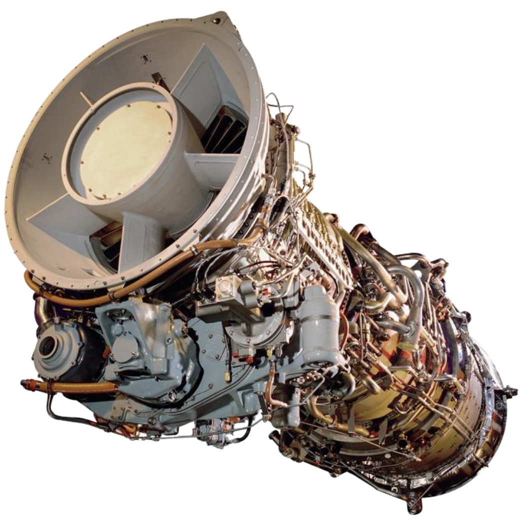
GE Marine Gas Turbines for Frigates

March 2018



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GE Marine Gas Turbines for Frigates

Introduction

The important role of a frigate is to escort and protect other high value fleet and merchant ships the world over. Frigates operate independently and possess sufficient capabilities (i.e. anti-submarine, anti-ship and anti-air) to provide missions in maritime and wartime environments.

With GE being the market leader in the supply of marine propulsion gas turbines and seeing the proliferation in the demand for frigates, we wanted to know how our gas turbines and product roadmap compared to the needs of frigates. Before we could answer that question, we needed to answer the following two questions:

1. What are propulsion trends for frigates?
2. What are key attributes or requirements, and how do they translate to gas turbine propulsion characteristics?

The key attributes of a frigate were taken from the July 2017 United States Navy Future Guided Missile Frigate (FFG(X)) Request for Information (RFI). It is anticipated the attributes would be common to many of the world's frigates.

Frigate Propulsion Trends and GE LM2500 Family Gas Turbine Suitability

GE performed an analysis of all the frigates built since 1960 excluding certain countries such as Russia and China. Classification of a ship as a frigate is a gray area as there is blending of smaller corvettes and larger destroyers. For this analysis, we used the Wikipedia listing of frigates. All of the following ship data was obtained from public information such as Wikipedia and *IHS Jane's Fighting Ships*.

The following data is based on the 461 frigates commissioned since 1970, which is when gas turbine propulsion replaced steam turbines as the propulsion of choice. Figure 1 presents the number of ships commissioned, in five-year periods, by propulsion type and average displacement. For multiple ships in a class, all ships are counted in the commissioning year of the first ship. Gas turbine (GT) propulsion includes a gas turbine with or without a diesel engine while diesel engine (DE) propulsion are ships completely propelled by diesels.

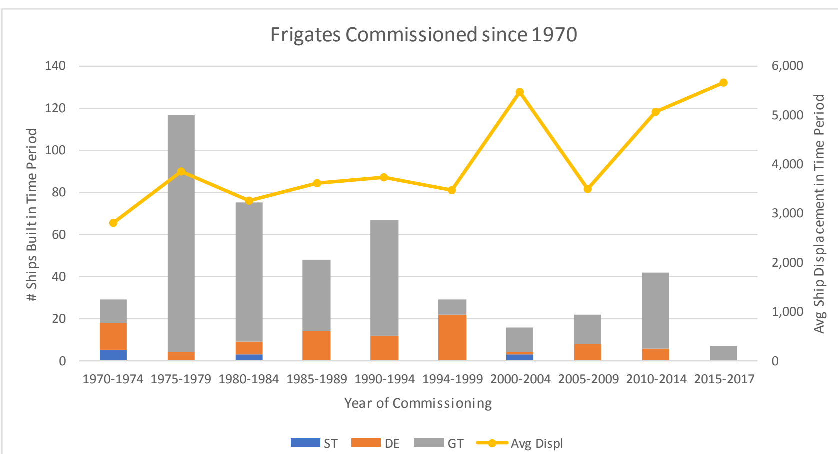

Figure 1: Frigate Propulsion Type and Displacement versus Time

Figure 2 presents a listing of notable frigate propulsion designs of various displacements that use gas turbines.

3000 - 3999T

Displ (T)	Country	Frigate	Number Built	Year First Ship Commissioned	Propulsion Type	Gas Turbine Type	Max Speed (knots)
3,600	Australia	Anzac	8	1993	CODOG	(1) GE LM2500	27
3,680	Germany	F122	8	1982	CODOG	(2) GE LM2500	30
3,320	Netherlands	Karel Doorman	8	1991	CODOG	(2) RR Spey	30
3,700	South Africa	Valour MEKO A-200SAN	4	2006	CODAG WARP	(1) GE LM2500	28
3,251	South Korea	FFX Batch 1	6	2013	CODOG	(2) GE LM2500	30
3,500	US	LCS Freedom	5	2008	CODAG	(2) RR MT30	>40
3,105	US	LCS Independence	5	2010	CODAG	(2) GE LM2500	>40

4000 - 4999T

Displ (T)	Country	Frigate	Number Built	Year First Ship Commissioned	Propulsion Type	Gas Turbine Type	Max Speed (knots)
4,110	Australia	Adelaide	6	1980	COGOG	(2) GE LM2500	29
4,770	Canada	Halifax	12	1992	CODOG	(2) GE LM2500	30
4,490	Germany	F123	4	1994	CODOG	(2) GE LM2500	29
4,000	Japan	Hatsuyuki	12	1982	COGAG	RR Olympus and Tyne	30
4,169	Taiwan	Cheng Kung	8	1993	COGOG	(2) GE LM2500	29
4,200	US	Oliver Perry	71	1977	COGOG	(2) GE LM2500	29
4,900	UK	Type 23	16	1987	CODLAG	(2) RR Spey	28

5000 - 5999T

Displ (T)	Country	Frigate	Number Built	Year First Ship Commissioned	Propulsion Type	Gas Turbine Type	Max Speed (knots)
5,800	Germany	F124	3	2003	CODAG	(1) GE LM2500	29
5,290	Norway	Nansen	5	2006	CODAG	(1) GE LM2500	31
5,300	UK	Type 22	16	1988	COGOG / COGAG	Batch 1: (2) RR Olympus and Tyne Batch 2: (2) RR Tyne and Spey	30

6000 - 7200T

Displ (T)	Country	Frigate	Number Built	Year First Ship Commissioned	Propulsion Type	Gas Turbine Type	Max Speed (knots)
6,000	France	FREMM	10	2012	CODLOG	(1) GE LM2500+G4	27
7,299	Germany	F125	4	2017	CODLAG	(1) GE LM2500	26
6,700	Italy	FREMM	10	2012	CODLAG	(1) GE LM2500+G4	30
6,050	Netherlands	De Zeven	4	2002	CODAG	(2) RR Spey	30
6,400	Spain	Alvaro de Bazan	5	2002	CODOG	(2) GE LM2500	29

Figure 2: Notable Frigate Ship and Propulsion Information by Displacement

Following are observations about propulsion selection that serve to identify cost and design drivers for a frigate propulsion system:

- Ship displacement averaged around 3,500T for ships commissioned until 1999. Since then, displacement has increased to an average of 5,700T.

- Gas turbines make up 80% of the prime mover market and are used in a variety of configurations often with diesel engines (i.e. CODAG.); diesel only applications (i.e. CODAD) make up the other 20%.

- Complete diesel powered vessels are typically used for smaller ships and only two are used for displacements greater than 4,000T: the French Cassard (5,000T) and the Danish Iver Hultfeldt (6,645T). Gas turbines are preferred when lower weight and volume, higher availability, lower maintenance requirements and lower noise are needed.

Figure 3 presents a comparison of the propulsion prime mover weight for three propulsion types, illustrating the weight benefit of a gas turbine powered ship.

Reference ships >5,800T (weight does not include off-engine skids and emission equipment)
  - 2 gas turbine CODOG: Spain F100 (2 LM2500 gas turbines + 2 CAT diesels)
  - 1 gas turbine CODAG: German F124 (1 LM2500 gas turbine + 2 MTU diesels)
  - CODAD: Danish Iver Huitfeldt (4 MTU diesels)

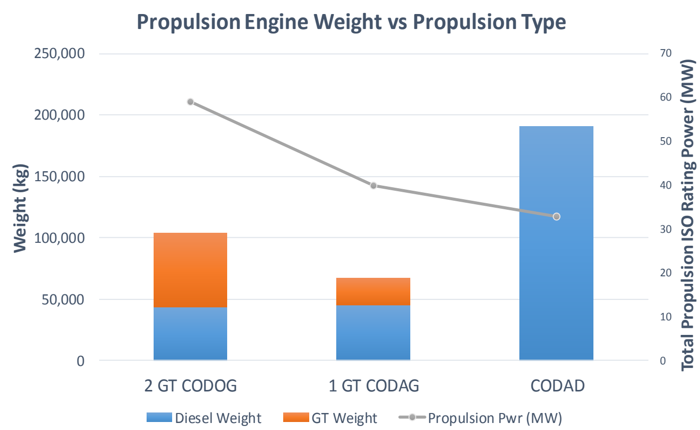

Figure 3: Frigate Top Speed Typically 28 to 30 knots

- The frigate top speed is between 28 to 30 knots; excluding the United States Littoral Combat Ship (LCS) which is > 40 knots (see Figure 4). Considerably more power, thus cost increase, is required with each knot of speed increase. For example, for a 3700T vessel 10 MW of additional power is required for a 2.6 knot increase (see Figure 16).

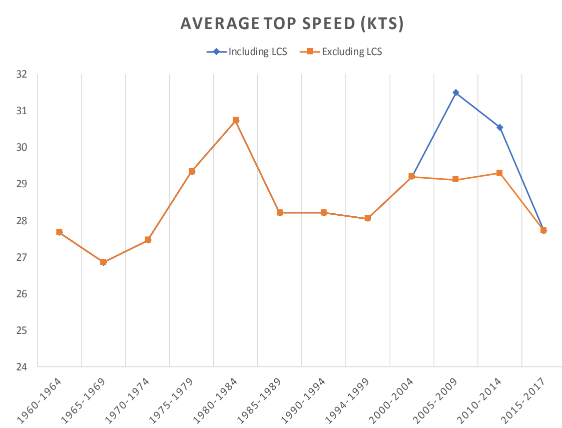

Figure 4: Frigate Top Speed Typically 28 to 30 knots

- 94% of the gas turbines powering active frigates (327 ships and 458 total gas turbines) are 25 MW[1] or below (see Figure 5). The 20 GE LM2500+G4 (35 MW[2]) gas turbines power the French and Italian FREMM's, 6,000T and 6,700T, respectively. The Rolls-Royce 40 MW MT30 powers the 3,500T 40+ knots U.S. Freedom LCS. Note the 25 MW GE LM2500 powers the 40+ knots Independence LCS. The Rolls-Royce Tyne, Spey and Olympus gas turbines are common United Kingdom engines but are no longer offered.

[1] All gas turbine ratings are presented at ISO conditions (59°F, sea level, 60% relative humidity, no inlet/exhaust losses)

[2] LM2500 is shown with power ratings between 16 to 25 MW. Product introduced at 16 MW and upgraded to present 25 MW.

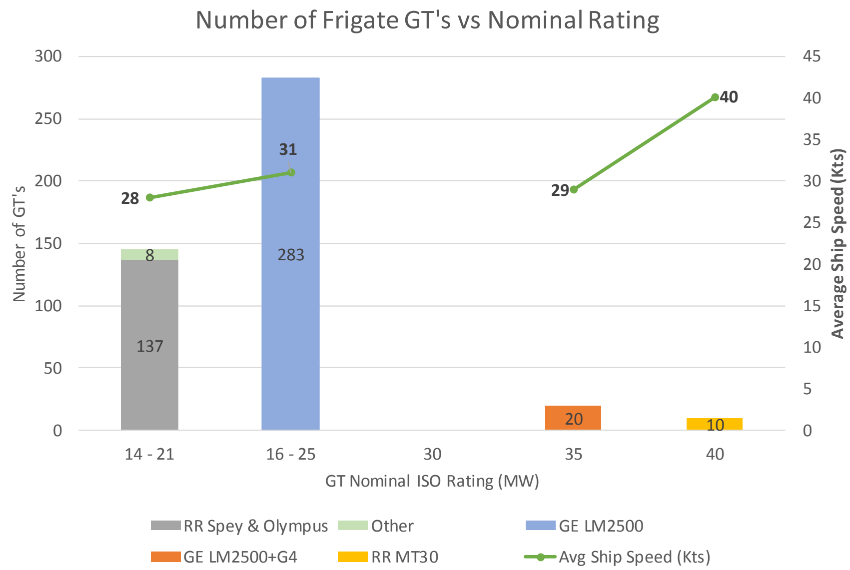

Figure 5: Gas Turbines on Active Commissioned Ships

- The number of gas turbines varies from one to two; this number is influenced by the following factors:

<u>Benefits of Two Gas Turbines</u>

- Survivability/redundancy
- Less space taken by cross-connect gear
- Greater speed
- Operational efficiency at part load

<u>Benefits of Single Gas Turbine</u>

- Less space taken by inlets and exhausts
- Lower initial cost

- The frigate has become a volume-critical ship. The propulsion plant of ships analyzed in 1981 show they consume 16% to 22% of the total ship volume.[3] The volume and related ship weight challenges have magnified in recent years as the mission requirements of frigates has increased. These requirements necessitated more room for weapons, radar, and additional systems such as hybrid electric motors and drives. A principle design objective of the propulsion plant is power density; that is, to provide the power needed in the smallest amount of space and weight.

[3] "Major Factors in Frigate Design", W. Garke and G. Kerr, SNAME Transactions, Vol. 89, 1981, pp. 179-210

Key Frigate Threshold Attributes

The just-released U.S. Navy FFG(X) frigate RFI provides a tiered ranking of key frigate attributes – many of which may become common to the world's future frigates. This is presented in Figure 6 and shows that many are directly applicable to gas turbine propulsion design.[4]

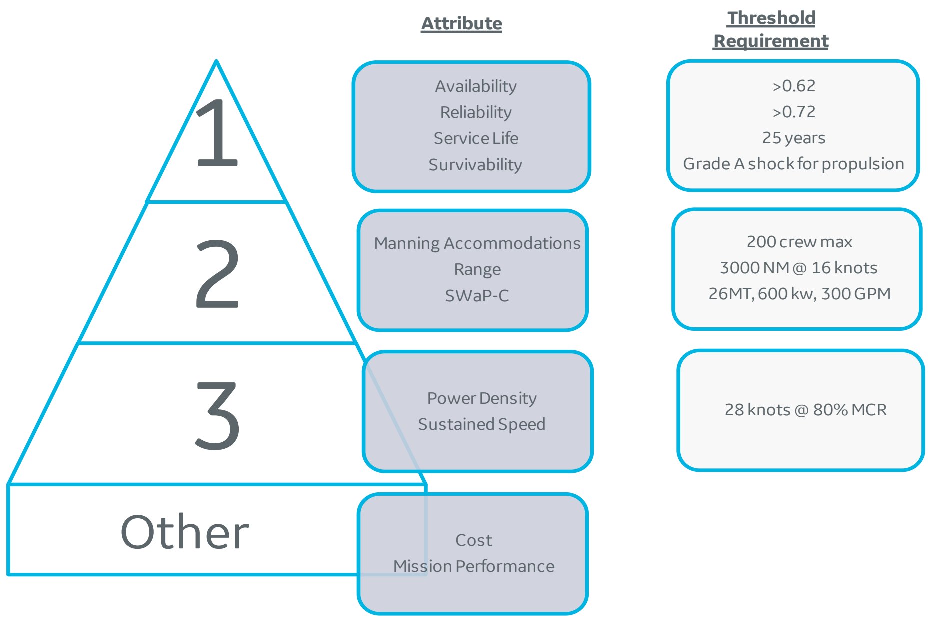

Figure 6: Frigate Key Attributes and Requirements

The following sections describe GE's propulsion gas turbine product line and design philosophy followed by GE's product roadmap, forming a foundation for an assessment of how GE gas turbines compare to these key attributes.

GE Gas Turbine Product Family and Experience (25 MW to 52 MW)

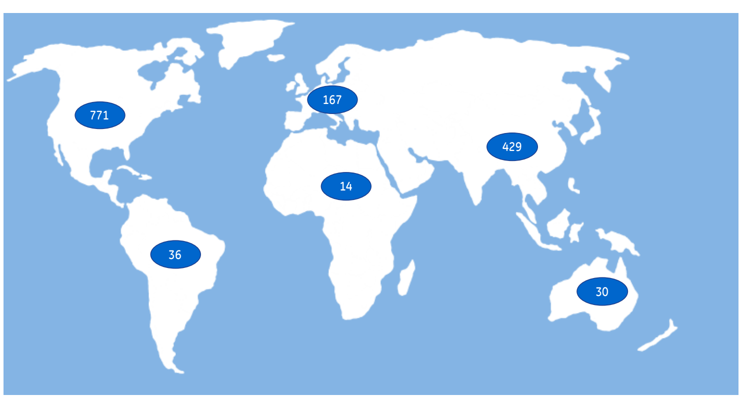

Figure 7: GE Military Marine Engine Deliveries on Every Continent

GE's Marine Solutions is proud to serve 35 navies, with 1,450 GE gas turbines operating onboard 646 naval ships worldwide (see Figure 7).

As the market leader in providing reliable propulsion power to all types of combatant ships, GE has delivered gas turbines to the world's navies powering corvettes, frigates, destroyers, cruisers, aircraft carriers and amphibious ships.

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[4] SWaP-C: size, weight and power/cooling for radar and advanced weapons

GE's nine depot service centers provide full overhaul capability worldwide, avoiding the need to send gas turbines overseas for shop maintenance.

GE is the only manufacturer of propulsion gas turbines in the United States. GE has a proven network of global manufacturing partners, which includes nine depot service centers, to satisfy local manufacturing content needs.

Fleet commonality of a single gas turbine affords a support pool of standardized spare parts, a common gas turbine infrastructure and training program for these fleets, and the flexibility to move propulsion crews across ship platforms with no incremental training. The extensive field experience of the LM2500 fleet across so many marine applications has resulted in a highly refined design. Because of this, the LM2500 is the most reliable gas turbine in the market with over 15 million hours in marine applications as well as another 70 plus million hours in industrial applications. These gas turbines reliably operate the world over in some of the most arduous conditions.

GE offers five propulsion gas turbines from 25 MW to 52 MW that enable architects to properly match installed propulsion power according to specific mission profiles and cost objectives (see Figure 8). Figure 9 represents the number of GE LM2500 family of gas turbines supplied for marine applications.

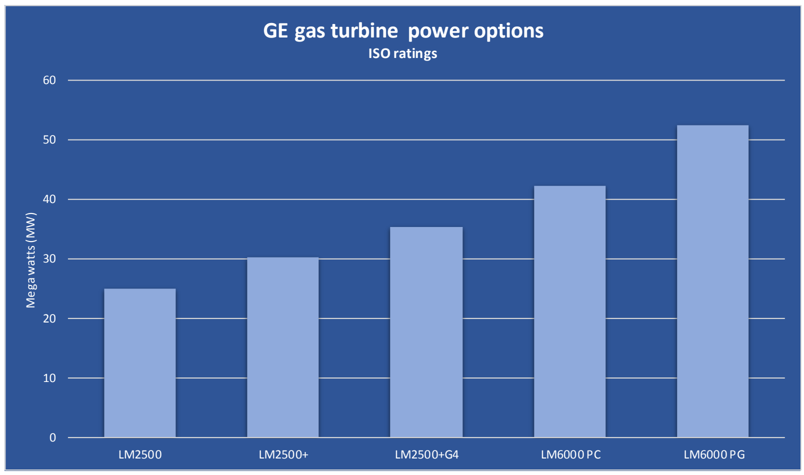


Figure 8: GE Marine Propulsion Gas Turbine Product Family

Applications	LM2500	LM2500+	LM2500+G4
Military Marine	1,188	6	27
Commercial Marine	25	26	2

Figure 9: GE Marine Number of Gas Turbines by Type

Recognizing there are significant differences between the parent aircraft engine and the aeroderivative gas turbine, only industrial variants should be considered for additional relevant experience. These GE marine engines share over 90% commonality with our industrial gas turbines. Many of the industrial applications operate in similarly demanding conditions such as compressor drivers or onshore/offshore platforms. The combined volume of marine and industrial units results in numerous savings such as product cost, spare parts and services. GE's LM2500 family gas turbine fleet also boasts extensive experience, high reliability and high availability.

Applications	LM2500	LM2500+	LM2500+G4
Total Engines	1,171	723	503
Total Hours	71.4 million	16.5 million	3.3 million
High Time Engine Hours	275,868	153,745	73,384

Figure 10: GE Marine Number of Gas Turbines by Type

Gas Turbine Design Philosophy

GE employs a two spool gas turbine design that offers a number of significant advantages over a three spool machine as used by Rolls-Royce. The two spool gas turbines offer shorter engine start-up times, strong reliability and ease of maintenance. Following is a short summary of the differences.

Three-spool machines, used by Rolls-Royce, have the following features:

- They typically use fewer variable stator vanes to regulate compressor flow at low speeds to limit surge. In the three-spool machine, the flow regulation is assisted by self-regulation of the third spool speed.
- Additional bearings are associated with a third shaft. The oil system and its distribution are more complex and the bearings generally run hotter. The rotors are more prone to have alignment, vibration and balancing issues.
- Three-spool machines have longer start up times due to the added number of rotor components and bearings, the synchronization of the multiple compressor rotors at low speeds, and oil system requirements.

GE employs a two-spool design that has considerably more experience in flight, industrial and marine applications. Surge protection at low speeds is accomplished via the use of variable stator vanes.

Another significant difference involves the high-pressure turbine blade designs. Rolls-Royce employs a shrouded High Pressure Turbine blade (HPT). The Rolls-Royce shrouded HPT is heavier (in some publications stated as much as 30% higher), and therefore takes more time to bring the rotor up to speed at the proper temperature. Rotational speed is lower because disk loading and blade stresses are greater with the added mass of the rotating shrouds. GE employs a shroud-less blade architecture, and controls clearances and tip leakage with stationary shrouds embedded in the turbine stator.

Gas Turbine Module Design Philosophy

Figure 11 presents the key design elements of GE's gas turbine module design.

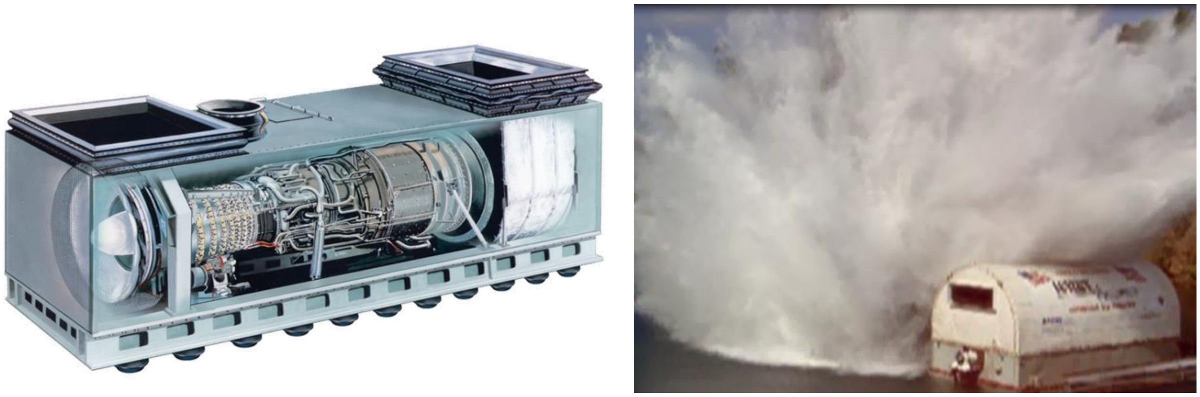


Figure 11: GE Module Design Philosophy and Shock Testing

- Shock qualified via barge test
- Full enclosure for optimal noise and thermal performance and crew protection
- Full complement of accessories (start and fire protection)
- Designed for in place maintenance
  - Line replaceable units (LRUs), fuel pumps, sensors, etc.
  - Top-case compressor: high pressure compressor horizontal split-line design facilitates unplanned foreign object damage (FOD) repair, blade blending, or replacement in place. Alternative designs require the removal of the gas turbine and complete tear down to repair a FOD-damaged blade.
- Easy gas turbine removal

GE Gas Turbine Module Product Development Roadmap

Figure 12 illustrates GE's gas turbine module product roadmap that is well underway. In 2019 GE will introduce its composite enclosure with ~50% lower enclosure wall weight and other component modernization. In 2020, the LM2500+ and LM2500+G4 engines will be shortened by 0.36 m (4%) to be the same length as the base LM2500; additional weight reduction will be introduced by a redesign of the base and other secondary components.

Available in Shipment Year =>	Today	2019	2020
Enclosure Design	Steel	Composite	Composite
Base Design	901D shock	901D shock	Lightweight base
Module + gas turbine weight LM2500 LM2500+/+G4	 22,000 kg 23,000 kg	 19,500 kg 20,500 kg	 16,000 to 17,000 kg (target)
Module length LM2500 LM2500+/+G4	 8.0 m 8.36 m	 8.0 m 8.36 m	 8.0 m 8.0 m
LSCA and selected auxiliaries	Off-module skid	Off-module skid	On module

Figure 12: GE Gas Turbine Module Improvement Roadmap

2019: GE Composite Module and Module Modernization Introduction

GE has been working with the U.S. Navy and General Dynamics Bath Iron Works since 2014 to introduce a lightweight composite enclosure. It is planned for units shipped in 2019, and was designed and performance-verified in accordance to a complete set of U.S. Navy military and shock specifications. To date, all fire resistance tests were satisfactorily completed by an accredited testing laboratory.

A series of component panel tests (steel and composite) and analyses, where appropriate, were performed that confirmed compliance. The enclosure will undergo barge shock testing to verify compliance (see Figures 13 and 14).

Figure 13: Composite Enclosure

Figure 14: Composite Sidewall during Fire Resistance and Structural Integrity Validation Testing

The five-sided carbon fiber composite enclosure has eliminated the need for bolting, and it provides the following benefits:

- 2,500 kg reduction in weight
- Access panels and doors: larger and increased number to reduce maintenance time
- Lower radiated noise offers improved crew accommodations
- Lower thermal radiation offers greater crew protection and less radiated heat into the engine room resulting in lower cooling requirements
- Lowered life cycle costs are achieved by reducing corrosion susceptibility and negating extensive repairs common with the employment of steel components.

As part of this program with the U.S. Navy and General Dynamics, modernized digital sensors and components such has transducers, heaters, flame and ice detectors are being introduced.

2020: Single Module Outline for all LM2500 Gas Turbines, Lighter Base and Integrated Skids in the Module

In 2020, GE will shorten the LM2500+ (30 MW) and LM2500+G4 (35 MW) modules by 14 inches (0.36 m) to be the same length as the base LM2500 (25 MW). The result is that all three LM2500 models will have the same module footprint. The benefit to the ship designer is more gas turbine power options (25, 30 or 35 MW) in the same length and volume; or 2.6 knots of additional speed in the same footprint if a LM2500 were to be replaced with a LM2500+G4 for a single gas turbine ship (4.6 knots for a dual gas turbine vessel).

Figure 15 presents the estimated ship speed increase for selected frigates by changing to the more powerful LM2500+G4 in the same footprint as the baseline LM2500 ship design. Figure 16 presents the MEKO A-200SAN ship resistance curve for the baseline vessel with the 10 MW additional power if a LM2500+G4 were employed. Note that for the ship to use this power, other propulsion system components would need to be upgraded such as gears, shafting, waterjets, propeller and bearings.

Displ (T)	***Country***	***Frigate***	***Propulsion Type***	***Ship as Designed***		***Ship with LM2500 +G4 in same footprint***		
				Gas Turbine Type	***Max Speed (knots)***	***Gas Turbine Type***	***Max Speed (knots)***	***Speed Increase (knots)***
7,299	*Germany*	*F125*	*CODLAG*	*(1) LM2500*	*26*	*(1) LM2500+G4*	*28.6*	*2.6*
3,700	*South Africa*	*Valour MEKO A-200SAN*	*CODAG WARP*	*(1) LM2500*	*28*	*(1) LM2500+G4*	*30.6*	*2.6*
6,400	*Spain*	*Alvaro de Bazan*	*CODOG*	*(2) LM2500*	*28*	*(2) LM2500+G4*	*33.6*	*4.6*

Figure 15: Selected Frigates Speed Increase with Power Dense LM2500+G4

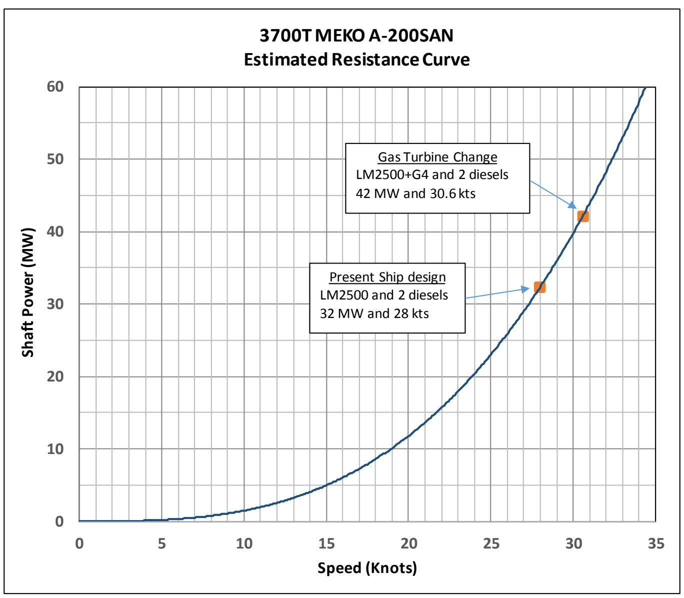


Figure 16: 3700T Estimated Ship Resistance Curve with LM2500+G4 Upgrade

For LM2500 family units delivering in 2020, other package improvements will be introduced including a lightened base by 2,500 to 3,500 kg. The Lube Scavenging and Conditioning Assembly (LSCA) and water wash skids will be integrated into the module.

Gas Turbine Size and Weight Comparisons

The size and weight of the propulsion equipment is a key attribute of the frigate. Smaller equipment allows more space for crew, combat systems and mission payloads. GE presently offers a gas turbine module with the best power density by weight (kW/kg); see Figure 17. GE's new composite module will yield a 12% improvement and the 2020 lightweight base design yields a 34% improvement from the current design.[5]

On a volumetric basis (kW/m^3), GE engines perform very well with the current LM2500+G4 being 34% more power dense than the Rolls-Royce MT30. The LM2500+ and LM2500+G4 models will be shortened 0.36 m to provide another 4% improvement for units delivered in 2020 (see Figure 18).

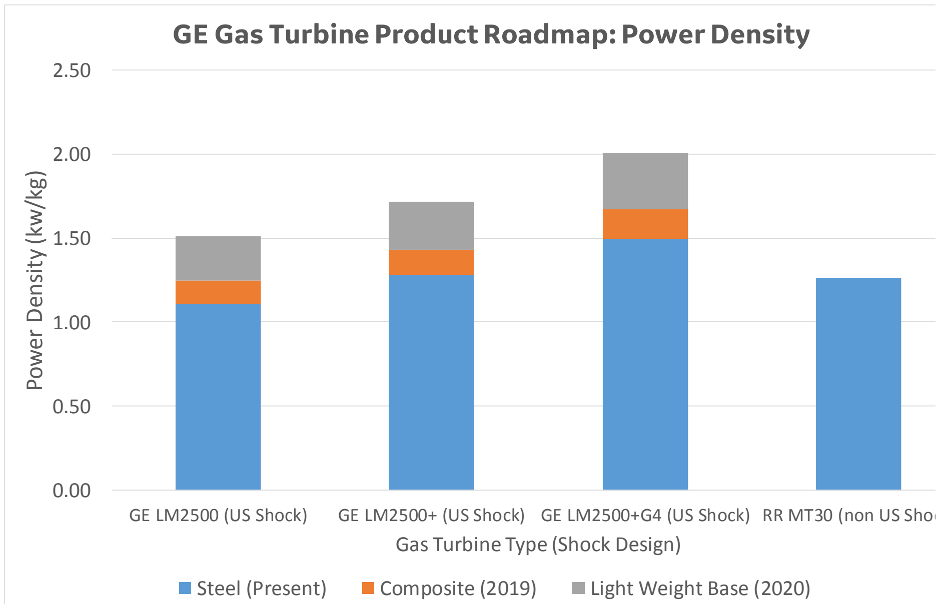


Figure 17: GE Gas Turbine and Module Power Density (kw/kg)

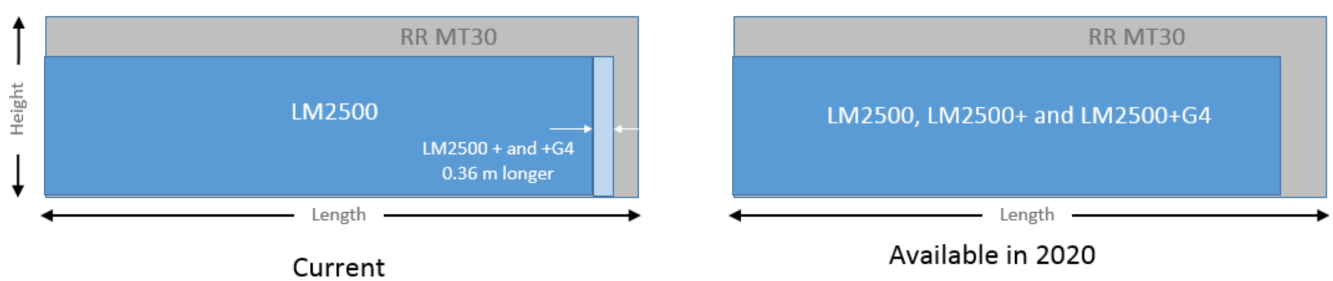


Figure 18: GE Gas Turbine and Module Volume

[5] RR MT30 data: https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/marine/rr-mt30-brochure-uk-2016.pdf

GE's Demonstrated Ability to Meet Attributes and Requirements

The following figures summarize how GE demonstrates its ability to meet the stated key attributes of frigates:

	Attribute	Threshold Requirement
1	Availability	>0.62
	Reliability	>0.72
	Service Life	25 years
	Survivability	Grade A shock for propulsion

GE's Demonstrated Ability to Meet Requirements

Availability

- 98% managed by large marine and industrial fleets
- Nine worldwide depot/service locations
- Large fleet of engines on every continent for interoperability and supportability either onshore or afloat
- Designed for in-place maintenance

Reliability

- 98%
- Two spool design: fewer bearings, simpler oil system and less prone to alignment and vibration issues
- Faster to start-up

Service Life

- >15 million operation hours and continual support of engine
- USN Oliver Perry in operation for 40 years
- An additional 70 million industrial operating hours

Survivability

- Only propulsion gas turbine shock tested

	Attribute	Threshold Requirement
2	Manning Accommodations Range SWaP-C	200 crew max 3000 NM @ 16 knots 26MT, 600 kW, 300 GPM

Manning Accommodations

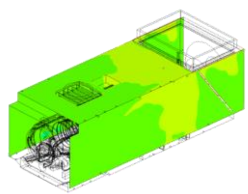
- Procedures and training in place. Low maintenance requirements (~120 hours/year)
- Crew ergonomics: composites enable more and lighter access panels and doors

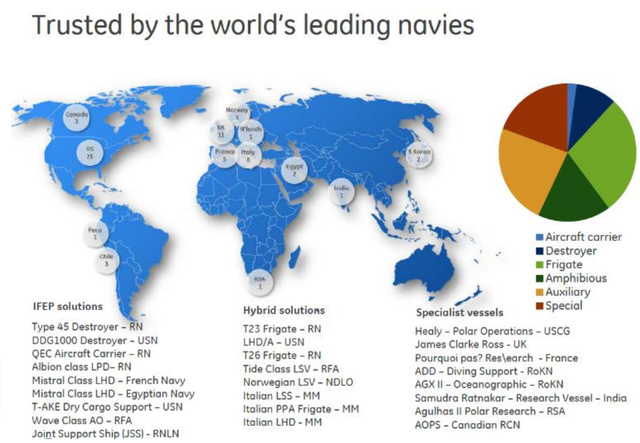
Range

- GE efficient gas turbines
- GE provider and integrator of hybrid electric drive

SWaP-C

- Composite module radiates less heat



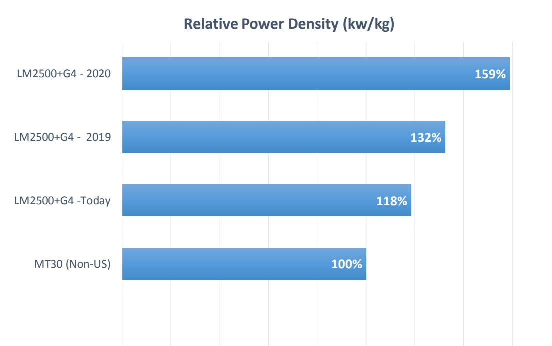


GE Electric and Hybrid Drive Experience
GE is the only HED provider on USN Ships

	Attribute	Threshold Requirement
3	Power Density Sustained Speed	28 knots @ 80% MCR

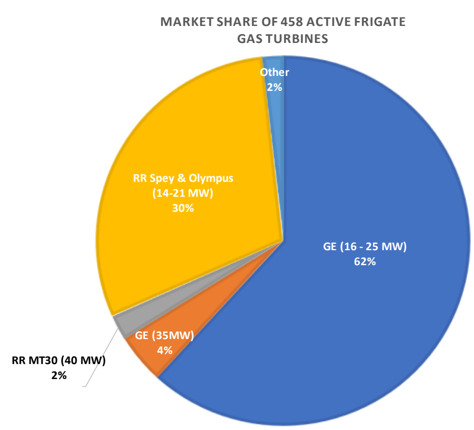
Power Density

- GE has the best power density; further improvements planned
  - Composite enclosure
  - Lightweight base
  - Single reduced length module design for LM2500, LM2500+ and LM2500+G4



Sustained Speed

- Three LM2500 models (25 to 35 MW) provide most cost effective
- Power needed for current and future frigates
  - 28 to 30 knots typical of commissioned frigates, of which all use gas turbines 35 MW or less



Conclusion

The important role of a frigate is to escort and protect other high value fleet and merchant ships the world over. Frigates operate independently and possess sufficient capabilities, while providing missions in maritime and wartime environments. The size of the frigate is increasing and it is becoming volume constrained due to requirements demand.

Gas turbine propulsion plays an important role since it propels 80% of the active frigate fleet worldwide, and essentially all ships greater than 4,000T, satisfying the frigates need for speed and power density amongst other things.

This paper has shown that the frigate key attributes and requirements directly translate to gas turbine attributes. **Thereby, the gas turbine shall be reliable, available, shock qualified, efficient, right size power to sustain speed, power dense and crew-accommodating that meets total cost objectives and performs to mission requirements.**

Further, this paper has shown that the GE LM2500 family of engines meets these key attributes and requirements in that they are proven and reliable with the right power to propel the world's frigates. GE is continually investing to modernize its product offering, improving upon our best-in-industry power density and module performance. These benefits translate into flexibility for the naval the architect to design ships that meet demanding frigate attributes and mission requirements.

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