density (15 °C)	kg/m³	865
Net calorific value	kJ/kg	42400

Exhaust gas emissions

Engine load	%	100.0	85.0	75.0	50.0	25.0
Engine output	kW	3600	3060	2700	1800	900
Speed	1/min	720	720	720	720	720
Charge air pressure (abs.)	bar	5.05	4.28	4.15	2.83	1.64
CW temperature before CAC (LT stage)	°C	25.0	25.0	25.0	25.0	25.0
Temperature of charge air at charge air cooler outlet	°C	40.0	40.0	40.0	40.0	40.0
Absolute humidity of combustion air	g/kg	6.0	6.0	6.0	6.0	6.0
Air flow rate	kg/kWh	6.3	6.3	6.9	7.5	8.5
Fuel oil consumption 4) (NCV = 42,400 kJ/kg)	g/kWh	180.6	177.2	184.3	189.7	211.7
Exhaust gas temperature at turbine outlet 6)	°C	320	320	320	323	342
Exhaust gas temperature control active	-	Yes	Yes	Yes	No	No
Exhaust gas volume flow 5)	m³/h	39841	33585	32850	23863	13834
Exhaust gas standard volume flow 5)	Nm³/h	18069	15232	14899	10772	6053
Exhaust gas mass flow 5)	kg/h	23387	19715	19284	13942	7834
O_2	g/kWh	810	810	947	1065	1200
	Vol%, dry	12.05	12.13	12.74	13.18	13.21
CO_2	g/kWh	600.3	588.7	612.7	629.9	703.1
	Vol%, dry @ act. O_2	6.45	6.38	5.96	5.64	5.60
H_2O	g/kWh	259.76	255.16	268.05	278.09	310.82
	Vol% @ act.% O_2	6.00	5.94	5.63	5.38	5.36
NO_x 1)	g/kWh	11.16	13.41	9.14	10.82	15.00
	mg/Nm³, dry @ 15% O_2	1590*	1940*	1280*	1470	1820
	ppm, wet @ act.% O_2	1085	1315	810	880	1090
	ppm, dry @ act.% O_2	1155	1400	855	930	1150
CO	g/kWh	0.35	0.42	0.34	0.66	0.88
	mg/Nm³, dry @ 15% O_2	50*	60*	50*	90	110
	ppm, dry @ act.% O_2	60	70	55	95	110
HC	g/kWh	0.43	0.53	0.55	0.67	0.64
	mg/Nm³, dry @ 15% O_2	60*	80*	80*	90	80
	ppm, wet @ act.% O_2	135	175	160	180	155
	ppm, dry @ act.% O_2	145	185	170	190	165
SO_2 2)	g/kWh	1.89	1.86	1.93	1.99	2.22
	mg/Nm³, dry @ 15% O_2	270*	270*	270*	270	270
	ppm, dry @ act.% O_2	135	135	125	120	120
TSP 3) 7)	g/kWh	0.352	0.346	0.358	-	-
	mg/Nm³, dry @ 15% O_2	50*	50*	50*	-	-

Notes

All values only for guidance, not guaranteed, except values with addition *

Measuring instrument tolerance not chargeable upon MAN Energy Solutions SE

Standard reference conditions (standard cubic meter Nm³): 1013 mbar; 0 °C

O_2, NO_X, CO, HC measurement acc. to ISO-8178;

act. O_2 = actual O_2 concentration as stated above; dry = concentration corrected according to water content in exhaust gas.

Footnotes

1)Calculated as NO_2

2)The SO_2 content in the exhaust gas is valid for fuel with sulphur content of max. 0.005 wt% and lube oil with a sulphur content of max. 0.7 wt%

3)Total solid particulates (TSP) = soot + ash, without condensed or adsorbed water, hydrocarbons and sulfates; measurement acc. ISO 12141-1, in stack equivalent to PM, US EPA method 17. The TSP content in the exhaust gas is valid for fuel with an ash content as specified above

4)Tolerances (fuel consumption):
+5 %; Fuel: MDO;
NCV = 42,400 kJ/kg (measured NCV of fuel analysis);
Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1

5)Tolerances: ±6 %/±4 % for flow quantity (control active/control not active)

6)±5 °C/±15 °C for temperature at turbine outlet (control active/control not active)

7)Only valid for loadpoints without influence of exhaust gas temp. control

Last change of engine base data (ID: 32_44CR_600kW_TIER2_E2_ECO1): 2020-10-01

Exhaust gas emissions

Operating data - Marine Plants

4307041 - Icebreaker - Glosten

Engine configuration:	**MAN 8L32/44CR B6, Mechanical propulsion CPP, 4800kW, 600kW/Cyl., 750rpm, ECOMAP 1 = Standard engine map, recommended combinator curve**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO 3046-1; ISO 15550	
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C	25
Relative humidity	%	30
Absolute humidity	g/kg	6.0
Air pressure	mbar	1000
Glycol concentration HT string	Vol%	0
Glycol concentration LT string		0
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50
Oxygen reference value	%	15.0

Fuel type: MDO

Sulfur content S	wt%	0.50
Nitrogen content N	wt%	0.10
Oxygen content O_2	wt%	0.00
Carbon content C	wt%	86.24
Hydrogen content	wt%	13.14
Ash content	wt%	0.01
Water content H_2O	wt%	0.02
Density (15 °C)	kg/m³	865
Net calorific value	kJ/kg	42400

Exhaust gas emissions

Engine load	%	100.0	85.0	75.0	50.0	25.0
Engine output	kW	4800	4080	3600	2400	1200
Speed	1/min	750	750	731	674	587
Charge air pressure (abs.)	bar	4.96	4.30	4.08	2.67	1.52
CW temperature before CAC (LT stage)	°C	25.0	25.0	25.0	25.0	25.0
Temperature of charge air at charge air cooler outlet	°C	40.0	40.0	40.0	40.0	40.0
Absolute humidity of combustion air	g/kg	6.0	6.0	6.0	6.0	6.0
Air flow rate	kg/kWh	6.2	6.3	6.6	7.2	7.2
Fuel oil consumption 4) (NCV = 42,400 kJ/kg)	g/kWh	181.8	177.7	182.7	186.8	201.9
Exhaust gas temperature at turbine outlet 6)	°C	320	320	322	321	369
Exhaust gas temperature control active	-	Yes	Yes	No	No	No
Exhaust gas volume flow 5)	m³/h	52039	44758	41597	30440	16342
Exhaust gas standard volume flow 5)	Nm³/h	23601	20300	18790	13792	6850
Exhaust gas mass flow 5)	kg/h	30546	26274	24320	17852	8865
O_2	g/kWh	776	807	862	1002	934
	Vol%, dry	11.80	12.10	12.31	12.94	12.19
CO_2	g/kWh	603.8	590.4	607.2	620.6	669.7
	Vol%, dry @ act. O_2	6.64	6.40	6.26	5.79	6.32
H_2O	g/kWh	260.31	255.81	263.82	272.81	290.87
	Vol% @ act.% O_2	6.14	5.96	5.86	5.50	5.91
NO_x 1)	g/kWh	10.87	13.20	11.00	14.17	15.49
	mg/Nm³, dry @ 15% O_2	1540*	1910*	1550*	1950	1970
	ppm, wet @ act.% O_2	1080	1295	1030	1205	1325
	ppm, dry @ act.% O_2	1150	1375	1095	1275	1410
CO	g/kWh	0.41	0.42	0.41	0.57	0.93
	mg/Nm³, dry @ 15% O_2	60*	60*	60*	80	120
	ppm, dry @ act.% O_2	70	70	65	85	140
HC	g/kWh	0.57	0.53	0.53	0.60	0.71
	mg/Nm³, dry @ 15% O_2	80*	80*	70*	80	90
	ppm, wet @ act.% O_2	185	175	165	170	200
	ppm, dry @ act.% O_2	200	185	175	180	215
SO_2 2)	g/kWh	1.91	1.86	1.92	1.96	2.12
	mg/Nm³, dry @ 15% O_2	270*	270*	270*	270	270
	ppm, dry @ act.% O_2	140	135	135	125	135
TSP 3) 7)	g/kWh	0.354	0.347	0.356	-	-
	mg/Nm³, dry @ 15% O_2	50*	50*	50*	-	-

Notes

All values only for guidance, not guaranteed, except values with addition *

Measuring instrument tolerance not chargeable upon MAN Energy Solutions SE

Standard reference conditions (standard cubic meter Nm³): 1013 mbar; 0 °C

O_2, NO_X, CO, HC measurement acc. to ISO-8178;

act. O_2 = actual O_2 concentration as stated above; dry = concentration corrected according to water content in exhaust gas.

Footnotes

1)Calculated as NO_2

2)The SO_2 content in the exhaust gas is valid for fuel with sulphur content of max. 0.005 wt% and lube oil with a sulphur content of max. 0.7 wt%

3)Total solid particulates (TSP) = soot + ash, without condensed or adsorbed water, hydrocarbons and sulfates; measurement acc. ISO 12141-1. In stack equivalent to PM, US EPA method 17. The TSP content in the exhaust gas is valid for fuel with an ash content as specified above

4)Tolerances (fuel consumption):
+5 %; Fuel: MDO;
NCV = 42,400 kJ/kg (measured NCV of fuel analysis);
Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1

5)Tolerances: ±6 %/±4 % for flow quantity (control active/control not active)

6)±5 °C/±15 °C for temperature at turbine outlet (control active/control not active)

7)Only valid for loadpoints without influence of exhaust gas temp. control

Last change of engine base data (ID: 32_44CR_600kW_TIER2_CPP_Curve_ECO1): 2020-10-01

Exhaust gas emissions

Operating data - Marine Plants

4307041 - Icebreaker - Glosten

Engine configuration:	**MAN 8L32/44CR B6, Electric propulsion, 4800kW, 600kW/Cyl., 720rpm, ECOMAP 1 = Standard engine map**
Fuel and emission:	**MDO, Tier II, E2 - cycle**
Reference according to ISO 3046-1; ISO 15550	
MAN SCR:	**SCR active (standard mode) – compliant with IMO Tier III (load >= 20%)**
Exhaust gas temperature control:	**320°C (load ≥ 5 %)**

Reference conditions

Air temperature	°C	25
Relative humidity	%	30
Absolute humidity	g/kg	6.0
Air pressure	mbar	1000
Glycol concentration HT string	Vol%	0
Glycol concentration LT string	Vol%	0
Exhaust gas back pressure at T/C outlet (100 % engine output)	mbar	50
Oxygen reference value	%	15.0

Fuel type: MDO

Sulfur content S	wt%	0.50
Nitrogen content N	wt%	0.10
Oxygen content O_2	wt%	0.00
Carbon content C	wt%	86.24
Hydrogen content	wt%	13.14
Ash content	wt%	0.01
Water content H_2O	wt%	0.02
Density (15 °C)	kg/m³	865
Net calorific value	kJ/kg	42400

Exhaust gas emissions

Engine load	%	100.0	85.0	75.0	50.0	25.0
Engine output	kW	4800	4080	3600	2400	1200
Speed	1/min	720	720	720	720	720
Charge air pressure (abs.)	bar	4.95	4.28	4.15	2.84	1.64
CW temperature before CAC (LT stage)	°C	25.0	25.0	25.0	25.0	25.0
Temperature of charge air at charge air cooler outlet	°C	40.0	40.0	40.0	40.0	40.0
Absolute humidity of combustion air	g/kg	6.0	6.0	6.0	6.0	6.0
Air flow rate	kg/kWh	6.2	6.2	6.9	7.5	8.5
Fuel oil consumption 4) (NCV = 42,400 kJ/kg)	g/kWh	181.4	177.2	184.3	189.7	211.7
Exhaust gas temperature at turbine outlet 6)	°C	320	320	320	323	342
Exhaust gas temperature control active	-	Yes	Yes	Yes	No	No
Exhaust gas volume flow 5)	m³/h	51923	44727	43803	31819	18445
Exhaust gas standard volume flow 5)	Nm³/h	23548	20286	19867	14363	8070
Exhaust gas mass flow 5)	kg/h	30478	26256	25713	18590	10445
O_2	g/kWh	774	808	947	1065	1200
	Vol%, dry	11.79	12.12	12.74	13.18	13.21
CO_2	g/kWh	602.9	588.8	612.7	629.9	703.1
	Vol%, dry @ act. O_2	6.64	6.38	5.96	5.64	5.60
H_2O	g/kWh	259.91	255.17	268.05	278.09	310.82
	Vol% @ act.% O_2	6.14	5.95	5.63	5.38	5.36
NO_x 1)	g/kWh	11.01	13.40	9.14	10.82	15.00
	mg/Nm^3, dry @ 15% O_2	1560*	1940*	1280*	1470	1820
	ppm, wet @ act.% O_2	1095	1315	810	880	1090
	ppm, dry @ act.% O_2	1165	1400	855	930	1150
CO	g/kWh	0.42	0.42	0.34	0.66	0.88
	mg/Nm^3, dry @ 15% O_2	60*	60*	50*	90	110
	ppm, dry @ act.% O_2	75	70	55	95	110
HC	g/kWh	0.45	0.54	0.55	0.67	0.64
	mg/Nm^3, dry @ 15% O_2	60*	80*	80*	90	80
	ppm, wet @ act.% O_2	150	175	160	180	155
	ppm, dry @ act.% O_2	160	185	170	190	165
SO_2 2)	g/kWh	1.90	1.86	1.93	1.99	2.22
	mg/Nm^3, dry @ 15% O_2	270*	270*	270*	270	270
	ppm, dry @ act.% O_2	140	135	125	120	120
TSP 3) 7)	g/kWh	0.354	0.346	0.358	-	-
	mg/Nm^3, dry @ 15% O_2	50*	50*	50*	-	-

Notes

All values only for guidance, not guaranteed, except values with addition *

Measuring instrument tolerance not chargeable upon MAN Energy Solutions SE

Standard reference conditions (standard cubic meter Nm³): 1013 mbar; 0 °C

O_2, NO_X, CO, HC measurement acc. to ISO-8178;

act. O_2 = actual O_2 concentration as stated above; dry = concentration corrected according to water content in exhaust gas.

Footnotes

1)Calculated as NO_2

2)The SO_2 content in the exhaust gas is valid for fuel with sulphur content of max. 0.005 wt% and lube oil with a sulphur content of max. 0.7 wt%.

3)Total solid particulates (TSP) = soot + ash, without condensed or adsorbed water, hydrocarbons and sulfates; measurement acc. ISO 12141-1, in stack equivalent to PM, US EPA method 17. The TSP content in the exhaust gas is valid for fuel with an ash content as specified above

4)Tolerances (fuel consumption):
+5 %; Fuel: MDO;
NCV = 42,400 kJ/kg (measured NCV of fuel analysis);
Attached pumps: lube oil: 1 resp. 2; HT-water: 1; LT-water: 1

5)Tolerances: ±6 %/±4 % for flow quantity (control active/control not active)

6)±5 °C/±15 °C for temperature at turbine outlet (control active/control not active)

7)Only valid for loadpoints without influence of exhaust gas temp. control

Last change of engine base data (ID: 32_44CR_600kW_TIER2_E2_ECO1): 2020-10-01

Maintenance schedule (Signs/Symbols)

Explanation of signs and symbols

The header of the maintenance schedule contains signs and symbols. They denote the following:

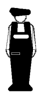
1, 2, 3	Sequential number of the maintenance job. The number sequence includes gaps for any necessary changes/additions.	
	Brief description of maintenance	
	Associated Work Instructions. The Work Instructions listed contain detailed information on the work steps required.	
	A	No Work Instructions required/available
	B	See the manufacturer's maintenance instructions (see Volume 030 for auxiliary system, engine-related)
	C	Have this work carried out by a MAN Diesel & Turbo SE Service Centre or a specialised company
	D	See associated maintenance work
	Personnel required	
	Labour time in man-hours	
by	Reference value for stating the time requirement	
24 ... 36000	Repetition period in operating hours	
X, 1 ... 7	Signs used in the interval columns. The explanatory note is repeated on each sheet.	

Table 1: Explanation of signs and symbols used in the maintenance schedule

Maintenance work groups

The maintenance jobs are grouped together in the maintenance schedule (systems) by system/function group, whilst in the maintenance schedule (engine) they are grouped together by sub-assembly.

Maintenance schedule (Systems)

Maintenance Schedule

1, 2, 3					per	24	150	250	500	1-2*	3-4*	5-6*	10-12*	20-24*	30-40*	50-60*
Fuel system																
004	Check the system components for leakage (visual inspection)	A	1	0.2	Engine	X										
005	Service tank: Check the fuel level; drain the service tank and settling tank	A	1	0.2	Engine	X										
006	Check Viscosimat (carry out comparative temperature measurement)	B	1	0.1	Unit	X										
007	Clean fuel filter (depending on the differential pressure)	B	1	3	Filter	1	1	1	1	1	1	1	1	1	1	1
008	Overhaul the fuel delivery pump	B	1	1	Pump	3	3	3	3	3	3	3	3	3	3	3
Lube oil system																
011	Check the system components for leakage (visual inspection)	A	1	0.2	Engine	X										
012	Service tank for engine and cylinder lubrication: Check oil level	A	1	0.1	Engine	X										
014	Examine oil sample (spot test)	010.000.002-02	1	0.2	Engine			X								
015	Have the oil sample analysed	010.000.002-01	1	0.3	Engine				X							
016	Change oil filling (depending on results of analysis), clean the tank	010.000.002-01				1	1	1	1	1	1	1	1	1	1	1

24 ... *Repetition interval in operating hours*
X *Maintenance work due*
*** *x 1000 h*
1 *As required/depending on condition*
2 *Checking of new or overhauled parts required (once after the mentioned time)*
3 *According to specification of manufacturer*
4 *If component/system is available*

1, 2, 3					per	24	150	250	500	1-2*	3-4*	5-6*	10-12*	20-24*	30-40*	50-60*
017	Check oil drain from piston, connecting rod and crankshaft bearings, from the gear drive system and the turbocharger (visually) - see also 401	A	1	0.2	Unit;Cyl.							X				
018	Check oil drain (visually) from camshaft bearings, high-pressure pumps and valve gear (in the rocker arm casing) - see also 401	A	1	2	Engine							X				
020	Overhaul the lubricating oil pump	010.220.010-01	2	10	Pump	1	1	1	1	1	1	1	1	1	1	1
021	Dismantle, clean and check lube oil pressure control valve	B	1	4	Valve							4				
023	Clean the lubricating oil service filter (depending on scavenging intervals)	B	1	3	Filter	1	1	1	1	1	1	1	1	1	1	1
024	Clean the lubricating oil indicator filter (dependent upon the differential pressure)	B	1	2	Filter	1	1	1	1	1	1	1	1	1	1	1
025	Clean the lubricating oil preheater (dependent on separating temperature at required flow rate). Possibly have cleaning carried out by a specialist company	B	1	4	Unit	1	1	1	1	1	1	1	1	1	1	1
026	Check, clean and overhaul the lubricating oil separator (self-discharging)	B	1	4	Unit	1	1	1	1	1	1	1	1	1	1	1
027	Clean the lubricating oil cooler (possibly performed by a specialist company)	C			Radiator	1	1	1	1	1	1	1	1	1	1	1
Cooling water system (cylinder and nozzle cooling)																
031	Compensating tank: Check the cooling water level	A	1	0.2	Engine	X										
032	Check the nozzle cooling water return (for unhindered flow and eventual traces of fuel - when using heavy fuel)	A	1	0.1	Engine	4										
033	cooling water: Check the corrosion protection - see also 401	010.000.002-03	1	0.5	Engine		X									
034	Have test of the cooling water sample carried out at laboratory	010.000.002-03	1	0.1	Engine					1						

24 ...	*Repetition interval in operating hours*
X	*Maintenance work due*
***	*x 1000 h*
1	*As required/depending on condition*
2	*Checking of new or overhauled parts required (once after the mentioned time)*
3	*According to specification of manufacturer*
4	*If component/system is available*

1, 2, 3	Task	Document	Personnel	Time	per	24	150	250	500	1-2*	3-4*	5-6*	10-12*	20-24*	30-40*	50-60*
035	Check cooling channels, chemically clean the system (cylinder cooling). Possibly have cleaning carried out by a specialist company	010.000.002-04			Engine	1	1	1	1	1	1	1	1	1	1	1
036	Cooling water heat exchanger: Clean the cooling spaces, possibly by specialist company	C			Unit	1	1	1	1	1	1	1	1	1	1	1
Compressed air and control air system																
042	Drain the water from the compressed air tank (if it is not automatically drained)	A	1	0.1	Unit	X										
043	Clean the inside of the compressed air tank, overhaul the valves (in accordance with the regulations of the classification society)	B	2	10	Unit	1	1	1	1	1	1	1	1	1	1	1
044	Control air system: Drain water separator and air filter	010.280.020-12	1	0.1	Engine	X										
045	Control air system: Clean the water separator and air filter	010.280.020-12	1	0.5	Engine							X				
Charge air system																
052	Charge air cooler/charge air pipe: Check condensed water discharge for quantity/free flow	A	1	0.1	Pipe	X										
053	Clean charge air cooler on both water and air sides, possibly by specialist company	010.170.040-01 010.170.040-02	2	15	Radiator	1	1	1	1	1	1	1	1	1	1	1
054	In case available: Charge air bypass/blow-off device: Check system components for leakages (visually). Check control and monitoring elements for proper function	010.170.010-04	1	0.5	Engine	1	1	1	1	1	1	1	1	1	1	1
055	Shut-off flaps on engine: Dismount and check for cracks. Every 6000 operational hours or once a year	010.170.010-04	1	2	Engine							4				

24 ... Repetition interval in operating hours
X Maintenance work due
** x 1000 h*
1 As required/depending on condition
2 Checking of new or overhauled parts required (once after the mentioned time)
3 According to specification of manufacturer
4 If component/system is available

1, 2, 3					per	24	150	250	500	1-2*	3-4*	5-6*	10-12*	20-24*	30-40*	50-60*
Exhaust gas system																
062	In case available: Exhaust gas blow-off device: Check system components for leakages (visually). Check control and monitoring elements for proper function	A	1	0.5	Engine	1	1	1	1	1	1	1	1	1	1	1
063	Exhaust pipe: Check the flange connections and the expansion joints for tightness (visually)	010.180.010-01	1	0.2	Pipe							X				
064	Shut-off flaps on engine: Dismount and check for cracks. Every 6000 operational hours or once a year	010.180.010-02	1	2	Unit							4				
Measuring, control and regulation systems																
072	Switching and shut-down devices: Check functional capability and switching points - also see 402	A	2	6	Engine					X						
073	Dismantle the control valves in the 10 and 30 bar system, replace wear parts	010.280.020-xx	1	24	Engine									X		
074	Batteries in the control cabinet: replace	A	1	0.5	Engine								X			
075	Inspect/overhaul the oil mist detector	B	1	1	Engine	3	3	3	3	3	3	3	3	3	3	3
Engine foundation/pipe connections																
082	Foundation bolts: Check pretension. Check firm seating of stoppers, brackets and resilient elements (in case of marine engines also after collision or grounding) - see also 402	010.010.030-03	2	8	Engine			2				X				
083	In case available: Resilient mounting: Determine the elastic elements' settling value	010.010.030-01	2	3	Engine							4				
084	In case available: Elastic pipe connections: Check all hoses	A	1	1	Engine					4						
085	Elastic pipe connections: Replace hoses for fuel, lubricating oil, cooling water, steam and compressed air	A	2	14	Engine	1	1	1	1	1	1	1	1	1	1	1

24 ... *Repetition interval in operating hours*
X *Maintenance work due*
*** *x 1000 h*
1 *As required/depending on condition*
2 *Checking of new or overhauled parts required (once after the mentioned time)*
3 *According to specification of manufacturer*
4 *If component/system is available*

1, 2, 3					per	24	150	250	500	1-2*	3-4*	5-6*	10-12*	20-24*	30-40*	50-60*
086	Screwed connections: check for tight fit/proper pretension (e.g. on exhaust gas and charge air pipe, charge air cooler and turbocharger) - see also 402	010.000.003-05	2	10	Engine							X				
Flexible coupling/turning gear																
092	In case available: Flexible coupling: Check the alignment and the rubber elements	010.030.010-11	2	8	Engine							4				
093	Coupling bolts: check for tight fit/proper preload - see also 402	010.030.010-03	1	1	Engine							X				
094	Inspect/overhaul the turning gear	B	1	1	Unit	3	3	3	3	3	3	3	3	3	3	3
Additionally required																
401	Check installed new parts or installed overhauled parts/ newly added lubricants once after the indicated interval - applies to 017, 018, 033	D			Unit	X										
402	Check installed new parts or installed overhauled parts/ newly added lubricants once after the indicated interval - applies to 072, 082, 086, 093	D			Unit			X								

24 ... *Repetition interval in operating hours*
X *Maintenance work due*
*** *x 1000 h*
1 *As required/depending on condition*
2 *Checking of new or overhauled parts required (once after the mentioned time)*
3 *According to specification of manufacturer*
4 *If component/system is available*

Maintenance schedule (Engine)

Maintenance Schedule

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
Operating data																
102	Check the exhaust clouding (visually)	A	1	0.1	Engine	X										
103	Check ignition pressures	010.060.080-01	1	0.1	Cyl.		X									
104	Record operating data	010.000.005-01	1	0.1	Engine	X										
Running gear/Crankshaft																010.030.010
113	Crankcase inspection/measure web deflection/measure axial clearance of crankshaft after shocks to the engine before/ after docking. Measure collisions or ground contact.	010.030.010-12 010.030.020-06	2	0.2	Cyl.		2		X							
Crankshaft bearing																010.030.020
122	Thrust bearing: check axial clearance	010.030.020-06	2	0.5	Bearing		2		X							
123	Lower one bearing cap and inspect the lower bearing shell. If it proves no longer fit for use, check all the bearings. Check release pressure of the bearing bolts	010.000.003-03 010.010.030-09 010.030.020-01 010.030.020-02	2	6	Bearing						X					
124	Replace all bearing shells	010.030.020-01 010.030.020-02 010.030.020-03 010.030.020-04	2	6	Bearing								X			

24 ... *Repetition interval in operating hours*
X *Maintenance work due*
**** *After 5000-6000 hours of service or after 2 years*
*** *x 1000 h*
1 *As required/depending on condition*
2 *Checking of new or overhauled parts required (once after the mentioned time)*
3 *According to specification of manufacturer*
4 *If component/system is available*

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
Crankshaft vibration damper / Camshaft vibration damper						010.030.030/010.090.070										
132	Remove the vibration damper of the crankshaft, check and replace the sealing rings	010.030.030-03 010.030.030-04	2	30	Engine								X			
133	Replace the crankshaft vibration damper	010.030.030-03	2	30	Engine									X		
134	Camshaft vibration damper: Replace viscous damper	010.090.070-02	2	6	Unit						4					
Connecting rod						010.040.010										
142	Remove and check one bearing shell. If it proves no longer fit for use, check all the bearings – including crankshaft bearings. Check release pressure of the bearing bolts.	010.000.003-03 010.040.010-02 010.040.010-04 010.040.010-05 010.040.010-06	2	4	Bearing						X					
143	Replace all bearing shells	010.040.010-05 010.040.010-06	2	4	Bearing								X			
Piston/piston rings/piston pin						010.040.050										
152	Remove, clean and check one piston (one per cylinder bank in a V-engine). Measure piston rings and ring grooves. Check the pressure for releasing the conrod shank bolts. Document any data recorded.	010.040.010-01 010.040.010-03 010.040.050-01 010.040.050-03 010.040.050-06 010.040.050-07	3	2	Cyl.				X							
153	Remove, clean and inspect all pistons. Measure the ring grooves. Replace all piston rings. Caution: Re-hone the cylinder liner when replacing the piston rings! Document recorded data.	010.040.050-01 010.040.050-03 010.050.010-07	3	2	Cyl.						X					
154	Remove one piston pin, check piston pin bushing, measure clearance.	010.040.050-05	2	0.3	Cyl.						X					

24 ...	*Repetition interval in operating hours*
X	*Maintenance work due*
**	*After 5000-6000 hours of service or after 2 years*
*	*x 1000 h*
1	*As required/depending on condition*
2	*Checking of new or overhauled parts required (once after the mentioned time)*
3	*According to specification of manufacturer*
4	*If component/system is available*

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
155	Dismantle one piston. Clean the components. Check the cooling water chambers and bores for onset of carbon deposits. If the layer thickness exceeds 1 mm, dismantle all pistons.	010.040.050-03 010.040.050-04 010.040.050-05	3	2	Cyl.						X					
156	Dismantle all pistons. Clean the components. Replacement of the piston crown is dependent upon the wear on the ring groove and the findings.	010.040.050-03 010.040.050-04 010.040.050-05	3	2	Cyl.								X			
157	Dismantle all pistons. Install new piston skirts.	010.040.050-03 010.040.050-04 010.040.050-05	3	2	Cyl.										X	
158	Replace all piston pin bushes. Bush replacement to be carried out by authorised workshop/service personnel.	010.040.050-05 C	3	2	Cyl.										X	
Cylinder liner																010.050.010
162	Measure one cylinder liner (one per cylinder bank in the case of a V-engine). Document any data recorded.	010.050.010-03	2	0.3	Cyl.				X							
163	Measure and rehone all cylinder liners. Document recorded data.	010.050.010-03 010.050.010-07	2	3	Cyl.						X					
164	Remove, clean and check all cylinder liners. Replace the sealing rings	010.050.010-01 010.050.010-04 010.050.010-05	3	4	Cyl.								X			
165	Replace all cylinder liners and sealing rings.	010.050.010-01 010.050.010-04 010.050.010-05	3	4	Cyl.											X

24 ...	*Repetition interval in operating hours*
X	*Maintenance work due*
**	*After 5000-6000 hours of service or after 2 years*
*	*x 1000 h*
1	*As required/depending on condition*
2	*Checking of new or overhauled parts required (once after the mentioned time)*
3	*According to specification of manufacturer*
4	*If component/system is available*

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
Cylinder head						010.060.010										
172	Remove, clean and check one cylinder head (one per cylinder bank in a V-engine). Check the pressure for releasing the cylinder head screws.	010.060.020-01 010.060.020-02 010.060.020-03 010.060.020-04	3	3	Cyl.				X							
173	Remove, clean and check all cylinder heads	010.060.020-01 010.060.020-02 010.060.020-03 010.060.020-04	3	3	Cyl.						X					
Inlet and exhaust valves						010.060.030/010.060.040										
233	Check the valve clearance	010.100.020-02	2	0.2	Cyl.			X								
234	Remove two inlet valves (two per cylinder bank in the case of a V-engine). Check the valve seats, valve cones, valve guides and valve rotators; replace worn parts. Check the valve cone rotation after refitting	010.060.030-01 010.060.030-02 010.060.030-04 010.060.030-06 010.060.030-08	2	1	Valve				X							
235	Remove all inlet valves. Check and rework valve seats and valve cones. Check valve rotators and valve guides; replace worn parts. Check the valve rotation after refitting	010.060.030-01 010.060.030-02 010.060.030-04 010.060.030-05 010.060.030-06 010.060.030-07 010.060.030-08	2	2	Valve						X					
236	Remove all inlet valves, replace valve cones, valve seat rings and valve guides. Check the valve rotation after refitting	010.060.030-01 010.060.030-02 010.060.030-06 010.060.030-08	2	1	Valve								X			

24 ...	*Repetition interval in operating hours*
X	*Maintenance work due*
****	*After 5000-6000 hours of service or after 2 years*
***	*x 1000 h*
1	*As required/depending on condition*
2	*Checking of new or overhauled parts required (once after the mentioned time)*
3	*According to specification of manufacturer*
4	*If component/system is available*

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
242	Remove two exhaust valves. (two per cylinder bank in the case of V-engine). Check valve seats, valve cones and valve guides. Replace worn parts. Check the valve rotation after refitting	010.060.030-01 010.060.030-02 010.060.030-04 010.060.030-06 010.060.030-08	2	2	Valve				X							
243	Remove all exhaust valves. Check and rework valve seats and valve cones. Check valve guides. Replace worn parts. Check the valve rotation after refitting	010.060.030-01 010.060.030-02 010.060.030-04 010.060.030-05 010.060.030-06 010.060.030-07 010.060.030-08	2	4	Valve						X					
244	Remove all exhaust valves, replace valve cones, valve guides and valve seat rings. Check the valve rotation after refitting	010.060.030-01 010.060.030-02 010.060.030-06 010.060.030-08	2	1	Valve								X			
Fuel injection valve with nozzle						010.060.060										
323	Remove the injection valves, replace the nozzle elements and all sealing rings.	010.060.060-01 010.060.060-02 010.060.060-03	2	3	Valve				X							
324	Remove injection valves, replace spring and spring plate	010.060.060-01 010.060.060-03	2	0.5	Valve					X						
Safety valves						010.020.100/010.170.010/010.180.010										
182	Safety valve on drive chamber covers: Check all valves for ease of movement.	010.020.100-01	1	0.1	Valve						X					
183	Safety valve on cylinder heads: Remove all valves and replace.	A	1	2	Valve							X				

24 ... Repetition interval in operating hours
X Maintenance work due
*** After 5000-6000 hours of service or after 2 years*
** x 1000 h*
1 As required/depending on condition
2 Checking of new or overhauled parts required (once after the mentioned time)
3 According to specification of manufacturer
4 If component/system is available

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
Control drive/gear rim																010.090.060
202	Check gears (visual inspection) and, if necessary, replace worn parts.	010.090.060-01	2	1	Engine				X							
Camshaft/camshaft bearing/cam follower																010.090.010/010.090.030/010.100.030
212	Check cams, rollers and cam followers (visually).	010.100.030-02	1	0.5	Cyl.				X							
213	Check cam follower bush on one cylinder	010.100.030-01	2	2	Cyl.						X					
214	Replace all cam follower bushes. Have the bushes replaced by an authorised service workshop.	C	2	2	Cyl.								X			
216	Camshaft bearing/Camshaft thrust bearing: Replace all bearing bushes. Bush replacement to be carried out by authorised workshop/service personnel.	C	2	1.5	Bearing								1	1	1	
Control lever, rocker arm, valve bridge																010.100.020
231	Check the rocker arm and associated bolted connections (visually)	010.100.020-01	1	0.1	Cyl.			X								
Variable valve timing (VVT)																010.100.050
221	VVT couplings (connections of eccentric shafts): Check fastening screws for firm seat (on 2 couplings per cylinder bank)	010.100.030-01	1	1	Engine			X								
222	Check conrod between eccentric shaft and VVT drive: Visual inspection of jointed heads; check screw connection for correct tightening	010.100.030-01 010.100.050-01	1	0.5	Engine				X							
223	Check VVT drive for leaks (visual inspection). Check flange bolts for correct tightening	010.100.050-01	1	0.5	Engine				X							
224	Check the VVT drive support, replacing it if necessary	010.100.030-01 010.100.050-01	1	0.5	Engine				X							

24 ...	*Repetition interval in operating hours*
X	*Maintenance work due*
**	*After 5000-6000 hours of service or after 2 years*
*	*x 1000 h*
1	*As required/depending on condition*
2	*Checking of new or overhauled parts required (once after the mentioned time)*
3	*According to specification of manufacturer*
4	*If component/system is available*

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
225	Checking the VVT end position sensors; visual inspection of cabling	010.100.050-02	1	0.5	Engine				X							
226	Replace the VVT drive	010.100.050-01	2	2	Engine								X			
Common-Rail high pressure pump																010.110.050
302	Check fastening screws of high-pressure pumps for secure fit	010.000.003-05 010.110.050-01	1	0.2	Pump		2									
303	Remove all high pressure pumps with a roller tappet, dismantle and check them. Replace pre-assembled pump element unit (pump element together with valve support). Replace worn parts.	010.110.050-01 010.110.050-02	2	4	Pump					X						
304	Replace solenoid of the throttle valve on high pressure pump and seal.	010.110.050-01 010.110.050-02	1	0.5	Pump					X						
305	Check throttle piece and spring of the throttle valve. Replace seals of throttle piece. Replace worn parts.	010.110.050-01 010.110.050-02	1	1	Pump					X						
Common-Rail accumulator unit with fitted components																010.110.054
311	Check valve groups and all high pressure/low pressure connections for leaks (visual check). Check leakage drains for free passage.	A	1	0.5	Engine		2	X								
312	Replace all valve groups (control valves).	010.110.054-03	1	0.5	Cyl.				1	X						
313	Replace the purge valve.	010.110.054-07 010.110.054-09	1	2	cylinder bank					1		X				
314	Replace the pressure limiting valve.	010.110.054-09	1	2	cylinder bank					1		X				
315	Check the non-return valve (flushing) and replace the compression spring.	010.110.054-10	1	0.5	cylinder bank				X							
316	Replace the non-return valve (purging).	010.110.054-10	1	0.5	cylinder bank							X				

24 ... *Repetition interval in operating hours*
X *Maintenance work due*
**** *After 5000-6000 hours of service or after 2 years*
*** *x 1000 h*
1 *As required/depending on condition*
2 *Checking of new or overhauled parts required (once after the mentioned time)*
3 *According to specification of manufacturer*
4 *If component/system is available*

1, 2, 3					per	24	250	1-2*	5-6**	10-12*	12-15*	18-24*	30-40*	50-60*	60-80*	80-100*
317	Replace all non-return valves (governing).	010.110.054-12	1	0.5	Cyl.					X						
318	Clean flush valve (removal of fuel depositions)	010.110.054-07 010.110.054-08	1	1	cylinder bank				X							
319	Replace all orifices. Replace worn parts. Clean all accumulator units inside.	010.110.054-01 010.110.054-02 010.110.054-04 010.110.054-05	1	2	Cyl.								X			
Insulation						010.180.030										
370	Visual check of the insulation mats	B			Engine		X									
371	Check of internal/coated insulations	B			Engine				X							
372	Check of bolted connections and fastenings	B			Engine				X							
Starter						010.260.050										
271	Check starter, overhaul it, if necessary.	B	1	1	Engine	3	3	3	3	3	3	3	3	3	3	3
272	Clean and lubricate the starter pinion and gear rim	010.260.050-01	1	1	Engine			X								

24 ...	*Repetition interval in operating hours*
X	*Maintenance work due*
****	*After 5000-6000 hours of service or after 2 years*
***	*x 1000 h*
1	*As required/depending on condition*
2	*Checking of new or overhauled parts required (once after the mentioned time)*
3	*According to specification of manufacturer*
4	*If component/system is available*

Appendix B Results for Operating Profiles 2, 3, and 4

ENGINE LOADS

Table 1 Engine loads as % of MCR: diesel electric & VSG for operating profile 2

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)	Harbor Gen (1320kW)
Open Water Transit	78.5%	78.5%	0.0%	0.0%	0.0%
Icebreaking	46.6%	0.0%	85.0%	85.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%	0.0%
On Station	0.0%	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	0.0%	0.0%	72.5%	72.5%	0.0%
Deployment – Towing Side Scan	0.0%	0.0%	72.5%	72.5%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%	79.1%
Ice Transit	0.0%	0.0%	0.0%	87.0%	0.0%

Table 2 Engine loads as % of MCR: diesel electric & VSG for operating profile 3

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)	Harbor Gen (1320kW)
Open Water Transit	78.5%	78.5%	0.0%	0.0%	0.0%
Icebreaking	46.6%	0.0%	85.0%	85.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%	0.0%
On Station	0.0%	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	0.0%	0.0%	72.5%	72.5%	0.0%
Deployment – Towing Side Scan	0.0%	0.0%	72.5%	72.5%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%	79.1%
Ice Transit	0.0%	0.0%	0.0%	87.0%	0.0%

Table 3 Engine loads as % of MCR: diesel electric & VSG for operating profile 4

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)	Harbor Gen (1320kW)
Open Water Transit	78.5%	78.5%	0.0%	0.0%	0.0%
Icebreaking	46.6%	0.0%	85.0%	85.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%	0.0%
On Station	0.0%	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	0.0%	0.0%	72.5%	72.5%	0.0%
Deployment – Towing Side Scan	0.0%	0.0%	72.5%	72.5%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%	79.1%
Ice Transit	0.0%	0.0%	0.0%	87.0%	0.0%

Table 4 Engine loads as % of MCR: hybrid – diesel electric with battery (charging) for operating profile 2

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	85.0%	0.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	85.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	85.0%	0.0%
Hotel Only	0.0%	0.0%	85.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

Table 5 Engine loads as % of MCR: hybrid – diesel electric with battery (charging) for operating profile 3

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	85.0%	0.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	85.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	85.0%	0.0%
Hotel Only	0.0%	0.0%	85.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

Table 6 Engine loads as % of MCR: hybrid – diesel electric with battery (charging) for operating profile 4

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	85.0%	0.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	85.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	85.0%	0.0%
Hotel Only	0.0%	0.0%	85.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

Table 7 Engine loads as % of MCR: hybrid – diesel electric with battery (discharging) for operating profile 2

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	0.0%	85.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	0.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	0.0%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

Table 8 Engine loads as % of MCR: hybrid – diesel electric with battery (discharging) for operating profile 3

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	0.0%	85.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	0.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	0.0%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

Table 9 Engine loads as % of MCR: hybrid – diesel electric with battery (discharging) for operating profile 4

Activity	Eng. 1 (4800kW)	Eng. 2 (4800kW)	Eng. 3 (3600kW)	Eng. 4 (3600kW)
Open Water Transit	85.0%	0.0%	85.0%	0.0%
Icebreaking	87.0%	87.0%	0.0%	0.0%
On Station, DP	0.0%	0.0%	87.0%	87.0%
On Station	0.0%	0.0%	87.0%	0.0%
Deployment – Dredging & Trawling	85.0%	0.0%	0.0%	0.0%
Deployment – Towing Side Scan	85.0%	0.0%	0.0%	0.0%
Hotel Only	0.0%	0.0%	0.0%	0.0%
Ice Transit	0.0%	0.0%	0.0%	87.0%

ENGINE HOURS

Table 10 Annual run time (in hours) of engines for each system for operating profile 2

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Run Time (hr) - Engine 1	3,024	3,624	3,024
Run Time (hr) - Engine 2	2,376	1,662	2,376
Run Time (hr) - Engine 3	2,352	3,741	2,352
Run Time (hr) - Engine 4	4,560	2,976	6,384
Run Time (hr) – Harbor Generator	1,824	0	0
TOTAL	**14,136**	**12,002**	**14,136**

Table 11 Annual run time (in hours) of engines for each system for operating profile 3

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Run Time (hr) - Engine 1	2,448	3,048	2,448
Run Time (hr) - Engine 2	1,800	1,416	1,800
Run Time (hr) - Engine 3	2,712	3,909	2,712
Run Time (hr) - Engine 4	5,088	3,384	6,960
Run Time (hr) – Harbor Generator	1,872	0	0
TOTAL	**13,920**	**11,756**	**13,920**

Table 12 Annual run time (in hours) of engines for each system for operating profile 4

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
Run Time (hr) - Engine 1	2,544	3,120	2,544
Run Time (hr) - Engine 2	1,680	1,581	1,680
Run Time (hr) - Engine 3	2,496	3,232	2,496
Run Time (hr) - Engine 4	5,328	3,576	7,080
Run Time (hr) – Harbor Generator	1,752	0	0
TOTAL	**13,800**	**11,509**	**13,800**

ENGINE MAINTENANCE

Table 13 30-year maintenance costs for each power system for operating profile 2

	Diesel Electric		Hybrid – diesel electric with battery		VSG – diesel electric with variable speed generators	
Lube oil change	$	472,609	$	450,523	$	452,735
Minor overhaul	$	1,334,698	$	1,276,295	$	1,283,467
Major overhaul	$	1,589,979	$	1,526,666	$	1,920,865
Alternator replacement	$	329,582	$	315,421	$	268,108
TOTAL	**$**	**3,727,000**	**$**	**3,569,000**	**$**	**3,925,000**

Table 14 30-year maintenance costs for each power system for operating profile 3

	Diesel Electric		Hybrid – diesel electric with battery		VSG – diesel electric with variable speed generators	
Lube oil change	$	471,667	$	431,088	$	436,313
Minor overhaul	$	1,331,891	$	1,168,323	$	1,191,975
Major overhaul	$	1,586,776	$	1,523,370	$	1,917,409
Alternator replacement	$	329,582	$	315,421	$	268,108
TOTAL	**$**	**3,720,000**	**$**	**3,438,000**	**$**	**3,814,000**

Table 15 30-year maintenance costs for each power system for operating profile 4

	Diesel Electric		Hybrid – diesel electric with battery		VSG – diesel electric with variable speed generators	
Lube oil change	$	471,523	$	430,152	$	435,930
Minor overhaul	$	1,331,509	$	1,165,779	$	1,190,927
Major overhaul	$	1,586,322	$	1,483,684	$	1,915,445
Alternator replacement	$	343,744	$	315,421	$	268,108
TOTAL	**$**	**3,733,000**	**$**	**3,395,000**	**$**	**3,810,000**

EMISSIONS

Table 16 Annual metric tons of emissions for each power system for operating profile 2

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
CO_2 – (MT)	25,409	25,096	25,370
NO_X – (MT)	490	565	527
SO_2 – (MT)	80	79	80
TOTAL	**25,979**	**25,740**	**25,978**

Table 17 Annual metric tons of emissions for each power system for operating profile 3

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
CO_2 – (MT)	24,461	24,202	24,440
NO_X – (MT)	481	543	513
SO_2 – (MT)	77	76	77
TOTAL	**25,019**	**24,822**	**25,030**

Table 18 Annual metric tons of emissions for each power system for operating profile 4

	Diesel Electric	Hybrid – diesel electric with battery	VSG – diesel electric with variable speed generators
CO_2 – (MT)	24,178	23,910	24,153
NO_X – (MT)	477	536	509
SO_2 – (MT)	76	76	76
TOTAL	**24,732**	**24,522**	**24,738**