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THE RESEARCH REPORT OF "A 90 DAY SEA TRIAL"

FUNDED BY THE FISHING INDUSTRY RESEARCH COMMITTEE

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THIS RESEARCH PROVES THE VIABILITY OF A CONVERSION SYSTEM
TO SUBSTITUTE NATURAL GAS FOR DIESEL FUEL IN MARINE ENGINES
A KAILIS/MACLEAN JOINT RESEARCH AND DEVELOPMENT PROJECT.

CONSULTING ENGINEERS: HYDRAULIC, GAS, ENERGY, MECHANICAL, CO-ORDINATING

Prior to describing the details of this research and setting out the results for consideration, I should like to take this opportunity to thank the Fishing Industry Research Committee, the Commonwealth Department of Science & Technology, the Minister for Minerals & Energy of Western Australia and the Energy Research Division of the State Energy Commission of W.A., for their encouragement, technical resources and financial assistance with this project. This assistance has been largely instrumental in our being able to establish the technical and economic potential of natural gas as a viable alternative source of fuel for the fishing industry.

INTRODUCTION

Since 1973 there has been a constant spiral in the cost of diesel fuel throughout the world. As a result the cost of fuel has become the major variable cost in the fishing industry.

Throughout Australia generally, and in Western Australia in particular, there is an abundance of natural gas whilst diesel and oil fuels are imported. If the fishing industry could convert from diesel fuel to natural gas as the main source of its energy, there would be an opportunity to break the "nexus" between its operating costs and the world oil price, thus greatly improving the Australian industry's profitability viz a viz other export fishing nations.

As the majority of the industry's use of energy is at sea, it was this section of the industry that has been intially examined. Here the substitution of natural gas for diesel fuel was considered possible to achieve by one of the techniques described below. No consideration was given to using Liquid Petroleum Gases, L.P.G., (Propane, Butane or a mixture of these gases) as they are heavier than air and this introduces a considerable number of safety problems, particularly in marine applications. Also these gases do not have correct physical attributes to allow them to form the major component of a fuel for use in a diesel engine.

The alternative methods of utilizing natural gas which were considered are:-

(1) The reconstruction of the existing diesel (Compression Ignition) engines as a spark ignition engines. This would require the addition of spark plug or plugs to each cylinder, and the alteration (lowering) of the compression ratio, the addition of an ignition and fuel/air induction system etc. The net effect would be to reduce power and complicate engine design and cost. However, this alternative has recently been shown to be technically possible through the work of "ARSHAD MAZHARULLAH" with bus engines in New Zealand.

(2) The adaption of liquid fuelled diesel engines to use straight natural gas in the "compression ignition" mode. This would require an increase in compression ratio and the addition of a fuel pre-heat system, as the ignition temperature of natural gas is considerably above (approx. twice) that of diesel fuel. Whilst technically possible this system would be expensive to install, unstable in operation and the effect on power developed would depend on the degree of success with ignition control.

(3) The partial replacement of liquid diesel fuel with natural gas to produce a dual fuel engine, with the diesel fuel supplying the source of ignition and the natural gas the major source of energy. The economic success of such a system depends on the percentage replacement of liquid fuel by natural gas and relative costs of these fuels.

If 80% substitution of diesel fuel by gas can be obtained with increases in efficency and power and little change to engine construction, the potential for major economies in operating costs exist. Such a system uses a small amount of liquid diesel fuel as the ignition source for the natural gas which is "naturally inspirated" with the combustion air. As the gas fuel is brought in with the air there is a minimum of mechanical modification of the existing engine required.

The system is also be very attractive for marine work, as the engine can be switched to 100% diesel fuel in an emergency or where range of sailing is beyond the limit of "on-board" gas supplies, and natural gas being only 0.6 the weight of air it has none of the safety problems (bilge fires & explosions) experienced when using L.P.G. (Liquified Petroleum Gas - "Bottle Gas") or petrol. Both the gas and the vapour of these products being considerably heavier than air sink to the bottom of the vessel.

Of these three alternative systems, number (3) (the dual fuel option) appeared to be the most attractive and thus it was chosen as the area to be researched.

The Storage & Transportation of Natural Gas

If the system is to be technically practical and financially viable it is also necessary to develop a technology for storing and carrying of the gas for the engine.

The transporting of the gas can be broken into 2 stages:-

(i) Collection and transportation of gas to the boat's berth or operating base.

(ii) The loading of the gas onto the vessel at the operating base and the transportation on board the vessel whilst fishing.

The alternatives for the supply and transportation to the berth, are by pipeline, by liquifying of the gas and transporting as Liquified Natural Gas (L.N.G.) - this is not generally believed to be viable due to the volumes of gas required not being sufficient to justify the capital cost, this is a belief to which the writer does not describe. Or alternatively, to compress the gas to a fraction of its normal volume and transport the gas in high pressure cylinders (Similar to giant oxy-bottles). In this form the gas is known as Compressed Natural Gas (C.N.G.). The point of compression being either at a remote source or at a pipe head on the wharf depending on availability of local services.

The carriage of gas on board the vessel could also be either as "L.N.G." (Liquified Natural Gas) or "C.N.G." (Compressed Natural Gas). "L.N.G". would require much less space and would have the advantage of being able to supply refrigeration on the vessel, the problems are the capital cost of storage tanks and the cost of producing L.N.G. Given the limits of current technology the economically more practical method of supplying gas to the vessels engine is to carry the gas in cylinders as C.N.G. after compressing the gas to 16500 kPa (2400 p.s.i.).

The technical details to optimise the economics of compression and the type and size of cylinders to be used for transporation requires considerable research and evaluation, particularly as it is capital intensive, and requires optimizing with respect to the operating and construction details to suit the individual vessel concerned.

Some Preliminary Costing Considerations.

Prior to making a commitment to a major research project whose aim was to establish the technical feasibility and the economic parameters of the system, a predictive financial analysis of the proposed operating system was carried out. This analysis was based on the assumption that all the desired operating parameters could be obtained as a result of the research. The major areas of economic restraint are the capital cost of the equipment, in particular cylinders, and the purchase price of the gas.

With respect to the capital cost of the cylinders it was assumed that the fuel replacement capacity of natural gas is approximately 1.05 cubic metres of natural gas at atmospheric pressure and 23^{o}C for each litre of diesel fuel (calculated on net calorific values). Thus a typical 350HP trawler using 50 litres/hour of diesel fuel with an 80% plus gas substitution will require 42 - 45M^3 of gas per hour.

There are a number of designs of high pressure storage cylinders manufactured varying from heavy walled steel through to filament wound aluminium, the most economic model will vary from boat to boat depending on boat design, space available, weight etc., the cost of two of the alternative designs of cylinders considered are:-

(1) A cylinder 1900mm long x 275mm dia weighing 100Kg will hold 18.5M^3 of gas at a filling pressure of 16,500Kpa (2400psi). Thus two and a half to three cylinders of this size are required per hour of operation of the 350H.P. trawler. For a typical operating day of 15 hours and mixture of trawling and travelling to and from fishing ground 43 cylinders with an all up weight of 4300Kg or 4.3 tonnes would be required.

(2) An alternative cylinder manufacturer produces a cylinder of 316mm diameter and overall length 980mm which contains approx. 12.5M^3 at 16.500Kpa and weighs 55Kg (this size cylinder was used on the research vessel to date), 63 cylinders of this size are equivalent to 43 of the cylinders above.

The cost of fitting out a vessel with a nominal 60 bottles of 12.5M^3/bottle capacity (nom 750 litres diesel equivalent) would be in the order of $30,000.00 including piping, valves, support brackets etc. The cost for fully electronic gas governing and engine conversion equipment would be $7,000.00. Thus a preliminary budgeting cost for conversion and equiping of a trawler is of the order of $37,000.00 on a "one off" basis for a one day gas fishing excursion time.

As the cost of diesel fuel after tax rebating is approximately 37c/litre, the cost of the diesel fuel equivalent to the gas in a bank of 60 cylinders (60 cylinders x 12.5litres x 37c) is $277.50 approximately. If the gas can be bought, compressed and delivered for 65% the price of diesel fuel (ie. 25c/litre) the saving per fill of a set of bottles will be $97.00 ie. an operating saving of $97.00/day. Thus on a 200 day fishing year there is the potential to save approximately $24,250.00 per annum on an outlay of $37,000.00. This result was encouraging and the research commitment was made.

The Operating System Using Gas

Initially research work which had started in engine laboratories in 1982, was limited to "naturally inspirated" diesel engines as these are by far the more numerous among the existing fleets, and their relatively simple air induction system supplied fundimental knowledge of basic combustion and control parameters. This information was subsequently used as a start point for work on "Turbo Charged" engines.

All engine efficiency, fuel substitution, control and development work and testing was initially done in a laboratory on a test bed with the engines connected to a Heenan & Froude water cooled Dynamometer to scientifically establish that the theoretical parameters used in the above "indicative returns" analysis were achievable. Also this ensured that all fuel, air, cooling water and exhaust gas temperatures being fully and acurately metered and recorded.

By this means the criteria controlling maximum fuel substitution efficiency and the effects of varying substitution percentages on running characteristics, ie. engine effiency, maximum power, maximum torque etc., were measured. These measurements of engine performance when operating on neat diesel fuel and with varying percentages of natural gas substitution over a full range of speed and output power where recorded and it was shown that the concept was practical, financially viable and potentially usable in the field.

These engine laboratory trials showed that when operating at 70% full load and above, at all operating speeds above 1200 R.P.M., in excess of 80% (measured as net thermal energy) substitution of diesel fuel by gas could be obtained with no loss of power, consistent with an overall fuel efficency equivalent to, or closely approaching those achieved on 100% diesel fuel operation. Peak replacement values of 90% gas and 10% diesel fuel and overall net thermal efficency of 41% (ie. in excess of 100% diesel operation) where obtainable under full load/full speed operating conditions.

For loads less than 70% of full load, substitution rates and overall fuel efficency decrease. At loads less than 40% of the potential engine output for the particular engine speed under consideration, the gas substitution rates are greatly decreased and overall engine thermal efficency is markedly decreased, however there is no loss of power. Engine laboratory trials also established that marginally higher substitution values could be obtained with Mercedes Model OM 404 Vee 12 (350 nominal HP) naturally inspirated engine, than with the OM355 6 cylinder (180 nominal H.P.) engine and whilst research with a Vee 12 Turbo Charged engine was very preliminary early results were very encouraging.

These laboratory trials indicated that the natural gas operation of the diesel engine was practical and potentially economic. On the basis of this information it was decided to test the results in the field by fitting out an existing trawler and holding sea trials.

Throughout the laboratory engine test work all control of gas had been manual with the mechanical governor of the diesel injection pump controlling the diesel fuel input and compensating for the speed and torque increases due to the gas injection ie. the diesel injection pump governor decreases the supply of diesel fuel as the engine speed is increased over the set governor speed due to gas injection. The increase in gas being due to the Operator altering the setting on the gas hand throttle. The limit of gas injection being that volume of gas which so minimizes diesel injection that ignition failure occurs.

Preparation for Sea Trials.

In order to achieve maximum validity of the results from the sea trial it was decided to delay fitting out of the trawler with gas equipment whilst laboratory work was carried out to develop an electronic automatic integrated diesel/gas speed control governing system. Such a system would allow the Skipper freedom to move about the trawler and would also compensate for the action of the sea on the trawler.

This work having been completed to a stage where a fundamental but practical operational system of electronic governing had been developed to control the gas supply (there is still a considerable potential for development work within this area.) Work was commenced on the preconversion evaluation of the trial vessel 'Katchula'.

The 'Katchula' is a steel hulled trawler of nominal 16.5M length and 2.8M beam and is fitted with a Mercedes OM355 6 cylinder 'Naturally Inspirated' diesel engine with a continuous rating of 185 H.P. at 2000 R.P.M. This vessel was built in the mid 1960's and has been refitted on numerous occasions.

The following preconversion work and preliminary pretrial tests were carried out:-

(1) The diesel engine from the trawler was removed, fully serviced, and the engine's test bed performance established against a "Heenan & Froude" dynomometer when running on both diesel fuel and diesel/gas dual fuel to establish a known basis of performance for sea trial results.

(2) Design and documentation for a carrier for 20 x 60 litre Faber (nominal 12.5m^3 of gas per cylinder) steel Compressed Natural Gas cylinders was completed. The carrier was to be a removable stern extension outrigger box. This extension box was to be fitted complete with bottles and designed to be connected and disconnected readily from the stern of the trawler. The completed design was approved by the "Marine & Habour Authority of W.A." and "Det Norske Veritas" but cost of construction was prohibited and the concept dropped after documentation and competitive market prices for construction received.

(3) Design, documentation and construction of Compressed Natural Gas bottle transportation containers (6 cylinders per container) was carried out. Two such containers were built to carry 12 cylinders in total, they are suitable for lifting onto a 1 tonne flat top road vehicle. The containers are used to transport the gas cylinders from compressor station in East Perth to decanting location at the trawler's berth in Fremantle, (a distance of 20 kilometres each way) where they fill by cascade decanting, the vessels built in, permanently installed, gas cylinders. Thus experience was gained on a "mini" scale into gas filling and transportation technology.

(4) The vessels cylinder installation technique was redesigned and connection of 20 permanently fixed, "on board" cylinders was considered to be the most cost effective alternative for research purposes to (2) above and this work including piping and connections, valving and metering was designed, and approval obtained from "Harbours & Marine Department of Western Australia" and the "Gas Department of the State Energy Commission of Western Australia" for the design.

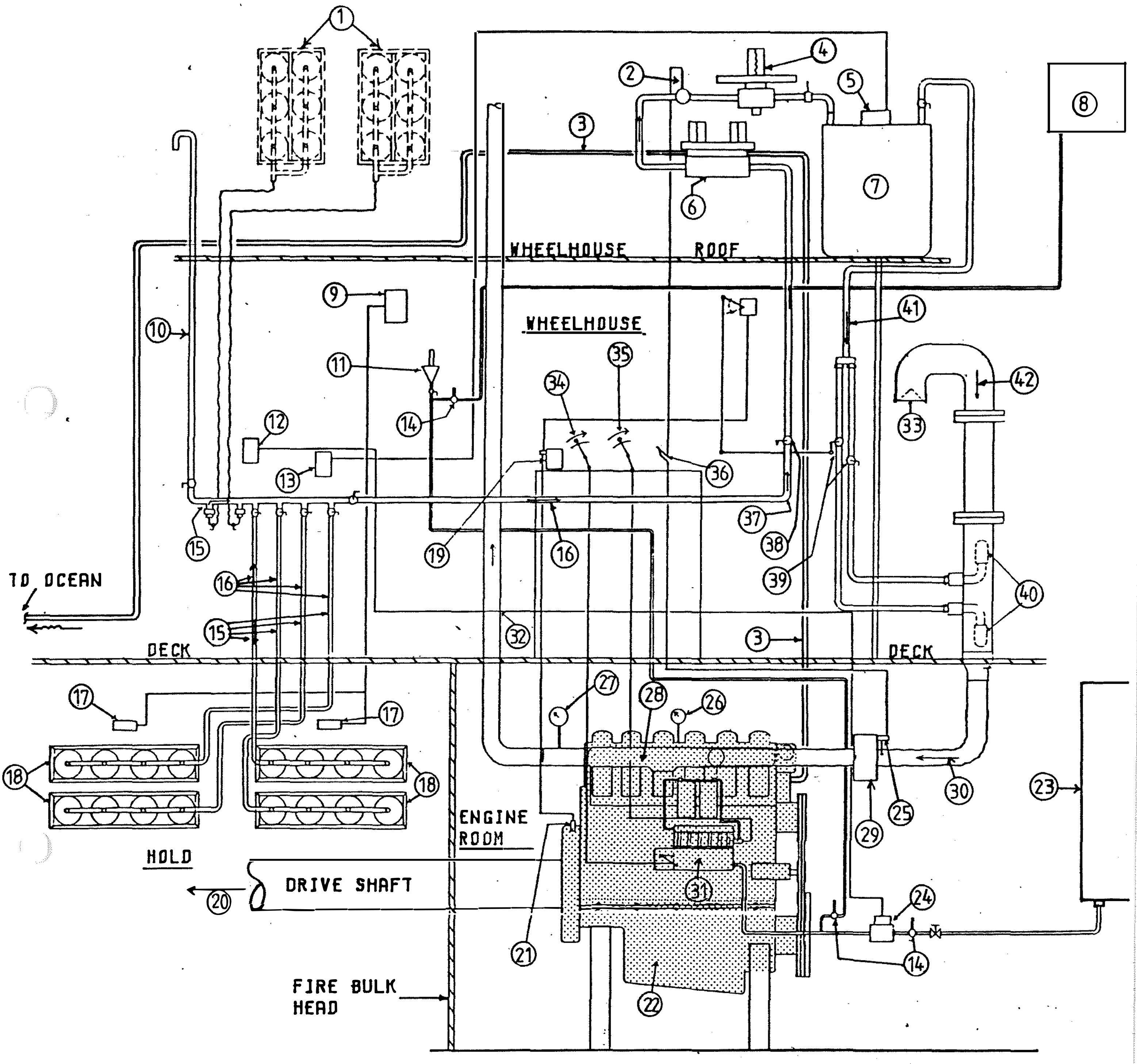
(5) The engine was re-installed in the vessel, gas piping and safety equipment installed and preliminary sea performance trails using diesel fuel only were carried out to establish diesel engine performance under actual operating conditions of steaming, trawling, manoeuvring etc. This was necessary to establish the engines most commonly encountered operating speeds, output torque, fuel consumption, exhaust temperatures etc, to ensure base parameters for future gas substitution trials where carried out within the appropriate parameter range.

These trials also brought to notice that possibly due to numerous re-builds and re-fits throughout the life of the trawler - not originally designed or built by the Kailis Group - that optimum co-ordination of hull performance, propellor output characteristics, and engine horse-power developed against R.P.M., was not occuring.

The events which lead to this condition can easily occur and as trawler skippers and engineers have few absolutes against which to compare their vessels overall performace it is likely that similar problems are common throughout the fishing industry. With this in mind the Joint-Venturers propose to develop specific performance measuring equipment against which to test all vessels, and would greatly appreciate comments from all sectors of the industry on this subject.

The Installation of Cylinders, Pipework, Safety, Control and Measuring Equipment for the Gas Supply.

In order to ensure a reasonable working and testing time at sea in any one day consistent with maximum husbanding of research funds, it was decided to install 20 Faber 12.5 cubic metre high pressure steel cylinders (950mm long x 315mm diameter x 54 kg. wgt). These bottles allow approximately 7½ hours of trawling and steaming at full load and maximum gas demand. Approximately twice as many bottles would be ideal from a Trawler Skipper's point of view when operating in a "day fishery", but the additional cost during experimentation



LAYOUT ARRANGEMENT OF RESEARCH VESSEL WITH MARINE DIESEL ENGINE ADAPTED TO OPERATE IN THE DIESEL/NATURAL GAS DUAL FUEL MODE

EXPLANITORY NOTES FOR ENGINE LAYOUT

1. CARRIER BOTTLES FOR TRANSPORTING COMPRESSED GAS FROM EAST PERTH TO FREMANTLE - 40KM ROAD TRANSPORT
2. SOLENOID VALVE FOR AUTOMATIC SHUT DOWN OF GAS WHEN ENGINE STOPS OR MANUAL SHUT DOWN BY SKIPPER FROM WHEELHOUSE
3. HEATING WATER TO H.P. GAS REGULATOR 6
4. LOW PRESSURE GAS REGULATOR
5. GAS QUANTITY METERING DEVICE - REMOTE
6. HIGH PRESSURE GAS REGULATOR
7. GAS METER FOR ACURATE MEASUREMENT OF GAS TO WITHIN 1%
8. DIESEL FUEL SUPPLY TANK FOR TESTING
9. GAS LEAK DETECTION PANEL
10. SAFETY RELIEF
11. GLASS SEPERATING FUNNEL USED TO ACCURATELY DETERMINE DIESEL FUEL RATES TO GREATER THAN 1% ACCURACY (CONTAINS 626ml BETWEEN MARKS)
12. DIESEL FUEL FLOW METER READ OUT FROM ELECTRONIC METER ON MAIN DIESEL SUPPLY
13. REMOTE INDICATOR FROM GAS METER - 1/10 OF M CUBE PER STEP
14. DIESEL FUEL TESTING SOLENOID
15. FLOW DURING FILLING
16. FLOW DURING OPERATION OF ENGINE
17. GAS LEAK DETECTION SENSOR
18. GAS BOTTLES - BUILT INTO HOLD
19. AMERICAN BOSCH ELECTRONIC SPEED CONTROL
20. TO PROPELLOR
21. ELECTRONIC SPEED CONTROL COUNTS NUMBER OF TEETH PASSING PER SECOND (155 TEETH ON FLYWHEEL)
22. 6 CYLINDER MERCEDES DIESEL MODEL OM 355 MAX CONTINUOUS RATING ON DIESEL FUEL 165 H.P. AT 2000 R.P.M.
23. MAIN DIESEL FUEL TANK
24. ELECTRONIC INDICATING DIESEL FUEL FLOW METER - MEASURING END
25. AUTOMATIC GAS SHUT DOWN SWITCH WHICH CLOSES DOWN ALL GAS SUPPLIES IF ENGINE NOT RUNNING - SEE 2
26. ENGINE COOLING WATER TEMPERATURE
27. ENGINE EXHAUST TEMPERATURE
28. INLET MANIFOLD
29. AIR FILTER
30. GAS/AIR MIXTURE
31. DIESEL INJECTOR PUMP
32. EXHAUST
33. AIR INLET - IN OPEN AIR
34. VARIABLE SETTING DIESEL FUEL THROTTLE
35. DIESEL INJECTOR CONTROL USED WHEN AUTOMATIC GAS CONTROL IN OPERATION
36. MANUAL GAS SWITCH - TO SOLENOID
37. HIGH PRESSURE GAS TO ENGINE
38. HIGH PRESSURE ISOLATOR ON WHEELHOUSE WALL
39. MANUAL AND AUTOMATIC CONTROL VALVES
40. TWIN AIR/GAS RADIAL MIXER
41. LOW PRESSURE GAS TO ENGINE
42. AIR TO ENGINE

was not warranted. Particularly as doubling the gas carrying capacity of the vessel requires a doubling of the capacity of the transporation and filling systems if it is to be effective.

The cylinders were mounted in the hold in two equal banks, one bank located on the port side the other on the starboard side. The two banks each containing 10 cylinders were constructed in 2 layers, with 5 cylinders in each layer. The cylinders were laid on their side with their major axis at right angles to the side of the vessel and with the valve end on each cylinder facing into the centre of the hold. A timber support system, similar in shape and construction to a wine rack with steel rods drawn down through the timber racks and attached to the frames of the hull was used to firmly hold and locate the cylinders. This form of mounting, whilst elemental, has proved extremely effective and there has been no movement of any kind in the heaviest of seas and no scuffing of the cylinders paintwork.

The outlets of the cylinder valves are connected in groups of 5 by horizontally manifolding together the outlets of all the cylinders in any one layer with 1/4 in diameter seamless stainless steel tube. The outlet end to each manifold was run separately back to a common header above deck and fitted with an isolation valve immediately prior to joining the common header.

This pipework system allows each group of 5 cylinders to form a separate entity which may be filled or emptied in isolation or as portion of a larger system, i.e. the 20 cylinders are separated into 4 groups of 5 cylinders.

This method of connection allows for cascade filling and emptying. In order to facilitate cascade filling the 6 cylinders on each carrier were manifolded to a single outlet per carrier and these cylinders are filled as a group to 16500 kPa (2400 pounds per square inch) at East Perth and transported to Fremantle. There the carrier outlet is connected by hose to the common header manifold on the vessel and with all other valves on the manifold closed the carrier is connected to the first bank of cylinders, (5 off) which are initially at atmospheric pressure. The resulting pressure from the flow of gas to equilibrium from the carrier cylinders to the bank on the vessel is approximately 9400 kPa. The carrier cylinders are then connected to the second bank of 5 cylinders on the vessel by openings and shutting the appropriate manifold valves, resulting pressure of approximately 5100 kPa is produced in the second bank at equilibrium. The carrier bottles are now connected to the third bank and the resulting pressure is at 2800 kPa and on the fourth bank equilibrium is reached approximately 500 kPa.

The second set of 6 carrier cylinders which had also been filled to 16,500 kPa was then connected to the first band of cylinders which have previously been filled to 9400 kPa, the pressure of the first group reaches equilibrium at approximately 13,600 kPa. The second carrier was then connected to the second bank of bottles etc. and by this method of cascade filling an efficient filling technique was developed without pumping the gas during the filling process.

However, it is obvious from the experience gained that a pumped transfer and large bore hoses with threaded couplings are desirable to minimize fitting time. In this regard the possibility of using a hydraulic actuated transfer compressor operating off the vessel's winching and steering hydraulics is currently under investigation.

The manifolding pipes and all other gas pipes were constructed from seamless stainless steel tubing and Swagelok high pressure fittings and all valves were ball quarter turn steel with Australian Gas Association approval for a maximum operating pressure of 65,000 kPa.

The header manifold into which each of the cylinder bank manifolds discharge is mounted above deck under the bullwark for protection. This manifold was fitted with two filling inlet points, (to allow both sets of carriers to fill at the same time if required. This dual filling decreases time to equilibrium but is less efficient with regard to total gas transfer) four inlet/outlet connections, - one to each bank of five cylinders - and an outlet supply valve to the engine and a high speed blow down safety valve.

Over each bank of cylinders in the hold a gas detector was mounted and the twin gas detectors electrically cabled above deck to the connected to a Gas Leak Detector monitoring panel.

Inlet and outlet ventilation to the hold was established by using four 100mm diameter vents, taken to within 150mm of the floor of the hold to allow to supply air, and 2 located at the opposite end of the hold taken from immediately under the deck over as discharge vents. By this method cross ventilation is set up. Should a leak occur the gas would rise to under the decking, activate the alarm and be ventilated through the high level vents. The low level vents being still available to allow air in for dilution.

The stainless steel high pressure gas discharge piping from the header manifold is carried hard up under the bullwark - being run always above deck and in the open - and then up the side wall of the wheelhouse to above the wheel house. Enroute, the gas at high pressure passes through a high pressure isolating valve whose handle has been extended through the wall of the wheelhouse allowing the isolation of the high pressure gas to be immediately available from within the wheel house, although the gas never enters the wheel house.

Diesel Fuel Supply, Pipework & Metering

The trawler is fitted with diesel fuel tanks which allow approximately 15 days operation. The fuel from these tanks runs by gravity through filters to the diesel injector pump via a solenoid valve used as the stop/start mechanism in the engine. Into this system a geared positive displacement liquid meter was installed after closing off the injector recirculation circuit. This meter was fitted with flow measuring and integrating circuits. The output of the meter was electrically cabled to the wheel house to an instantaneous flow indicator mounted on the chart desk, the flow indicator has two ranges, 0 to 60 and 0 to 12 litres per hour full scale deflection, whilst the flow integrator totals the volume of fuel supplied continuously.

The flow indicator is extremely useful in bringing to the Skippers notice continuously the rate of using diesel fuel. Thus an immediate indication is given that the supplementary gas supply is decreasing the demand for diesel fuel. However, in common with most positive displacement meters there is a considerable variation in accuracy of the meter across a full range of flows. As a result of this inaccuracy a positive liquid in glass sight measuring system was installed which guaranteed the accuracy of metering the diesel fuel.

The liquid in glass system consisted of mounting a 626 cc glass separation flask high on the wall in the wheel house and supplying the flask with an alternative supply of diesel fuel. The outlet fuel from the glass measuring flask was passed directly to the inlet side of the diesel injector pump while appropriately located solenoids set in the fuel circuits ensure that no fuel enters the diesel engine except from the measuring flask. The diesel flow measurements were made against a stop watch by timing the liquid level fall in the flask between two markers. The liquid content between the markers having been established as 626 millilitres.

As the time to use 626 millilitres on full loads, (wholly diesel operation) is aproximately 70 seconds, accuracy of measurement of 1% is obtained. However, on maximum gas operation (minimum diesel) the time taken for the liquid to empty from the glass measuring cylinder is in excess of 8 minutes, to accelerate the measuring process the cylinder was also has marked at the 180 millilitre level. There is a corresponding decrease in flow time to approximately two minutes, thus again guaranteeing accuracy of measurement to well within 1%.

Whilst operating on gas a series of flue gas analysis were taken to determine the presence of hydrocarbons and carbon monoxide in the exhaust gas. These were found to be small which is consistent with the high operating efficiency of the engine. The flue gas free carbon content also decreases dramatically when using gas as the major fuel component. On low loads with excess gas supplied it has been shown previously in laboratory tests that there is an immediate carry over of gas into the exhaust system and that this is a major contributor to engine thermal efficiency decrease with lowering loads. However, at no stage does the carryover reach anywhere near combustible levels. Is it this mechanism which allows some experimenters to claim apparently high diesel/gas replacements at low loads, and the subsequent claims of 80% replacement of diesel fuel with gas over the entire engine operating speed range.

Method of Carrying out Full Sea Trials

After establishing the parameters of performance of the engine and the vessel on diesel fuel as previously described a series of trials commenced during which gas substitution was commenced. Initially these trials consisted of establishing the parameters of engine performance with the gas substitution being controlled by hand operation of the gas regulating valves.

During this series of trials, considerable difficulty was experienced obtaining consistent performance of the engine, due to variation in gas pressures and flow with time. The difficulty was traced to a fine mat filter in the high pressure gas regulating valve which had become blocked with oil from the gas stream. The gas having been poluted by oil carried over during compression.

As a result of the operating difficulties which occurred during it became obvious that pressure indicating gauges which show gas supply pressure in the H.P. header manifold, the intermediate pressure pipework downstream of the high pressure regulator, and the output pressure of the low pressure regulator where required to be fitted in the wheel house. .

Although gas supply difficulties occurred no difficulties were experienced with the performance of the the engine or the vessel when the intermittent gas failures occurred. The diesel governor automatically compensated for the loss of gas flow. The only indication to the Skipper was the fall off in substitution rate of gas for diesel fuel which showed up immediately on the diesel flow meter. After remedial work on the compressor, this problem did not re-occur.

Having established the parameters of the engine under gas operation using manual control were quite similar to laboratory trials, except that the engine was not required to produce more than 75% to 80% of rated loaded at 2000 RPM due to propellor load characteristics and that it was the Skippers practice to operate the Trawler with engine speeds in the vicinity of 2100 to 2150 RPM. Trials were commenced with both the gas and diesel fuel under automatic control.

The automatic electronic speed control which was used to regulate the gas supply did so by measuring the rate at which the teeth on the ring gear pass a fixed point on the flywheel housing. The controller maintains constant rate of passing by decreasing or increasing the gas supply through a regulator arm attached to the same valve as used for manual operation on gas. Prior to changing to automatic operation the rack of the diesel injector pump is suppressed to a minimum level to ensure just sufficient diesel fuel is supplied at all speeds to ignite the gas. This system of operation proved to be extremely effective and reliable and maintained very good diesel fuel to gas operating percentages.

The use of gas is suspended manually during idling, net pulling, net washing etc., i.e. whenever the engine speed is below approximately 1400 RPM. At this speed and below the amount of diesel fuel used is small and the efficiency of the gas replacement is poor thus savings using gas at these times are small.

Whilst operating speeds below 1400 RPM are infrequent, the inconvenience of moving the rack setting mechanism has lead to preliminary work commencing on the development of a more convenient diesel/gas electronic speed control system. The system under development will automatically adjust the gas supply to optimise the diesel replacement at all engine speeds without any specific action on the part of the Skipper.

On a daily basis trails were held to measure and establish the actual operating parameters of the diesel engine and the trawler at varying engine speeds and under the varying load conditions encountered during both steaming and trawling. Once these had been established and the optimum criteria for operating in both conditions had been established and the crew had become familiar with operating on gas, normal fishing operations commenced. These fishing operations continued over a period of weeks interspersed with days of engine and control gear testing and adjustment.

Fuel Substitution Rates and Operating Economics During Full Sea Trails.

On a typical night fishing operation the vessel was able to trawl for 7.5 hours with the on board gas supply available (20 cylinders) and consistently produced a substitution rate in excess of 82% over entire time gas was available without allowing for the periods of straight diesel fuel used winching, washing, and shooting. At these times no gas was used as the engine loads were too low to allow efficient gas substitution.

In the 7.5 Hour period the total quantity of diesel fuel used varied between 49 and 51 litres each night. This result was remarkably constant particularly in light of the fact that there were marked variations in weather and sea conditions from moderate to calm through to strong winds and heavy seas. Under normal operation using straight diesel operation the engine consumes 34 to 36 litres/hour ie. 260 to 265 litres in a 7.5 hour period.

Similar tests were carried out on steaming to the fishing ground when the replacement precentage was again in the order of 80% although engine loads are well below those which would produce optimum gas utilization.

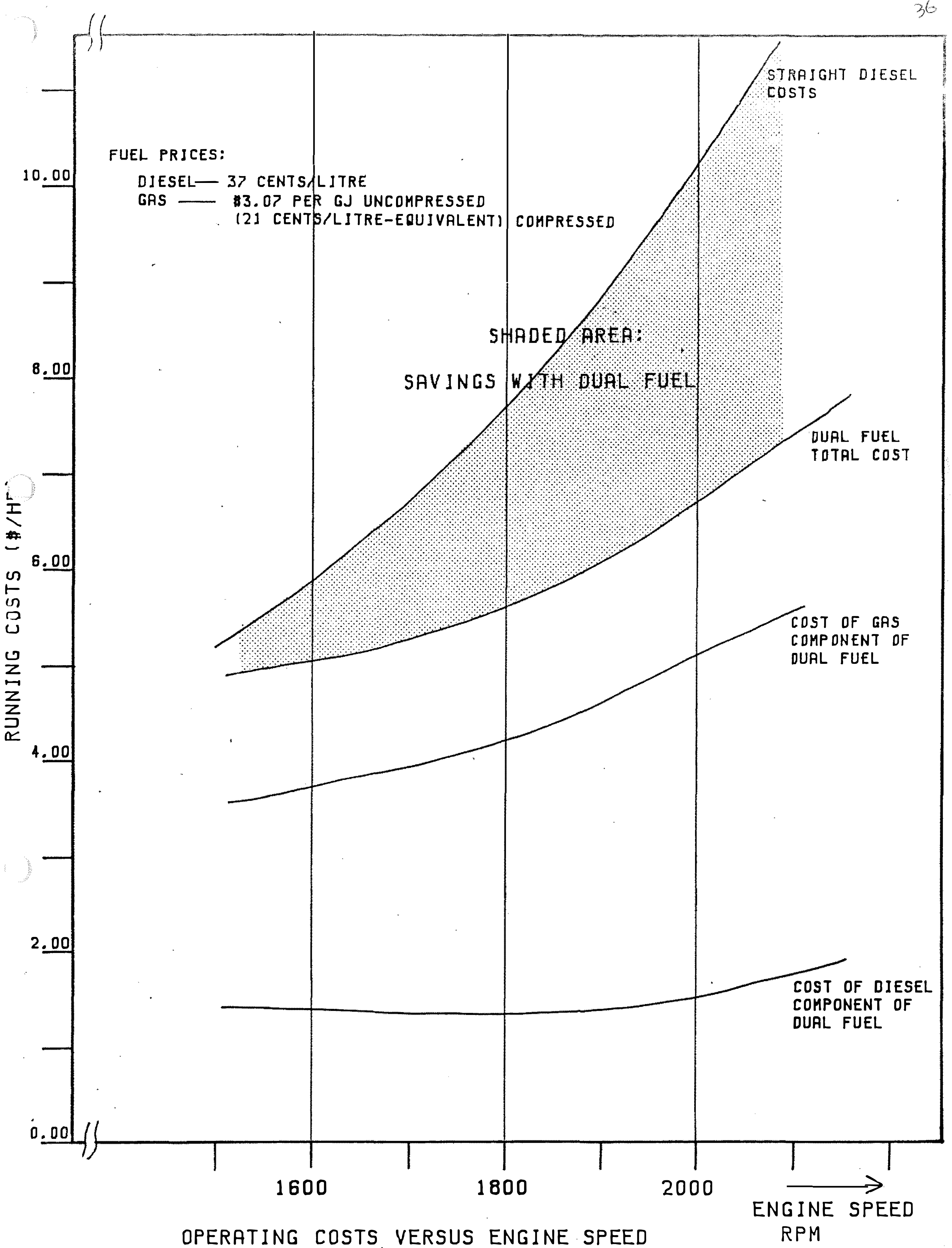
The fuel utilisation curves for various speeds both when Steaming and when Trawling are shown in Figs.1 and 2. These curves are converted into hourly running costs and savings during gas operation on an hourly basis and are set out in Fig.3 and 4.

IT SHOULD BE NOTED THAT THESE CURVES PLOT THE SEA TRIAL RESULTS OF THE TEST VESSEL "KATCHULA" WHICH IS A STEEL HULLED VESSEL APPROX-IMATELY 16.8 M IN LENGTH AND IS FITTED WITH A MERCEDES OM 355 (185HP) ENGINE. THESE RESULTS WILL BE GENERALLY TRANSFERABLE TO OTHER VESSELS APPROX. IN PROPORTION TO THEIR ENGINE HORSE POWER.ie IF THE ENGINE UNDER CONSIDERATION HAS TWICE THE H.P. THEN THE HOURLY OPERATING SAVINGS WILL BE APPROX. DOUBLE THOSE SHOWN, PROVIDED THE ENGINE DEVELOPS APPROX. FULL LOAD AT FULL ENGINE SPEED

Observations

These sea trials have demonstrated that natural gas can be successfully substituted - both on a practical and an economic basis - for diesel fuel in marine diesel engines, and thus can form the major alternative source of fuel for naturally inspirated engines. The work to date

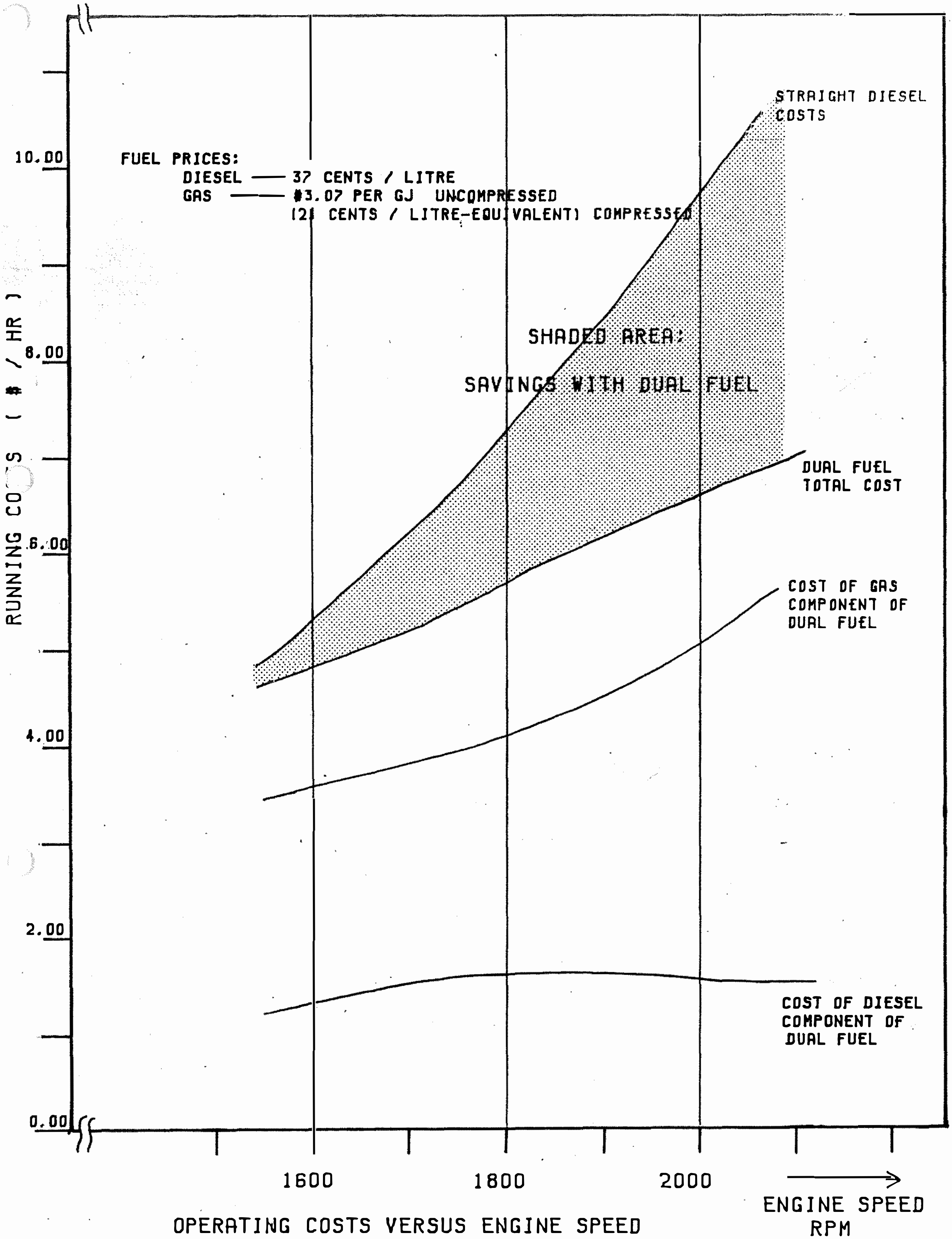
Figures 1 and 2 unavailable



OPERATING COSTS VERSUS ENGINE SPEED

RESULTS OF SEA-TRIALS (TRAWLING)
USING A 6-IN-LINE MERCEDES OM 355 (185 HP)

FIG 3



OPERATING COSTS VERSUS ENGINE SPEED

RESULTS OF SEA-TRIALS (STEAMING)
USING A 6-IN-LINE MERCEDES OM 355 (185 HP)

FIG 4

has been carried out using a Mercedes OM 355 (185 HP continuously rated) six cylinder marine diesel engine.The criteria for this substitution and the results achieved by the substitution are as follows:-

1. The required gas injection and control equipment can be retro-fitted to an installed engine and the equipment in no way inhibits the engine's performance when operating solely on diesel fuel. It also allows instant change over in either direction between full diesel and diesel/gas (dual fuel) operation.

2. A total replacement of diesel fuel does not take place as diesel fuel must be supplied at all times to form a source of ignition for the gas.The physical characteristics of natural gas are such that spontaneous compression ignition cannot occur at the compression ratios and temperatures occuring in a commercial diesel engine. Thus the engine when using gas must operate in the "dual fuel" mode using some diesel fuel as "Pilot Ignition" fuel for the gas.

3. The engine, gear box, propellor and hull characteristics of the test vessel are such that the installed engine cannot produce more than 80% of the manufacturer's specified continuous fully rated output power at the recommended maximum continuous operating speed of 2000 RPM, or alternatively not more than 92% of the full rated continuous HP at 2150 RPM. As a result the optimum fuel replacement rates for the engine have not been obtained, even so the results obtained are more than satisfactory from a commercial point of view.

4. The percentage of the total energy supplied by the "Pilot Ignition" fuel decreases with increasing load. From 16% diesel(122.9MJ diesel and 1024.4MJ gas) at 1600 RPM and 42% of full load output to 14.9% diesel at 2110 RPM and 92% of full load output.

5. The total energy used - measured as the input fuel's nett available Megajoules - by the engine in the dual fuel mode is considerably more than when using pure diesel fuel for light loads.(ie.Steaming at 1600 RPM on dual fuel 757.8 MJ/Hr are used, whilst with diesel 511.9 MJ/Hr).However, as the load increases the relative difference in fuel utilization between the modes decreases, until at 92% full load they are equivalent. This is the maximum load attainable with the engine as installed in the test vessel.

The sea trial results are consistent with the engine test laboratory trials in which the total energy input of the dual fuel system was less than that of the 100% diesel fuel system at full engine loads.

6. To obtain optimum economic returns from a dual fuel operation the trawler's design and operating characteristics should be such as to maximise the load on the engine at all times consistent with not physically damaging the engine.

7. Although high replacement percentages of diesel fuel by gas can be obtained for all loads and engine speeds as low as 1200 RPM much of the replacement at low speeds and loads is due to poor gas combustion efficiency. The lowest engine speeds and loads at which economic replacement can be obtained will depend on the relative cost of diesel fuel to natural gas.Given the performance parameters of the test vessel and an uncompressed cost of gas of $3.00 per Gigajoule and a cost for diesel fuel of $0.37 per litre,the engine speed at which dual fuel commences to produce savings is 1600 RPM when steaming.- ie. when the engine is at approximately 42% full load, and at approximately 1500 RPM while trawling, both far below potential operating loads at sea.

8. The basis of the gas costs as set out above are those currently available in Sydney NSW, similar cost structures are available in Victoria and South Australia. The State Energy Commission of West Australia has as yet not developed a costing strategy for gas for processing to C.N.G. as a substitute for diesel fuel.

The operating costs as listed in Table 1. are based on a similar diesel fuel price of $0.37 per litre assuming the trawler operator is in receipt of $0.07 fuel tax rebate, and a compressed gas cost of $0.21 per litre equivalent (35.95 MJ Net). They also assume 12 Hr per day operation for 250 days per year.

9. The gas cylinders as installed in the test vessel during the sea trials allowed the vessel to trawl continuously for 7.5 Hrs on an average fishing night.In this time the engine uses between 49 - 51 litres of diesel fuel the remainder of the fuel being supplied

by gas. Had the vessel been using only diesel fuel it would have used 255 litres in the same time. This is a continuous operation and even allowing for the 100% diesel fuel operating periods of light loads during hoisting etc. fuel replacement in excess of 80% was regularly obtained.

10. The gas cylinders should be separated into banks and built into the hold in a separate gas tight compartments, with individual relief hatches to each compartment at deck level. So optimizing the speed of release of any gas from the compartment in the event of a malfunction of a cylinder, valve or pipe work.

11. The volume of gas contained within the cylinders should be sufficient to allow at least one days trawling and steaming thus maximising capital returns and minimising operator inconvenience. The type and construction of the most suitable cylinders will depend on the parameters of the vessel's construction and the cost and reliability of the alternative cylinders available. This is an area in which further detailed study is required and it is anticipated that this work will commence in the near future, particularly in light of the large proportion of the capital charges for which the cylinder installation is responsible.

10. Consistent with the investigation of cylinder types it would be desirable to optimise the energy content of the cylinder by adjusting the gas analysis of the filling gas with the addition of fractional quantities of higher hydrocarbons, this is also an area of on going research.

13. The pipework forming the filling manifolds should be designed on the basis of a centro-peripheral model with mechanical threaded connections for filling hoses located above deck.This connection mechanism will allow higher filling speeds than those currently in use in the automotive industry.

14. Cylinders, valves, gauges, etc. which are not constructed from stainless steel will require specialised anti-corrosion finishes, an area of particular concern is in the vascinity of the identification numbers stamped at testing into the cylinders.

15. In order to prevent leakage at glands, sliding interfaces etc. all automatically operated valves should be of the solenoid or magnetic flux coupling type.

16. A detailed investigation of the quantity and the energy level potential of the cooling available during the pressure reduction stage of the gas system should be made to establish it's potential as an ancillary source of refrigeration. This is an immediate area of on going research.

17. It is essential to develop a fully automatic (preferrably electronic) gas control mechanism which immediately adjusts the gas supply to optimise the quantity of gas supplied for any given diesel throttle setting established by the vessel's skipper. Such a mechanism should interupt the supply of gas when the engine operating conditions are such that the use of gas would not be economic. The system should also require the skipper only to control the engine by use of the familiar diesel throttle. This is believed to be a most immediate and important area of on going research if the present work is to be of universal assistance to the industry.

Conclusions

The work to date has clearly shown that marine diesels as commonly used in the fishing industry in Australia can be retro-fitted or be purpose built to operate with natural gas as the major component of their fuel and that there is considerable economic potential advantage to be gained by the users of these vessels provided the operating characteristics of the fishery are suited to vessels using C.N.G.

It is currently anticipated that the research work will continue and that the research vessel currently operating out of Fremantle will be the first of many commercial fishing boats operating around the Australian Coast using Natural Gas as their major source of fuel.

TABLE 1

SEA TRIAL FUEL AND ENERGY UTILIZATION,

OPERATING COSTS FOR VARYING SPEEDS AND LOADS,

AND FUEL REPLACEMENT PERCENTAGES.

(MERCEDES OM 355, 6 CYLINDERS, 165 MAX. HP CONT. RATED AT 2000 RPM)

OPERATING CONDITIONS	RPM	DIESEL L / H ($ / H)	DIESEL MJ / H	GAS M3 / H ($ / H)	GAS MJ / H	TOTAL MJ / H (KW)	GAS %	ENGINE EFFIC. %	POWER HP (KW)	LOAD % FULL	TOTAL FUEL PRICE $ / HOUR	FUEL ECONOMY $ / HOUR (%)	SAVINGS $ / YEAR
STEAM DIESEL	1600	14.22 (5.26)	511.9	0.	0.	511.9 (142.2)	0.	34.0	65.7 (48.3)	42.2	5.26	----	----
STEAM GAS	"	3.41 (1.26)	122.9	18.17 (3.71)	634.9	757.8 (210.5)	83.8	22.9	" "	"	4.97	0.29 (5.5)	870.
TRAWL DIESEL	1630	16.69 (6.17)	601.0	0.	0.	601.0 (166.9)	0.	37.0	84.1 (61.8)	53.3	6.17	----	----
TRAWL GAS	"	3.83 (1.42)	138.0	18.40 (3.76)	643.1	781.1 (217.0)	82.3	28.5	" "	"	5.18	0.99 (16.0)	2,970
TRAWL DIESEL	1705	18.94 (7.01)	681.8	0.	0.	681.8 (189.4)	0.	37.5	96.6 (71.0)	58.7	7.01	----	----
TRAWL GAS	"	3.84 (1.42)	138.2	20.14 (4.11)	703.8	842.0 (233.9)	83.6	30.4	" "	"	5.53	1.48 (21.1)	4,440
TRAWL DIESEL	1740	19.26 (7.13)	693.4	0.	0.	693.4 (192.6)	0.	36.5	95.6 (70.3)	56.9	7.13	----	----
TRAWL GAS	"	3.95 (1.46)	142.3	20.28 (4.14)	708.7	851.0 (236.4)	83.3	29.7	" "	"	5.60	1.53 (21.5)	4,590

TABLE 1 (CONTINUED)

OPERATING CONDITIONS	RPM	DIESEL L / H ($ / H)	DIESEL MJ / H	GAS M3 / H ($ / H)	GAS MJ / H	TOTAL MJ / H (KW)	GAS %	ENGINE EFFIC. %	POWER HP (KW)	LOAD % FULL	TOTAL FUEL PRICE $ / HOUR	FUEL ECONOMY $ / HOUR (%)	SAVINGS $ / YEAR
STEAM DIESEL	1800	19.43 (7.19)	699.4	0.	0.	699.4 (194.3)	0.	36.6	96.7 (71.1)	56.1	7.19	----	----
STEAM GAS	"	4.67 (1.72)	168.0	20.64 (4.21)	721.1	889.1 (247.0)	81.1	28.8	" "	"	5.93	1.26 (17.5)	3,780
TRAWL DIESEL	1810	21,26 (7.87)	765.4	0.	0.	765.4 (212.6)	0.	37.5	108.4 (79.7)	62.7	7.87	----	----
TRAWL GAS	"	3.65 (1.35)	131.5	22.50 (4.59)	786.2	917.7 (254.9)	85.7	31.3	" "	"	5.94	1.93 (24.5)	5,790
TRAWL DIESEL	1900	24.36 (9.01)	877.1	0.	0.	877.1 (243.6)	0.	37.8	125.3 (92.1)	70.2	9.01	----	----
TRAWL GAS	"	4.17 (1.54)	150.0	23.56 (4.81)	823.4	973.4 (270.4)	84.6	34.1	" "	"	6.35	2.66 (29.5)	7,980
TRAWL DIESEL	1900	24.63 (9.11)	886.7	0.	0.	886.7 (246.3)	0.	38.0	127.4 (93.6)	71.1	9.11	----	----
TRAWL GAS	"	4.33 (1.60)	155.7	24.24 (4.94)	847.1	1002.8 (278.6)	84.5	33.6	" "	"	6.54	2.57 (28.2)	7,710
TRAWL DIESEL	1900	25.04 (9.26)	901.4	0.	0.	901.4 (250.4)	0.	37.9	129.1 (94.9)	72.3	9.26	----	----
TRAWL GAS	"	3.95 (1.46)	142.3	23.92 (4.88)	835.9	978.2 (271.7)	85.5	34.9	" "	"	6.34	2.92 (31.5)	8,760

TABLE 1 (CONTINUED)

OPERATING CONDITIONS	RPM	DIESEL L / H ($ / H)	DIESEL MJ / H	GAS M3 / H ($ / H)	GAS MJ / H	TOTAL MJ / H (KW)	GAS %	ENGINE EFFIC. %	POWER HP (KW)	LOAD % FULL	TOTAL FUEL PRICE $ / HOUR	FUEL ECONOMY $ / HOUR (%)	SAVINGS $ / YEAR
TRAWL DIESEL	1900	25.32 (9.37)	911.6	0.	0.	911.6 (253.2)	0.	36.0	130.9 (96.2)	73.3	9.37	----	----
TRAWL GAS	"	4.42 (1.64)	159.1	23.66 (4.67)	834.4	993.5 (276.0)	84.0	34.9	" "	"	6.51	2.86 (30.5)	8,580
TRAWL DIESEL	1930	24.76 (9.16)	891.5	0.	0.	891.5 (247.6)	0.	36.1	126.3 (94.3)	70.9	9.16	----	----
TRAWL GAS	"	3.93 (1.45)	141.6	24.41 (4.98)	852.9	994.5 (276.3)	85.8	34.1	" "	"	6.43	2.73 (29.8)	8,190
TRAWL DIESEL	1990	27.48 (10.17)	989.4	0.	0.	989.4 (274.8)	0.	37.8	141.4 (103.9)	76.4	10.17	----	----
TRAWL GAS	"	4.46 (1.65)	160.6	25.59 (5.22)	894.3	1054.9 (293.0)	84.8	35.5	" "	"	6.87	3.30 (32.4)	9,900
TRAWL DIESEL	1990	27.48 (10.17)	989.4	0.	0.	989.4 (274.8)	0.	37.8	141.4 (103.9)	76.4	10.17	----	----
TRAWL GAS	"	4.66 (1.72)	167.6	25.12 (5.13)	877.7	1045.3 (290.4)	84.0	35.8	" "	"	6.85	3.32 (32.6)	9,960
STEAM DIESEL	1995	25.55 (9.45)	919.8	0.	0.	919.8 (255.5)	0.	37.2	129.3 (95.0)	70.3	9.45	----	----
STEAM GAS	"	4.26 (1.58)	153.2	26.04 (5.32)	909.9	1063.1 (295.3)	85.6	32.2	" "	"	6.90	2.55 (27.0)	7,650

TABLE 1 (CONTINUED)

OPERATING CONDITIONS	RPM	DIESEL L / H ($ / H)	DIESEL MJ / H	GAS M3 / H ($ / H)	GAS MJ / H	TOTAL MJ / H (KW)	GAS %	ENGINE EFFIC. %	POWER HP (KW)	LOAD % FULL	TOTAL FUEL PRICE $ / HOUR	FUEL ECONOMY $ / HOUR (%)	SAVINGS $ / YEAR
TRAWL DIESEL	2000	27.65 (10.23)	995.5	0.	0.	995.5 (276.5)	0.	37.9	142.6 (104.8)	77.1	10.23	----	----
TRAWL GAS	"	4.06 (1.50)	146.0	26.92 (5.49)	940.5	1086.5 (301.8)	86.6	34.7	" "	"	6.99	3.24 (31.7)	9,720
TRAWL DIESEL	2000	28.71 (10.62)	1033.5	0.	0.	1033.5 (287.1)	0.	38.0	146.4 (109.1)	80.2	10.62	----	----
TRAWL GAS	"	4.02 (1.49)	144.9	27.23 (5.56)	951.4	1096.3 (304.5)	86.8	35.8	" "	"	7.05	3.57 (33.6)	10,710
TRAWL DIESEL	2060	30.66 (11.34)	1103.8	0.	0.	1103.8 (306.6)	0.	38.1	156.9 (116.8)	84.5	11.34	----	----
TRAWL GAS	"	4.68 (1.73)	168.3	27.80 (5.68)	971.3	1139.6 (316.6)	85.2	36.9	" "	"	7.41	3.93 (34.7)	11,790
TRAWL DIESEL	2060	31.52 (11.66)	1134.7	0.	0.	1134.7 (315.2)	0.	37.9	162.6 (119.5)	86.0	11.66	----	----
TRAWL GAS	"	4.42 (1.64)	159.1	29.27 (5.97)	1022.8	1181.9 (328.3)	86.3	36.4	" "	"	7.61	4.05 (34.7)	12,150
STEAM DIESEL	2105	30.45 (11.27)	1096.3	0.	0.	1096.3 (304.5)	0.	37.3	154.6 (113.6)	81.3	11.27	----	----
STEAM GAS	"	4.52 (1.67)	162.7	29.91 (6.10)	1045.3	1208.0 (335.6)	86.5	33.8	" "	"	7.77	3.50 (31.1)	10,500

TABLE 1 (CONTINUED)

OPERATING CONDITIONS	RPM	DIESEL L / H ($ / H)	DIESEL MJ / H	GAS M3 / H ($ / H)	GAS MJ / H	TOTAL MJ / H (KW)	GAS %	ENGINE EFFIC. %	POWER HP (KW)	LOAD % FULL	TOTAL FUEL PRICE $ / HOUR	FUEL ECONOMY $ / HOUR (%)	SAVINGS $ / YEAR
WASH NETS DIESEL	2150	31.30 (11.58)	1125.2	0.	0.	1125.2 (312.6)	0.	37.3	158.6 (116.6)	82.6	11.58	----	----
WASH NETS GAS	"	4.75 (1.76)	170.8	30.61 (6.24)	1069.7	1240.5 (344.6)	86.2	33.8	" "	"	8.00	3.58 (30.9)	10,740
TRAWL DIESEL	2110	33.64 (12.45)	1210.9	0.	0.	1210.9 (336.4)	0.	38.4	175.8 (129.2)	92.0	12.45	----	----
TRAWL GAS	"	4.99 (1.85)	179.5	29.32 (5.98)	1024.4	1203.9 (334.4)	85.1	38.6	" "	"	7.83	4.62 (37.1)	13,860

CALCULATION DATA :

-- CNG METERED AT 4 KPA GAUGE PRESSURE
-- DIESEL OIL METERED IN A 626 c. c. CAPACITY GLASS FUNNEL TO A PRECISION OF MORE THAN 2 c. c.
-- DIESEL OIL CALORIFIC VALUE (NET) = 35.95 MJ / L
-- CNG CALORIFIC VALUE (NET) -- AT 1 ATM ABSOLUTE PRESSURE = 33.6 MJ / M3
AT 4 KPA GAUGE PRESSURE = 34.94 MJ / M3
-- DIESEL OIL PRICE = 37 CENTS / L (PRICE FOR PRIMARY PRODUCERS, AFTER A REBATE OF 7 CENTS / L)
-- CNG PRICE (COMPRESSED) -- 21 CENTS PER LITRE EQUIVALENT ($5.84 PER GJ)
20.41 CENTS / M3 (AT 4 KPA)
-- CNG PRICE (UNCOMPRESSED) -- $ 3.07 PER GIGA JOULE (GJ)
-- ENGINE EFFICIENCY -- WORKING ON DIESEL -- BASED ON MANUFACTURER'S DATA
WORKING ON DUAL FUEL -- RATIO BETWEEN DELIVERED POWER , AT SAME RPM ON DIESEL , AND ENERGY INPUT
-- SAVINGS PER YEAR -- BASED ON A YEAR OF 250 WORKING DAYS, 12 HR / DAY.