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**Development of multi-fuel, power dense engines for maritime combat craft**

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The NATO and UK Single Fuel Policies outline the intent for a single battlefield fuel (JP8) to minimise fuel logistic requirements in theatre. This policy also establishes targets for the removal of petrol (gasoline) from operations by 2015. In response to this policy, the Royal Navy established its own objectives for the removal of petrol-reliant equipments within the maritime domain.

The Diesel Engines Group, with cooperation from EP Barrus Ltd, developed a 44hp outboard engine prototype, which is capable of operating on naval fuels. This 44hp project is part of an overall development programme that aims to provide a family of outboard engines that will operate on fuels that will continue to be supported by platforms at sea, while still meeting the necessary performance requirements for small boat operations. Engineers remain challenged to provide robust, non-petrol burning units at the required powers while still meeting the necessary levels of equipment power-density for each application—standards that were historically simple to meet with conventional, carburetted, two-stroke, petrol outboards. This paper discusses the 44hp project and the challenges facing the team for the continued development of a family of power-dense, non-petrol outboard engines.

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**AUTHOR’S BIOGRAPHY**

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**BACKGROUND**

**Single fuel concept**

The NATO single fuel concept defines a strategy to achieve maximum equipment fuel-commonality through the use of a single battlefield fuel. This policy articulates the shift to kerosene-based JP8 (NATO F-34/AVTUR) fuel for use in military aircraft, vehicles and equipment.* The objective of this policy is to simplify the associated logistical supply chain and supporting infrastructure for fuels in theatre. The concept, which originated in 1986, has subsequently been adopted as the NATO Single Fuel Policy (SFP) and is being executed in three phases:

- **Phase 1.** Replacement of F-40 fuel with JP8 for use in land-based aircraft (complete)
- **Phase 2.** Replacement of diesel fuel (F-54) with JP8 in land-based vehicles and equipment compression ignition (CI) engines (ongoing)
- **Phase 3.** Elimination of petrol (F-67/CIVGAS/gasoline) from military use on the battlefield* (ongoing).

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*The original direction at 1 states the intent to eliminate and/or reduce the requirement for gasoline to such quantities that national or bilateral agreements would only be required to ensure fuel support through the use of jerry cans/drums/collapsible tanks.
The economic requirements to support in-theatre fuel stores are significant and support the necessary actions to reduce and rationalise consumption and transport, where the fuel delivery costs to front and back line operations is estimated between 100 and 600 USD/gal.\textsuperscript{2}

The SFP has already been adopted independently by many NATO member states. The US DoD targeted the removal of gasoline-reliant equipment by 2010,\textsuperscript{1} while the UK MoD strives to complete this Phase 3 objective by 2015.\textsuperscript{5} In many applications, project teams continue to struggle to identify equipments able to operate on the single battlefield fuel, while still meeting the performance and portability standards easily met by the current, in-service, spark ignited (SI) engines.

Fuel management within the RN
The Royal Navy’s response to the SFP included a plan for the phased-removal of petrol from the maritime battlespace to be completely realised by 2015.\textsuperscript{7} The RN however, would continue to use marine diesel fuel (F76) as their primary fuel in main and auxiliary engines, in addition to JP5 (F44) kerosene for naval air operations. This policy would primarily impact small boat operators who have historically relied on temporary and sometimes ad-hoc petrol stowage to support their maritime combat craft operations. For the Navy, removing any requirement to support gasoline stowage at sea would reduce the safety risk of fire and explosion associated with the stowage of higher-flashpoint fuels.\textsuperscript{8} Replacement of these outboards with units capable to run on JP5 and/or F76 could also increase the range and persistence of their small boat operations.

MOD DEVELOPMENT PROGRAMMES
Maritime equipment targets
In 2006, the RN defined the timescales for the removal of petrol, highlighting certain gasoline-dependent applications normally supported by ships and submarines:

a) Royal Marines operations: 50 hp;
b) Diving operations: 40 hp;
c) Special operations: 30 hp; and
d) Counterterrorism/Interdiction operations: approximately 250 hp.

In response to these targets, the Diesel Engine Group (DEG) was challenged to source and/or develop equipment solutions that were not reliant on petrol, but still capable of meeting established performance requirements.

User requirements
The following key UK requirements were defined at programme outset:

a) Fuel capability: The engine must be capable of operating on JP5 and F76 type fuels (herein referred to as ‘fleet-fuels’). Diesel capability may be desired in many applications due its prevalence on all ships/submarines.
b) Power density: In order to configure to existing combat craft and integrate with naval platforms and transport aircraft launch/recover systems, both the size and mass of the units are of critical importance.
c) Specific fuel consumption (SFC): Minimum fuel consumption rates were defined which directly impact craft payload, range and persistence.
d) Military specifications: A number of system-functions that are tailored to military use/environments. (ex. submersible, pull-start only, cold start, shock, signature).
e) Developmental costs: Minimal.

Development options
Initially, a market survey was commissioned to investigate the potential technologies that could be applied to provide power-dense JP5 and F76 (herein referred to as ‘fleet-fuel’) capable solutions. A number of development options were considered, and each was weighed against key requirements, including affordability and technological risk. The in-service engine along with potential engine solutions considered for fleet-fuel capable outboards are briefly described below:

a) Baseline engine: In-service two-stroke petrol outboard motor (OBM) (carburetted or electronic fuel injection):
   - Petrol only. High power density, robust, simple design. SFC varies.

b) Two-stroke spark ignited, direct injection (SIDI) OBM:
   - May be reconfigured to accept fleet-fuels. Reduced power density. Higher SFC. Requires modifications and electronics/controls suite.

c) Cross-cutting technologies:
   - Automotive compression ignition (CI) engine: Fleet-fuel capable. Low power density. Low SFC. Engine requires marinisation.
   - Lightweight CI engines: These engines include diesel configurations originally developed for lightweight applications (ex. Unmanned Air Vehicles (UAVs)). Potentially low SFC. Units may require modifications and marinisation.

d) Novel engine types: Numerous other engine configurations exist that could be successfully configured to OBM applications.

Engine adaptation
Kerosene and diesel fuels are considered heavier and less volatile than gasoline and did not historically provide adequate performance when introduced into conventional SI engines. Early attempts at reconfiguring these commercial-off-the-shelf (COTS) carburetted outboards for operation on kerosene and/or diesel fuel were largely unsuccessful.

Over the past decade, increasing emissions legislation has forced equipment manufacturers to adopt cleaner-burning engine technologies. Some original equipment manufacturers (OEMs) have been successful in applying the latest fuel-injection equipment to the two-stroke engine in an effort to meet legislated emissions standards, while retaining some of
the benefits of its lighter weight. The high levels of fuel atomisation provided from units fitted with this complex injection equipment is the same technology that could provide for operation on fleet-fuels.

Other engine options could include reconfiguring a suitable, non-marine engine for the outboard motor application. Project managers must consider the following areas for modification and re-engineering during concept evaluation:

**General marinisation:**
- Water cooling;
- Oil system re-configuration;
- Air management/system design;
- Drivetrain coupling/articulation;
- Misc marinisation (waterproofing, coatings etc);
- Weight savings.

**Mil specification:**
- Post-submersion re-start (PIRS) modifications;
- Rope start (small outboard only);
- Shock hardening;
- Cold temperature capability.

The marinisation of these engines has inherent risks associated with cost-overruns and inadequate performance. Each down-selected engine must be assessed early against the KURs and other important requirements to determine each area of critical risk and whether those risks will be tolerable before defining subsequent mitigation strategies.

### 40–50 HP MFOBM DEVELOPMENT PROJECT

Modification of a spark-ignited, direct injection (SIDI) solution was deemed the most cost-effective option to provide fleet-fuel capability to the 40–50hp outboard. At that time, the alternatives of cross-cutting and novel technologies were all considered high-risk and scored lowest on the RN options analysis.

In 2005, DEG contracted support for this development from the outboard motor service provider, EP Barrus, with combustion design and engineering support from Orbital Engine Corporation, of Perth Australia. Orbital was mainly chosen because of their experience of fuel injector design and subsequent development of the Mercury Optimax OBM, fuel injection system.

Coincidentally, the United States Naval Surface Warfare Centre had partnered with Bombardier Recreational Products (BRP) in an effort to develop a power-dense, JP5/8 capable outboard engine of marginally higher powers (55hp).††

DEG originally intended on developing an engine solution that would potentially meet the requirements of both 40 and 50hp user groups. As one group’s requirements for minimum power grew, it became clear that the output of the MoD developed unit would fail to meet the higher powers needed for minimum speed/sea state performance objectives. The much larger BRP 55MFE possessed the power reserves to propel the heavily loaded craft, even in higher sea states, and was identified as the preferred solution.

The MoD-developed 44hp, Tri-Fuel Outboard (TFO) remains the unit destined for service, primarily in the fleet mine-hunting role due primarily to its capability to run on F76, which is the only fuel supported by the Mine Counter Measures Vessel (MCMV) platforms.

#### Designing for multi-fuel capability

Two-stroke SIDI engine: The 44TFO engine (Fig 1) development was applied to the Tohatsu Low Pressure Direct Injection (TLDI) production engine with the specifications shown in Table 1.

<table>
<thead>
<tr>
<th>Base engine</th>
<th>Tohatsu M50B TLDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston displacement</td>
<td>697cc</td>
</tr>
<tr>
<td>Bore x stroke</td>
<td>68mm x 64mm</td>
</tr>
<tr>
<td>Maximum power output</td>
<td>36.8 kW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>5500rpm</td>
</tr>
<tr>
<td>Cylinder head</td>
<td>Standard</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>6.4:1</td>
</tr>
<tr>
<td>Fuel system</td>
<td>Air assisted direct injection (lateral rail assy, water cooled)</td>
</tr>
<tr>
<td>ECU</td>
<td>Mitsubishi M3i electronic control unit</td>
</tr>
<tr>
<td>Spark plugs</td>
<td>NGK IZFR5J</td>
</tr>
<tr>
<td>Air injectors</td>
<td>Synerject PH 37–116</td>
</tr>
<tr>
<td>Ignition</td>
<td>Inductive</td>
</tr>
<tr>
<td>Gear reduction ratio</td>
<td>1.85 (1:3.24)</td>
</tr>
</tbody>
</table>

| Table 1: MoD MFOBM (44hp) - Tohatsu base engine specification |

†† The BRP 55MFE is now a commercially available JP5/8/gasoline outboard, which achieves exemplary performance primarily due to their proprietary E-TEC system design. This design achieves high levels of fuel atomisation and combustion control through the incorporation of patented FICT (“voice-coil”) fuel injection technology.
**Direct injection (DI) strategies**

High levels of atomisation and fuel/air mixing are critical for the ignition of low-octane fuels in SI combustion where compression ratios are much lower than normally found in CI engines. The rate of vaporisation of the fuel droplets depends primarily on the size, distribution and their velocity, in conjunction with the fuel’s volatility. Injector design becomes critical in control of these parameters, dictating both the fuel spray (size, distribution) and penetration (axial length of plume).

There are few commercially available systems designed to achieve this level of air/fuel mixing within the two-stroke engine. The MoD employed an SIDI system proven in the Mercury Optimax outboard engine family, using an air-assist direct injection (DI) system designed by Orbital (Fig 2). This DI strategy relies on aggregate air pressure generated from a single piston air compressor. Injector assist air pressure is provided via a crank-driven, single-piston air compressor, where fuel pressure is achieved via a two-stage fuel pump assembly.

The air-assist injection ensures a fresh air supply around the fuel droplets, enabling the mixture to ignite even under conditions where there are high levels of retained exhaust gas (lower oxygen content) in the cylinder, which is typical of two-stroke operation at low loads.

The control of both fuel and air charges together through a common injection system replaces a conventional throttle and carburettor, allowing greater control of the cylinder air and fuel ratio during each compression stroke. This improved control provides the ability to introduce the fuel and air required in a single event, which limits the fuel’s exposure to the pressures and temperatures inside the combustion chamber, and thus reduces the time for onset of auto-ignition (knock).

**Engine control**

Multi-fuel combustion control is achieved through electronic variation of the spark, air and fuel timing in relation to crank angle tailored for combustion of each fuel type. Combustion of each fuel is defined through EEPROM logic within the Engine Control Module (ECM). This set of logic is referred to as a fuel or engine ‘map’. Additional maps are included for transient operating regimes to include: Wide Open Throttle (WOT) acceleration (ie, high level rate-of-change of RPM), extreme temperature and starting. Each map is designed to maximise performance of its characteristic combustion properties, while limiting temperatures and pressures in order to protect engine components.

**Design challenges**

**Engine knock**

As mentioned above, these low-octane fuels (kerosene and diesel) have a tendency to pre-ignite (or ‘knock’) when used in SI engines. This undesirable combustion phenomena results in sharp pressure rises which can result in the uncontrolled release of significant quantities of the fuel’s chemical energy; energy which may be transferred harmfully to engine components.

The two main factors that affect an engine’s tendency to knock are:

- The combustion chamber design characteristics that promote complete combustion;
- The quality/properties of the fuel.

Diesel fuel is designed to have a relatively high cetane number, which represents a strong tendency to ignite, and thus a short ignition delay; all favourable properties for use in a CI engine, but proportionately negative when used in a SI engine. Good fuel/air mixing in the combustion chamber can be assisted by design of the cylinder geometry, which also promotes complete gas exchange (ie, efficient scavenging). The requirement for complex design in the 44TFO combustion chamber is relaxed by the strategy to inject atomised fuel for stratified and controlled delivery without any need for complex piston crown or cylinder head designs.

**Design compression ratio**

A primary combustion chamber characteristic is the engine’s compression ratio (CR). In order to reduce the susceptibility of the heavier fuels to knock, the design CR of the 50hp petrol block was reduced to accommodate lower combustion temperatures across the operating conditions.
The final CR design was chosen as a best compromise, demonstrating favourable torque characteristics without excessive knock.

**Spark control and design**

In practice, spark plug fouling has been a major concern when operating on JP5/8 and diesel fuels due to the combustion deposits and subsequent reduction of electrode efficiency. The use of F76 results in high levels of deposits on both piston rings and spark plugs and has to be controlled through the correct positioning and design of the plug electrode (Fig 3). Normally, spark timing for a given operating condition is set to give maximum brake torque with an appropriate offset for knock protection. This set-point must change for variations in load and fuel type. For each fuel map, spark energy and duration has to be defined across the engine operating range and is programmed in the ECM.

A proven method to control knock is to retard the spark advance close to Top Dead Centre (TDC), which essentially commences all ignition events later in the compression stroke. This strategy is used extensively in the multi-fuel OBM to control knock on both kerosene and diesel fuels.

**Bore oiling**

Due to the decreased pressure ratios needed to control knock, an accumulation of unburnt carbon deposits in the combustion chamber results when operating on low octane fuels. These deposits rest primarily along piston ring surfaces, recessions and at the spark plug tip. To combat this problem, ECU controlled bore oiling has been introduced (Fig 4) into the cylinder near the exhaust port and is supplied from a dedicated oil pump in order to remove combustion deposits away from these surfaces.

**MoD 44hp Tri-fuel engine performance**

Currently, the 44TFO development engine is operating effectively on all three fuels – JP5/8, F76 and gasoline. The configured engine maps produces an output of between 43 and 47hp. Fig 5 shows the performance on all fuels and illuminates the overall reduction in maximum power from the original petrol engine design of 50hp. This reduction in output is an unavoidable result of the reduced compression ratio and the imposed knock limits of the design. The knock limiting strategies embedded in the calibrations are clearly shown when comparing the torque curves for the engine across all fuels, which demonstrate a significant decrease in mid-range torques on the heaviest fuels. Maximum power at high RPMs are more closely matched across fuels since cycle times are sufficiently rapid, which reduces the time available for gases to pre-ignite.
Design trade-offs
This engine design incorporates the necessary complex controls, injection equipment and ancillaries, providing the required capability to tune engine performance across all fuel types. This capability was realised without sacrifice to the desired ‘driveability’ and engine responsiveness across all fuels. Multi-fuel engine designers may expect to sacrifice approximately 16% in maximum power output and approximately 10% increase in unit mass when comparing performance with the applicable, conventional two-stroke, petrol baseline engine. Although commendable performance had been achieved through this design, the associated penalties in power-density and unit complexity (potential impact to robustness) is still considered unpalatable by many user groups.

25hp and 250hp projects
Modification of COTS SIDI units at 25/250hp continues to be assessed. Based on the experiences with the 44TFO and BRP 55MFE MFOBM technologies, it is anticipated that meeting the power density requirements of the 25/250hp outboard applications may not be possible with the current selection of COTS SIDI engines.

Fig 6: 40–55hp outboard power density comparison

Fig 7: 25–30hp outboard power density comparison
Although the focused efforts to reduce overall system mass has concentrated on engine/ancillary weight reduction, potential savings may be realised by reducing the mass of the cowl and transmission/leg assemblies. These reductions have to be carefully assessed due to potential cost impacts and any detrimental effect to system robustness.

POWER DENSITY COMPARISONS

In ideal circumstances, the project managers would be best served by an extremely light-weight diesel engine where the system and efficiencies could be optimised for kerosene and diesel combustion, while still maintaining robust, reliable architecture at reasonable system cost. This potential option has historically been very difficult to meet, mainly given the normally larger and heavier construction of the diesel engine block designed to withstand higher in-cylinder peak pressures.

The following graphs (Figs 6,7,8) represent the power-density comparisons across the programme’s outboard/engine families. The figures illustrate the weight/size differences of SIDI, four-stroke petrol and other diesel engine configurations when compared to the conventional two-stroke units currently in service. Overall, these comparisons convey the difficulties facing outboard engine designers when wishing to convert/modify existing COTS units to fleet-fuel operation while meeting power density targets. It is important to note that the baseline, in-service, power dense two-stroke engine will soon to be unsupported by OEMs due to re-profiling of outboard engine families in order to meet the latest emissions legislation.

40–55 hp outboard comparison

Fig 6 illustrates the relative power densities for comparable outboard motors in the 40–55hp range (27–41 kW). A line-plot is used in these graphs to clearly outline the differences in parameters across each unit. The highest comparable power densities are achieved by the conventional outboard designs in both the two-stroke Evinrude 55hp Enforcer and the Mercury 50hp. It can be seen that the MFOBM variants (MoD and BRP) show a loss of power density between 20–30% when compared to the baseline unit. Undesirable losses in power density are suffered by the conventional diesel and the COTS, four-stroke SI engines.

25–30 hp outboard comparison

Fig 7 shows a comparison of COTS outboard options for the applications between 25 and 30hp (18–23 kW). This graph compares outboards to the baseline Mercury/Mariner 25hp OBM, and illustrates the potential loss of power density associated with reconfiguring COTS units for fleet fuel capability.

A number of engines primarily developed for lightweight, aerospace applications remain attractive for application to outboard motors due to their high power density and similar design drivers. Although not an exhaustive representation, there are very few options for reconfiguration at the 25hp (18kW) power band (Fig 8 shaded area). The Ricardo HF UAV, four-stroke, supercharged CI engine (Fig 9) is one example of an engine that demonstrates an appealing option for the 25hp outboard, with power density over twice that of the other engine variants, due primarily to the high levels of supercharging applied to the four-stroke design. The highest power-densities are achieved on the smaller, less powerful SIDI designs.
250+hp engine comparison
Again, various fleet-fuel capable engine designs are compared for powers above 200hp, where it is noted that only a few COTS options exist at the required size/weight. At this power level, greater sensitivities to SFC are present when compared to the smaller OBMs, as increased fuel quantities are required to support the large craft. Fig 10 shows a number of power-dense engine blocks that could be considered for the MoD large-outboard programme. The more conventional turbocharged, two-stroke diesel engines (Deltahawk, Centurion and Wilksch), while relatively power-dense through the use of compact design and lightweight materials, pale in comparison to the aero-engine turbines. Gas turbines represent the highest power-density standards, but have unacceptable fuel consumption rates for MoD applications. The two Opposed Piston (OP) designs possess attractive benefits of diesel engine efficiencies while still preserving extremely high levels of power density.

THE OPPOSED PISTON DIESEL ENGINE
The OP design possesses the natural benefits of two-stroke power density, while housing two pistons with opposite travel within a single cylinder (Fig 11). This configuration reduces construction materials, assembly and material strength/size requirements through stress-balanced construction.

The design boasts a significant reduction in parts-count and mass due to the removal of assemblies and components.

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**Fig 10:** Larger engine (>200hp) power density and SFC comparison

**Fig 11:** OPOC™ opposed piston engine (image courtesy of EcoMotors)
normally required to service a conventional piston engine. The OP engine possesses the following favourable design attributes:

- High power density,
- High specific torque,
- High power to bulk ratio,
- Simple construction,
- Potential for high reliability and low maintenance,
- Excellent multi-fuel tolerance,
- Ease of serviceability.

Although this configuration possesses the necessary traits to meet or exceed requirements, it does not represent a panacea in engine design. The OP engine must address certain design challenges to maximise its potential for successful outboard application:

- Crankshaft torsional vibration issues;
- Piston ring wear (due to port-contact);
- Oil consumption issues and related emissions performance (excessive consumption and carry-over into exhaust streams);
- Increased complexity of air-charging systems over four-stroke designs;
- Increased complexity of fuel injection strategies (requires radial injection systems in the absence of conventional top gear or cylinder head apertures);
- Heat management issues (high thermal loading of piston crown and liner due to lack of cooling cycles).

It is recognised that the OP engine possesses a strong potential to score relatively high across all KURs, albeit with its characteristic design challenges. The OP configuration is currently the subject of detailed investigation for possible application to the large OBM development programmes (Fig 12), where it has been initially assessed against existing package volume and mass constraints.

**SUMMARY**

In response to the NATO Single Fuel Policy and the subsequent removal of gasoline from naval platforms by 2015, the UK MoD MFOBM programme continues to progress the development of outboard engines capable of operation on JP5/8 and F76 (diesel) fuels. The projects for engine replacement at the 40–50hp levels currently reside at levels of maturity nearing full-scale adoption by user groups, whereas the 25 and 250hp projects have remained stalled over the last several years due to the lack of suitable COTS engine availability which could deliver the requisite power density and performance needed for these applications.

Some recent developments in engine technology/configurations have provided some attractive equipment options at these powers, where the common requirements for robust, simple, heavy-fuel engines could successfully be leveraged to the outboard motor. In order to meet the Royal Navy’s objectives for complete gasoline removal from platforms, significant investment in these projects must be made in order to provide non-petrol burning engines for use in the marine environment.

**ACKNOWLEDGEMENTS**

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